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DESIGN HANDBOOK FOR IMAG
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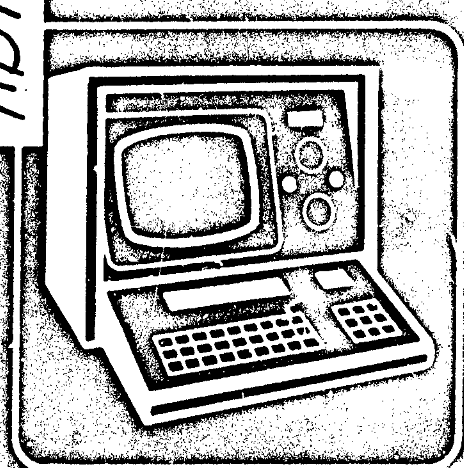

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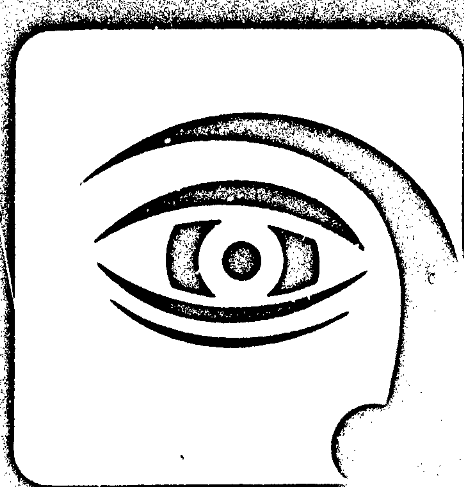

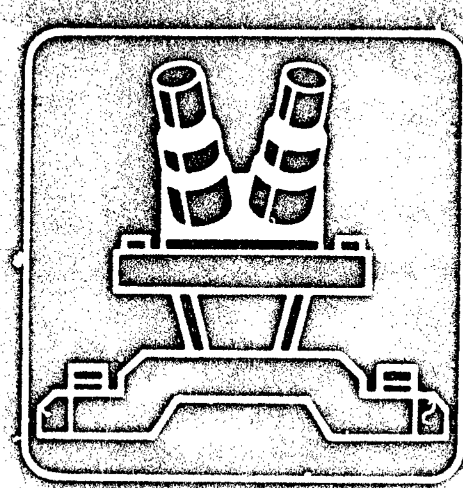

DESIGN HANDBOOK FOR IMAGERY INTERPRETATION EQUIPMENT

Richard J. Farrell
John M. Booth

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BOEING AEROSPACE COMPANY
Seattle, Washington 98124

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This Handbook is being released in both hardbound and loose-leaf form. It is planned that the loose-leaf version will be updated as new material becomes available. Users are encouraged to send their comments, criticisms, and suggestions for future revisions to the authors. In particular, suggestions for information which should be included to improve the usefulness of the Handbook are solicited. Comments should be directed to the authors at:

Boeing Aerospace Company
Box 3999
Seattle, Washington 98124

FOREWORD

This handbook is a major revision of an earlier document, *The Human Engineering Design Guide for Image Interpretation Equipment*, by R. A. Schindler, with later additions by R. J. Farrell, J. F. Sadler, A. A. Garra, and Dr. T. E. Sitterley.

The handbook is intended to give the reader ready access to information on those equipment design features that have a major influence on the performance of imagery interpretation tasks. The data that are presented have been extracted largely from the technical literature on vision, human engineering, and interpretation performance studies. Acknowledgements are due a large number of individuals who contributed to the effort. Technical assistance was received from the following individuals: Dr. Harry Andrews of the University of Southern California; Dr. Jay Enoch of Florida State University; David Gilblom of Sierra Scientific Corporation; George L. LaPrade, Goodyear Aerospace Corporation; Dr. Richard R. Legault of the Environmental Research Institute of Michigan; Dr. Herschel Leibowitz of The Pennsylvania State University; Dr. John Merritt of Human Factors Research, Incorporated; and Claude Patterson of the Aerospace Corporation.

In addition, significant contributions were made by the following persons on the staff of the Boeing Aerospace Company: Cal Abel, Charles D. Anderson, Dr. Robert Boyle, Dr. S. James Briggs, Dona Eckelberger, Dr. Charles Elworth, Patrick M. Fagan, Bruce Kenyon, Dr. Conrad L. Kraft, Jon Leachtenauer, Richard A. Schindler, Eric Schoenbeck and John Schroeder.

In addition to providing technical consultation during the development of the handbook, Dr. Elworth prepared the glossary and the index.

The compilation of the large volume of reference material necessary for the preparation of this handbook would not have been possible without the efficient service provided by Dorthy Slind and the entire staff of the Boeing Aerospace Technical Library.

The production required the efforts of many individuals in the group. Among these were Charles Okerlund and Richard Aleshire, who handled the production logistics, Ellen Levenseller, who did the editorial work, and Amy Nikaitani, who coordinated the graphics production and prepared most of the figures for the handbook. The final layout was performed by Stanley Yamashita.

To the many others not named here who also contributed much time and effort to the preparation of this work, we express our sincere appreciation.

R. J. Farrell
J. M. Booth

SUMMARY AND USER GUIDE

This handbook contains information, analyses, and recommendations intended to help in the design or procurement of imagery interpretation equipment. The material of this type that is specific to imagery displays appears in three sections:

- Section 3.0 Optical Imagery Displays
- Section 4.0 Electro-Optical Imagery Displays
- Section 5.0 Special Imagery Display Topics

Two other sections contain information of a more general nature:

- Section 6.0 Workstation Design
- Section 7.0 Facilities

The material in these sections falls into five categories:

- Recommendations These indicate, as precisely as possible, the best design for a display feature. They are printed in bold type at the front of sections where they appear.
- Supporting Analyses and Data These indicate the basis for each recommendation and allow the designer to decide the applicability of a recommendation to a particular situation. In some cases, these analyses and data can also be used to help decide if a certain display feature is worth what it will cost.
- Scales and Nomographs–These are included to facilitate conversion between units used in engineering and those used when describing the human operator of the display.
- Tutorial Material–This is general background material included for the benefit of a reader unfamiliar with a particular topic.
- References These are included at the back section to identify the source for the conclusion cited in the text, or to identify a sources of information. The letter ratings acc ing many of the references are described i 1.3.

There are several ways the reader can locate m a particular topic within this handbook:

- Tables of Contents These appear at the fr book and at the beginning of each major Some contain black edge marks to aid in fi sections listed.
- Checklists for Specific Displays–Section for each major equipment category, th features the designer should consider and t or figure in which these are discussed.
- Index–An index is provided that permits e to the subject matter contained in the handl
- Cross References–Many cross references are in the text to facilitate locating other material.

The other two sections of the handbook co following material:

- Section 8.0, Glossary, contains definitions o the technical terms used in the text. T italicized the first time they appear in eac and whenever they are defined within Section 8.0 also lists the abbreviations and c factors used throughout the text.
- Section 1.0, Introduction, provides a summ imagery interpretation process for the bene designer who is not familiar with this top summarizes sources of trouble in other dis suggests some techniques for evaluating new

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1.8 EVALUATION OF PROTOTYPE DISPLAYS

1.0 INTRODUCTION

1.1 PURPOSE

The goal of this handbook is to provide, in a concise form, information, analyses, and recommendations useful in the design and procurement of imagery interpretation equipment.

When the interpreter and the equipment are made more compatible through the successful application of the information and principles discussed here, benefits will occur in the following areas:

- Improved system performance
- Reduced training costs
- Improved utilization of personnel
- Fewer accidents
- Fewer errors due to equipment misuse
- Increased operator acceptance of the display
- Improved understanding of cost/benefit design trades

1.2 ASSUMPTIONS

The analyses and recommendations in this handbook are based on two assumptions about the display user. Because these apply so frequently, they are generally not repeated. They are:

- Normal visual ability - Unless the topic under discussion deals specifically with the impact of abnormal or limited vision on display design, the display user is assumed to have a normal visual system, possibly through the use of corrective spectacles.
- Shirtsleeve environment - The display will be used in a normal office-type environment. As a result, no allowance need be made factors such as arctic clothing or a pressure suit. This assumption primarily affects display dimensions.

1.3 CONTENT

The design information, analyses, and recommendations in this handbook are contained in five sections, 3.0 through 7.0. These five sections fall into two groups as follows:

- Sections 3.0, 4.0, and 5.0 contain material specific to imagery display equipment.

- Sections 6.0 and 7.0 contain more general information that applies both to imagery display equipment and to most other situations that involve a human operator. Because this material has been presented so thoroughly in other sources, only summaries appear here. If more detail is required, the references listed in each section should be consulted. One that appears frequently, the *Human Engineering Guide to Equipment Design*, edited by Van Cott and Kinkade (available from the U.S. Government Printing Office) will be particularly useful.

The material contained in Sections 3.0 through 7.0 falls roughly into five categories:

- Recommendations
  These indicate, with as much precision as possible, the best design for a particular display feature. To make them easier to locate, they are printed in bold type at the beginning of each section.

- Supporting Analyses and Data
  These serve three purposes. First, they provide an indication of how much support exists for a particular recommendation. Second, they allow the reader to decide whether a recommendation developed for all imagery displays is also correct for a specific device and application. Third, they can be used to help decide if a particular display feature or refinement is worth what it costs.

- Scales and Nomographs
  Each of these illustrates the relationships among several variables. In most cases, one variable is a physical unit commonly used in engineering and another is a corresponding physical unit commonly used when presenting information about the human operator. As a result they can be used to reduce the work involved in applying the design recommendations to a specific piece of equipment.

- Tutorial Material
  This material is included both for the benefit of a reader unfamiliar with a particular topic, and to provide a consistent terminology for use when discussing design recommendations.

- References
  These indicate the source for the data or conclusion presented in the text, or they identify additional sources of information on the topic. References are listed at the end of each section. The letter ratings which follow many of the references are described in Section 1.4.

There are several ways to determine the location of material on a specific topic within this handbook. These are:

- Tables of Contents
  Two tables of contents appear at the front of the handbook. The first lists the major sections and includes black index marks at the edge of the page to aid in locating sections. The second lists every numbered section in the handbook. A table of contents also appears at the beginning of each major section. When the section is long, these also include index marks at the edge of the page.

- Equipment Feature Lists
  Section 2.0 lists, for each class of imagery display equipment, the specific features the designer should consider. These lists also identify the section or figure in the handbook where design information on each feature can be found.

- Index
  The last section contains a complete index that lists the location of terms and concepts discussed in the text. In addition, it lists the terms defined in the glossary.

- Cross References
  Extensive cross referencing is used within the text to indicate location of other relevant material.

Technical terms that are defined in Section 8.0, the glossary, are italicized the first time they appear in a section and are also italicized when they are defined in the text.

1.3 CONTENT (CONTINUED)

Standard metric units are used wherever possible, followed by the English equivalent. Conversion values are included in Section 8.0. When the values given are only approximate, both the metric and English value have been rounded, making the conversion differ slightly from the exact value.

1.4 EVALUATION OF REFERENCES

The approach in preparing this document has been to work from original research reports whenever these were available. Secondary sources, and conclusions and recommendations presented without supporting data in other handbooks, have been used only when better information was not available.

The research summarized in this document, though always the best available, varies widely in quality and in relevance to the topics discussed here. In order to provide the reader with some indication of how much reliance can be placed in each set of test data presented, one of the following ratings has been assigned whenever possible to the study in which the data was collected:

- A--Highly reliable data from a well designed and conducted experiment utilizing an adequate number of subjects from a population representative of the potential display user. These values are highly unlikely to change.
- B--Probably reliable data, but improvement in the data collection process is desirable. These values will probably show only small changes.
- C--Fairly reliable data, but the shortcomings of the experiment, at least for the present application, may be seriou. With additional testing, these values might change, though probably not drastically.
- D--Data from a small experiment that might better be called a pilot study or preliminary test. Also, data that may not exactly apply to the topic under consideration. These are included only because no other data on this particular topic are available.
- X Reliability of the data is unknown, usually because it was obtained from a secondary source that did not adequately describe the original experiment. Most data obtained from handbooks fall into this category.
- The absence of a letter rating means that no evaluation was performed, either because of limitations on resources or because it was not appropriate to rate the reference.

Some of the factors that affect the reliability and relevance of a set of experimental data to a display application are discussed in Section 1.8. In addition, it is very important to keep in mind the impact of task difficulty, both in the test situation and in the work situation. In general, a difficult task is much more sensitive to variation as a result of viewing conditions than is a simple task. As an example, a subject will be able to read large high-contrast letters at the same constant high rate over a much larger range of viewing conditions than if the letters are small and have low contrast. Similarly, a target search test in which all the targets have been specially selected to be difficult to see will result in a performance loss under viewing conditions that would not cause a measurable change with a test made up of randomly selected targets. As another example, the benefit from viewing imagery in stereo is likely to be too small to measure when averaged across many randomly selected targets, but given sufficient time it is possible to find selected targets and to ask selected questions about those targets that would be extremely difficult to answer without stereo. As a result, the question "Is stereo useful?" has a meaningful answer only in the context of a specific application.

1.0 INTRODUCTION

1.5 THE DISPLAY USER'S TASK

The goal in describing the imagery interpretation process in this section is to provide the display designer with better insight into the problems and needs of the display user.

Most of the material in this handbook applies to imagery displays regardless of their purpose. This section, however, is limited to the interpretation of imagery to obtain information of military significance. When reading this section, it is well to keep in mind that the procedures followed in interpreting imagery vary from one organization to the next and that even within a single organization there are likely to be several variations. As a result, even though the statements made here are very general, there are sure to be many exceptions to them.

Imagery interpretation can be divided into several general categories. However, these do not always occur, they may be combined, and they do not necessarily follow the sequence in which they are described below.

- Quality check–When the imagery reaches the interpretation facility, there may be a quick scan to determine the quality. The factors of interest include approximate ground resolution, the specific ground areas covered, and whether these are obscured by ground fog or clouds.

- Search–Viewing the imagery in order to find new targets is known as "search." The search might be for any reportable target, or it might be limited to one specific type of target. The search might be performed in two steps, the first very rapid and directed toward finding only very high-priority targets, and the second slower and more thorough in order to be certain that all targets have been found. The search might involve either a small or a large area on the ground or on the imagery. It might be completed in minutes or it might require many days. The latter case is generally more important in terms of manpower utilization. Figure 1.5-1 summarizes one approach to search.

- Surveillance–It is sometimes necessary to view a known target on the imagery in order to report any changes that have occurred. The interpreter may depend on a written report to learn what was on the prior imagery, but he may also have a copy available. In addition, he may be familiar with the target. The quality of the coverage of each known target may also be cataloged for use in case of a future requirement to retrieve imagery showing this target as it appeared over a period of time.

- Interpretation of a new target–When a new target is found, it is studied in whatever detail is justified by its importance and by the time available. Important or difficult to interpret targets are likely to be discussed with supervisory-level interpreters and perhaps with experts on the particular type of target involved. This may result in several individuals using a single display in quick succession.

- Reporting a new target–Once a new target has been identified, a report on it must be prepared. This may be in written form, or it may be composed on a computer terminal and entered directly into a data bank. In some organizations, the report goes through several stages of editing by supervisory personnel prior to being released. The content of a typical report is described below.

- Mensuration–The dimensions of details in a target may be measured as an aid in identification or for inclusion in a report. This is generally done on a comparator, and the imagery dimensions may be converted to ground dimensions by a computer connected to the comparator. The measurements may be made by the interpreter, or by an individual who specializes in operating the comparator.

- Detailed analysis–In some cases, the interpreter will perform a thorough and detailed analysis of the development or the current status of one target or a class of targets, or on some more general topic. This often requires the interpreter to make use of imagery collected over a period of time.

The basic items required in order to interpret imagery are the imagery itself, a display on which to view it, and a statement of specific interpretation task to be performed. A number of other items are usually provided also. These are grouped loosely under the term "collateral materials." They may exist in the form of hard copy, for example as a piece of paper or film, or even as a reduced size image in a microfiche storage and display

1.5 THE DISPLAY USER'S TASK (CONTINUED)

device. Alternatively, they may be stored in an electronic data base for display to the interpreter on a computer terminal. The kinds of material involved include the following:

- Information on any known targets involved, in text form, perhaps on a computer printout or a cathode ray tube (CRT) display. This information includes the name and code number of each target, its geographic coordinates, the number of the map on which it appears, a description of any prominent geographic features, and a description of the target and its status as it appeared on previous coverage. It may also include the anticipated location of the known target on the new imagery.
- Maps of appropriate scale, which may or may not be annotated to show known targets.
- Some indication of the geographic area covered by the imagery to be viewed, generally in the form of a map overlay.
- If available, special background material, such as photo keys that show the kind of target being sought, or perhaps a report that a particular kind of target is suspected of being present in the area covered by the imagery.
- Report forms, either in hard copy or in the form of a cathode ray tube (CRT) display if the report is to be fed directly into an electronic data base.

A report prepared by an interpreter on a new target will usually contain the following information:

- The target name and code number, if these have been assigned
- The imagery on which the target was found, generally in terms of imagery frame, roll, and flight numbers
- The date the imagery was collected
- The imagery coordinates of the target
- The latitude and longitude of the target, usually measured on a map
- If the target is important and the time and imagery are available, information about the status of this ground feature as it appeared in previous coverage (where it was not reported)
- The location of the target relative to prominent ground features, such as cities, roads, and rivers
- A description of the important features of the target, including its size and its important features.
- A count of the number and type of order-of-battle items, such as aircraft, ships, or ground vehicles present

Speed requirements vary widely. A report on critical targets may be required within a few minutes or hours after receipt of the imagery, while several days or even weeks may be available to search for routine targets.

The map and the imagery will usually be viewed with the same orientation. Since the preferred orientation for viewing the imagery is fixed by the need to have any large obliquity fall away from the observer, and by a general preference to have shadows fall toward him, it is seldom possible to use the map with its normal orientation of north at the top. Because a single frame of imagery may cover an area at the edge of a map, it is sometimes necessary to use two or even more maps at once. A place to display one or several folded maps within convenient visual access of the imagery display is therefore a very desirable feature.

In most organizations, the interpreter will make frequent use of imagery coordinates. These are usually based on an X-Y, or Cartesian, coordinate system with the reference point at some specified mark or edge on the imagery. Typical units are centimeters measured to the nearest tenth. The interpreter assigned to check several known targets on new coverage may be provided with their predicted imagery coordinates and hence will need to locate each of these coordinates on the imagery. Also, the imagery coordinates of each new target found will be included in the report as an aid in finding it again on that imagery. The most common method of locating or determining a pair of imagery coordinates is by means of a transparent grid overlay. As one might expect, on many displays this is very cumbersome. An automatic

1.5 THE DISPLAY USER'S TASK (CONTINUED)

coordinate readout device would be helpful but would have to be very simple and reliable to compete with the grid, even as cumbersome as it is.

The importance of specific ground features varies over both time and geographic area. As a result, a ground feature that is a target in one time and location may not be in another. This makes it very difficult to obtain a consistent, operationally useful definition of just what a target is, and interferes seriously with attempts to measure the impact of a new display on target detection performance. Probably the best available definition is that a target is anything that should be reported.

As Figure 1.5-1 describes, many interpreters search for targets in a manner that requires access to mark the imagery area being viewed. In a complex display, providing this access can be a serious problem.

An item important to many interpreters that can create a problem for the display designer is the grease pencil. Its use in annotating suspect targets is described in Figure 1.5-1 below. It is also used by some interpreters to mark the known targets on a frame, and by some to divide a large search area into several smaller areas, thereby decreasing the chance of missing a portion of the assigned search area. A grease pencil, besides being inexpensive and easy to obtain, is easy to apply, easy to see, and easy to remove from the film. The problem for the designer is that the grease pencil wax may be transferred from the film to a surface that must be kept clean, such as a glass platen used to hold the film flat.

In some image interpretation facilities, the problem of grease pencil wax getting on the display has been eliminated by the use of felt-tip pens containing ink that can be removed with a special solvent. This does not eliminate the need for the interpreter to reach the film area being viewed in order to mark it. A device that automatically keeps track of and returns the imagery to any one of several locations, as commanded by the user, would eliminate this problem also, but only at considerable expense.

1.5 THE DISPLAY USER'S TASK (CONTINUED)

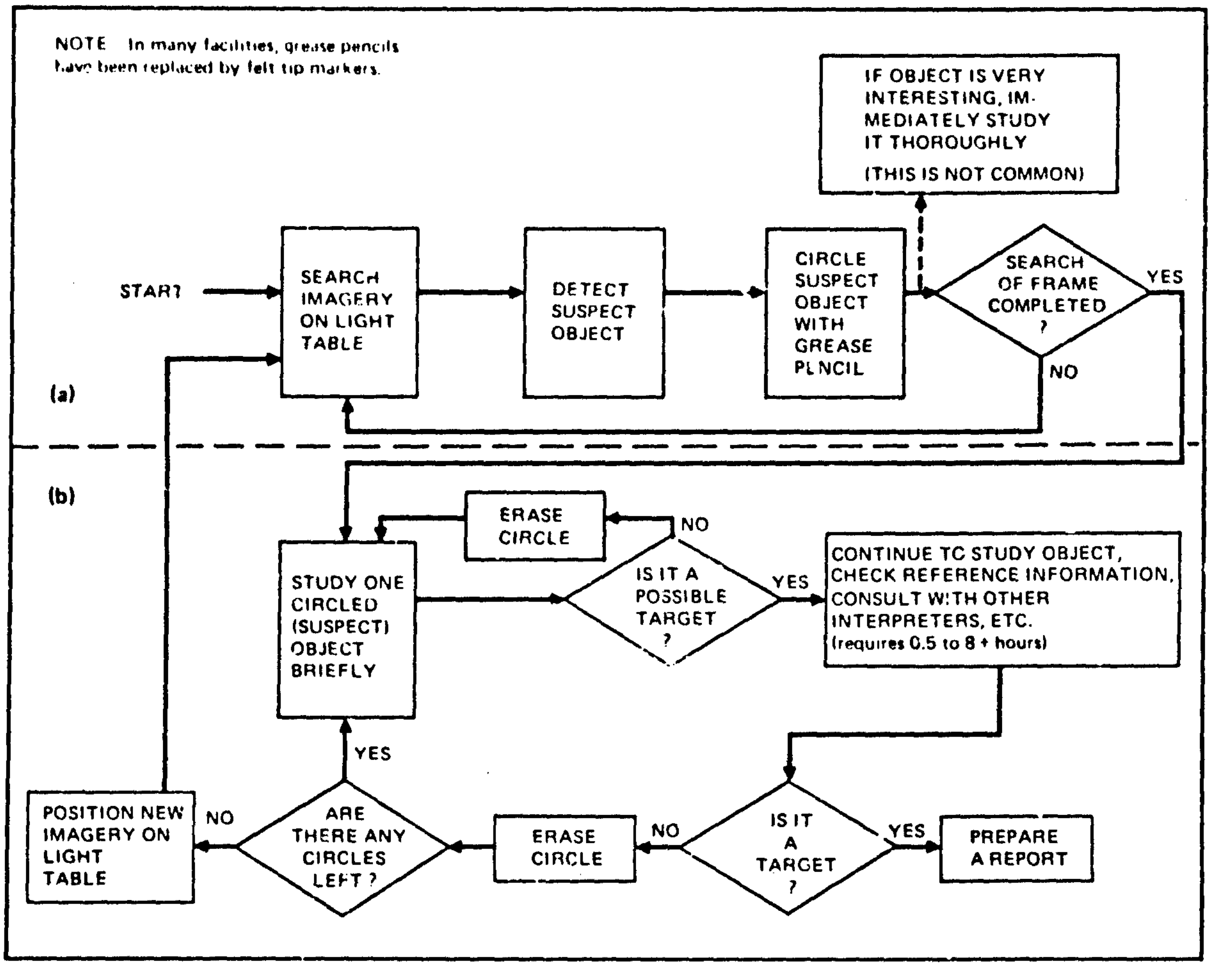

Figure 1.5-1. The Grease Pencil Method of Search.
While there are numerous variations in how search is performed, the method illustrated here is followed, in a very general way, by many interpreters. A major feature of the process shown is the division of search into two parts. The first, part (a), involves the careful viewing of a large area of film to find possible targets, each of which is circled with a grease pencil. This continues until several centimeters to several meters of film, depending on the individual, have been searched. Then part (b) of the process, the checking of each marked object to determine if it really is a new target, is performed. This is an iterative process, with most of the possible targets eliminated immediately and others being checked several times before being either eliminated or accepted as a previously reported or new target.

There are several differences between these two parts of the search process that may contribute to their being performed separately. They require somewhat different display conditions, with (b) usually involving higher magnification and, in some cases, stereo. Part (b) also differs in that it often involves consultation with other interpreters, while (a) is essentially solitary. Finally, it may simply be easier for most individuals to retain for a period of time the mental attitude required for only one part of the process, rather than switching frequently between them.

1.6 CHARACTERISTICS OF IMAGERY

The relevant characteristics of the imagery to be used on a display will normally be included in the procurement specification for the display. Hence, this section is limited to a general summary of the possible kinds of imagery, plus a review of special problems sometimes encountered.

The most common type of imagery is black and white, or achromatic, silver halide film sensitive in the visual region of the spectrum. Others include: color, or chromatic, film; nonsilver halide film; film sensitive to radiant energy outside the visible spectrum; and electronic signals, usually recorded at some point on magnetic tape, representing either radiant energy in various parts of the electromagnetic spectrum or a special signal such as a radar return. When resolution is particularly important, most film is viewed as a positive transparency contact printed from the original negative.

Typical nominal film widths are 70 mm (2.8 in), 125 mm (5 in), and 230 mm (9 in). Exact dimensions for typical achromatic films, and film reels, can be found in military specification MIL-F-32G. Film may arrive at the display in a roll, or web, of up to 300m (1,000 ft), though much shorter rolls are more common. It may also arrive as a film chip which will vary from a few centimeters to a meter or so in length. One advantage of chips is that they reduce the distribution problems when several interpreters must view the film on a single roll.

Most film includes a border that contains essential information such as the frame and roll number and small marks that serve as reference points for determining film coordinates. On some film, a data block containing collection system flight parameters such as time and altitude in coded form is also present.

Film is often very difficult or even impossible to replace, so it is important that the display not damage it. Scratches and overheating are the two most common problems. This does not mean, however, that the film will necessarily arrive at the display clean and undamaged. In some organizations, at least part of the film will arrive with grease pencil marks or with splices where portions of frames have been removed. Splices can be particularly troublesome when made with poor quality tape, which can result in adhesive sticking to parts of the display. All display parts that come in contact with film should therefore be suitable for cleaning. Another potential problem with tape splices is their thickness, which can interfere with the action of mechanisms such as a vacuum platen.

Most roll film has a tendency to curl, usually toward the emulsion side. The amount of curl varies with many factors, including the amount of tension on the film. In addition to the obvious requirement to keep film flat and in the object plane of the display during viewing, film curl must be considered when allowing for clearance between the film and parts of the display. (See Section 1.7.)

1.7 PROBLEMS WITH PROTOTYPE DISPLAYS

One way to obtain a better display is to avoid the features that led to difficulties with earlier designs. Hence this section provides a summary of some of the problems that have occurred, both with prototype imagery displays and with other kinds of equipment.

Many of these problems occur, at least in part, because the display designer and the display user have very different points of view. The designer by necessity is intimately familiar with the inner workings of the display and is likely to be very concerned for its success. To the interpreter, a new display is only another tool to be used to perform some task he is probably performing with fair success already. As a result, unless the potential advantages of a new display are both large and immediately obvious, he will have very little tolerance for complicated controls or for repeated equipment failures, nor is he likely to be very impressed with promises that any operating difficulties he is experiencing will be corrected on future production models.

Carrying this idea a little further, it is useful to contrast proper design practice with what sometimes happens. The correct starting point for the design of a display is a description of the display performance requirements and of the display functions to be controlled by the operator. This list of functions should be used to determine the operating controls and secondary displays required and these in turn should be used as the basis for designing the control electronics and mechanics. In one complex imagery display this sequence was reversed. After the optics were selected, the control electronics were designed, after which a set of controls was added. The result was a display so difficult to learn to operate that the only successful user was an interpreter who saw the controls as a challenge.

It is easy when designing a display workstation to treat the operator as a rigid manikin and to ignore all the actions he will be performing and all the materials he will be using. For example, the workspace must be adequate not just for the range of operator body sizes expected (Section 6.1), but also for many changes in body position to maintain blood circulation and reduce fatigue. Space is also required for displaying maps and for reading and writing on computer printouts. The operator will probably need pencils and ashtray within reach while looking into the display, and some may even want space for a coffee cup. One of the best ways to determine if a planned display is compatible with the operator's bodily dimensions is by building a cardboard or plywood mockup. The evaluation of such a mockup should include a realistic range of body sizes (Section 6.1.1) and individuals familiar with imagery interpretation work.

Some displays, particularly those intended for special purposes such as precise mensuration or for comparing different pieces of imagery, require a careful and lengthy setup that can be ruined by the accidental manipulation of the wrong control. Since these devices are operated primarily while looking into the display, the tendency to not look carefully at each control before using it increases the chance of error. This was a particularly bad problem in the case of a comparator which required up to half an hour to set up one frame of imagery, after which a certain pushbutton had to be depressed once for each of the dozen or so pointings to be made. Unfortunately, depressing a pushbutton adjacent to this one, which differed from it only in color and labeling, required that the whole process be restarted. The addition of interchangeable plastic overlays that would allow the operator to depress only the pushbuttons required during each phase of the operation would eliminate this problem, but they are undesirable because they demand additional operating steps and they might become lost. A more elegant solution would be to position the controls in separate groups so that such errors would be unlikely (Section 6.3.1). Other approaches would be shape coding (Section 6.3.2), the use of completely different kinds of controls (Section 6.2), or the use of devices that preclude inadvertent operation.

A similar, though less serious problem occurred in a stereo display in which magnification and image rotation for each optical train were controlled by identical, adjacent knobs. In this case, accidental rotation of the wrong knob caused a moderate increase in setup time, and when the setup was difficult tended to cause a large increase in frustration level. Since knob location was limited by mechanical restraints, the easiest solution would have been shape coded knobs (Section 6.3.1).

1.7 PROBLEMS WITH PROTOTYPE DISPLAYS (CONTINUED)

New attachments, or performance requirements nobody remembered to tell the designer about, can be a problem. In one case, a new light table held roll film flat enough to clear the sample microscope provided to the designer, but when a new objective lens with a short *working distance* was added to the microscope mounted on the prototype light table, it frequently caught on the edge of the film. A similar case occurred when the designer of a vacuum platen intended to hold roll film flat for viewing was provided with a clean, uncut sample film to use while building the platen. He was apparently not aware that the platen would also have to work with film that had been cut and taped back together. In addition to the surface irregularity caused by the thickness of the tape, slight misalignment of the two ends of film at the taped joint increased the amount of curl in the film and interfered with the action of the platen. It was also never established whether it would be possible to remove grease pencil wax without causing damage to the delicate optical surface of the platen (see Section 1.5).

In displays intended for viewing a moving image, which includes almost all imagery displays, a frequent problem is irregular, or jerky, motion at low velocity. As is discussed in Section 3.10, tolerance for such variation in the velocity is extremely low.

Excess acoustic noise is likely to be a problem in any display in which air is required for cooling the imagery. Because of the kind of noise they make, it is likely to be a serious problem whenever an air compressor or vacuum pump must be used with the display.

"Hold-downs" are pieces of plastic or rubber, often in the shape of rings, that are commonly used to hold film flat on a light table. On rare occasions, these are inadvertently left on the film when it is translated, with the result that they pass through the rollers at the end of the light table and are temporarily wound with the film on the film reel. One prototype display included a light table on which such hold-downs were to be used. A problem existed because it also contained delicate components that might have been damaged if the hold-downs had been left in place while the film was moved.

For frequently repeated tasks, it is important to avoid long, complex procedures. Loading roll film into a complex display is a task that often violates this rule. One very sophisticated display was seldom used, largely for this reason. In another display, a prototype in this case, elimination of film threading by installing a permanent leader that was attached with masking tape to the end of a roll of film being loaded was not a very successful solution, because it was a difficult procedure to perform smoothly.

Devices that work well in one application or location may not in another. For example, toggle switches work well in many situations, but when mounted on the lower front edge of a light table, they must be provided with guards or they will be broken off by the arms of the interpreter's chair. Pushbuttons are also useful, but if they are located near where the display user may rest his elbows, they are likely to be activated accidentally.

1.8 EVALUATION OF PROTOTYPE DISPLAYS

A normal step in the development of a new display is the construction of a prototype unit that can be evaluated to establish whether the display is useful and to determine what modifications should be made in production units. One part of such an evaluation is engineering testing. This should determine if contract specifications such as image quality, compatibility with different film sizes, and limits on surface temperatures have been met, if good construction practice has been followed, and if reliability is likely to be acceptable.

Another part of the evaluation is the determination of just how suitable the display is for use in an operating work environment. That is, will it improve work output? Will it improve operator comfort so that the same output rate can be maintained for a longer period of time? Is it compatible with all phases of the work operation? Does it impose any new requirements on the work situation and are these acceptable? Is it difficult to learn to operate, so that personnel will require extensive training? Do the operators find it acceptable? If not, can the problems be easily corrected? Are there any changes to the operator interface, such as the relocation of a control, that would make it easier to use?

The evaluation of whether the display is suitable for the operating environment can be conducted at many different levels. One approach is to add a tag saying "New Equipment Please Evaluate" to the display and leave it in the hall next to the interpretation work area with the hope someone will come along and use it. At the other extreme, in both information obtained and cost, is a formal test program in which selected interpreters are first trained to operate the display, after which their performance is measured while they use the new display, and any competing displays, with test imagery and tasks carefully selected to represent the normal work situation.

The second approach provides a much better basis for deciding whether a new display is worthwhile, and should be used when possible. If the available ·ources limit the evaluation to something closer to the first approach, then at a minimum it is necessary to establish sufficient controls over who uses the equipment and over the method of data collection so that the results are meaningful. Whatever approach is used, the following guidelines should be followed:

- Before conducting the evaluation, think through the data analysis process to determine how the results must be presented in order to allow making the necessary management decisions.

- Rather than attempting to measure absolute performance level on the new display, design the test as a comparison between the new display and the current model it is intended to replace.

- Conduct an operational evaluation only on a properly functioning display. Interpreters will have a very low tolerance for equipment that is difficult to use because it has been poorly constructed, or that keeps breaking down.

- Provide each user with sufficient training to ensure that the display is not rejected because someone didn't know how to operate it.

- Inform each operator in person, not just by memo, about the purpose of the display and his role in evaluating it. Besides reducing confusion, this will make the operator more enthusiastic about the evaluation, though not necessarily more satisfied with the display.

- Establish a schedule showing who will use the display and when. This will help ensure an adequate number of users, and an adequate range of work tasks.

- When selecting the work tasks to be performed on the display, keep in mind that more difficult tasks are more sensitive to differences between viewing conditions. For a general purpose display, a representative work task should provide the best indication of the operational performance that would be obtained with the display. However, when testing time is limited, task items specially selected to be very difficult will be more effective in determining if one display is better than another.

- If work performance is to be measured, be sure that all operators are aware that the intent is to evaluate equipment, not personnel, and that their performance scores will remain confidential.

1.8 EVALUATION OF PROTOTYPE DISPLAYS (CONTINUED)

- When feasible, brief the test subjects on the outcome of tests in which they participated.

- Determine the data to be collected from the management decisions for which they will be used. For example, a decision on whether or not to buy a production quantity of the display being evaluated requires different information than a decision on whether a specific feature of the display should be incorporated into a future model.

- Establish a formal procedure for data collection. If the data must be limited to operator opinions, ask specific questions covering each area in which information is required, not just general questions such as "What did you think of it?"

- If data must be limited to operator judgments, require the operator to use the display to perform realistic tasks before asking for the judgments. This will provide him with a much better basis for making a fair appraisal of the display.

- Use a sufficient number of operators, from a sufficiently wide range of organizations, as is required to obtain meaningful results.

- Whenever possible, use established statistical procedures to determine the margin for error in the results and the probability that the differences observed were due to chance variation in the data.

Since prototype displays often represent an improvement in the available adjustment range of features such as image luminance or image translation velocity, they can be used to obtain valuable information about the operational use of these features that will help set requirements for future displays. Prototype displays should be provided with test points and scales that would make it possible to obtain such information without modifying the display. For example, the knobs that control luminance, magnification, image rotation and similar functions, in addition to their normal labeling, should include a scale that would allow their precise setting to be recorded. These need not be calibrated, since this can be performed in the field. Test points should be provided for signals from the operating mechanisms for functions where visual access to the control settings is difficult and for controls (such as joysticks and track balls) whose nature prevents the use of scales. Test points should also provide access to signals related to functions that change rapidly during use, such as image velocity. Such test points would have made data like that shown in Figure 3.10-9 much easier to obtain.

SECTION 2.0
CHECKLISTS FOR SPECIFIC DISPLAYS

2.1 ALL TYPES

2.2 BINOCULAR

2.3 BIOCULAR

2.4 SMALL EXIT PUPIL

2.5 SCREEN

2.6 ELECTRO-OPTICAL

2.7 LIGHT TABLES

2.8 TUBE MAGNIFIERS

2.9 COMPARATORS

2.10 STEREO

2.11 COLOR

SECTION 2.0 CHECKLISTS FOR SPECIFIC DISPLAYS

When the designs or procurement specifications are being prepared for a display system, it is useful to have a list of the display features that should be considered. This section provides several such lists. More than one of these lists will apply to most displays. For example, a microstereoscope mounted on a light table and intended for viewing color imagery would involve the following lists: Sections 2.1 (which applies to all displays), 2.2, 2.4, 2.7, 2.10, and 2.11.

Because of the complexity of many of the design recommendations contained in the later sections of this document, the lists given here are limited to identifying the display characteristics that should be considered, plus the section numbers where specific design recommendations or supporting data can be found. In a few cases a display characteristic is listed here so that the designer will be reminded of it, even though it is not discussed elsewhere in the book.

Screen and aerial image displays are defined in the introduction to Section 3.0, and binocular and biocular displays are defined in Section 3.7.1. These and any other terms that are unfamiliar can probably be found in the glossary (Section 8.0) or the index .

2.1 ALL IMAGERY DISPLAYS

2.1.1 Is the image luminance adequate for best vision, even when the film has the maximum density? (Sections 3.2.6, 3.2.5)

2.1.2 Is an adequate luminance control and control range provided? (Sections 3.2.6, 6.2.1)

2.1.3 Is the illuminant spectral distribution adequate for best achromatic vision? (Section 3.2.7)

2.1.4 Will temporal variation in image luminance, or in light reaching the eye from any other part of the display, cause noticeable flicker? (Sections 3.2.10 and 4.2)

2.1.5 Are all sources of glare and veiling luminance eliminated or at least easily shielded by the operator? (Sections 3.2.12, 3.2.13)

2.1.6 Is the quality of the displayed image as good as necessary given the available imagery quality? (Section 3.3)

2.1.7 If possible, is a binocular viewing capability provided? (Section 3.7.2)

2.1.8 Is an adequate magnification range provided? (Section 3.3.1, 3.3.2)

2.1.9 Are aberrations excessive with a static image? (Section 3.4). With the image moving at anticipated velocities? (Section 3.4.4,3.4.5,3.10.3)

2.1.10 Is the display field sufficiently large? (Section 3.5)

2.1.11 Is the display field larger than can be effectively used? (Section 3.5)

2.1.12 Is the displayed image at the best viewing distance for the eye? (Section 3.6)

2.1.13 Is the focus range adequate? (Section 3.8.1)

2.1.14 Is the focus mechanism adequate? (Section 3.8.2, 3.8.3)

2.1.15 Is the minimum non-zero image velocity adequate? (Section 3.10.3)

2.1.16 Is the maximum image velocity adequate? (Section 3.10.3)

2.1.17 Is the entire range of image velocities free of noticeable jerk? (Section 3.10.3)

2.1.18 Is the image velocity control system adequate? (Section 3.10.4)

2.1.19 Does the image velocity for a given control input remain nominally constant as magnification is changed? (Section 3.10.4)

2.1.20 Can the image be rotated as required? (Section 3.10.6)

2.1.21 Does the relationship between image translation control input and image translation directions remain constant with image rotation? (Section 3.10.7)

2.1 ALL IMAGERY DISPLAYS (CONTINUED)

2.1.22 Does vibration degrade the quality of the display image? (Section 3.11)

2.1.23 Are the physical dimensions of the display and the operator compatible? (Sections 6.1, 6.1.1)

2.1.24 Are all control types appropriate? (Section 6.2)

2.1.25 Are all controls and displays in the appropriate relationship to each other? (Section 6.3)

2.1.26 Are all controls and displays in appropriate locations? (Sections 6.1.4, 6.1.5, 6.3.1)

2.1.27 Are secondary display parameters adequate? (Section 6.4)

2.1.28 Are adequate scales provided to show control settings? (Sections 6.3.4, 6.5, 3.7.3, 3.8)

2.1.29 Does the combination of control and display choice and layout plus labeling make the operation of the display obvious with minimal training? (Sections 6.2, 6.3, 6.5)

2.1.30 Are all possible hazards eliminated? (Sections 6.6.4, 6.8, 6.9.9)

2.1.31 Are personnel made aware of all hazards that cannot be eliminated? (Sections 6.8, 6.5)

2.1.32 Does the display generate sufficient noise to be hazardous? (Section 6.6.4) To interfere with communication? (Section 6.6.4) To cause operator discomfort? (Section 6.6.5)

2.1.33 Are all requirements for preventive maintenance, including the maintenance schedule, made obvious to the operator? (Sections 6.9.1, 6.9.11)

2.1.34 If there is any reason to know display operating time, has a meter been provided?

2.1.35 Has adequate provision been made for repair? (Section 6.9)

2.1.36 Are adequate operating and maintenance manuals provided? (Section 6.10)

2.1.37 Is film support and hold down adequate?

2.2 BINOCULAR DISPLAYS

2.2.1 Is the interpupillary distance (IPD) range adequate? (Section 3.7.3)

2.2.2 Is the interpupillary distance (IPD) setting displayed? (Section 3.7.3)

2.2.3 Are the images to each eye registered adequately? (Section 3.7.4)

2.2.4 Will differences in images to each eye cause the image to appear excessively curved? (Section 3.4.5)

2.2.5 Do the images to each eye match in viewing distance? (Section 3.7.7)

2.2.6 Do the images to each eye match in quality? (Section 3.7.8)

2.2.7 Do the images to each eye match in luminance? (Section 3.7.9)

2.2.8 Is there an adequate differential focus range? (Sections 3.8.1, 3.8.3)

2.2.9 Is the differential focus mechanism adequate? (Section 3.8.3)

2.2.10 Is the differential focus setting displayed? (Section 3.8.3)

2.2.11 Does the eye convergence angle approximately match the viewing distance? (Section 3.7.4.2)

2.2.12 If there are small exit pupils, is the eye relief adequate for display users wearing spectacles? (Section 3.9.5)

2.2 BINOCULAR DISPLAYS (CONTINUED)

2.2.13 If there are small exit pupils, is face clearance adequate? (Section 3.9.6)

2.2.14 If there are small exit pupils and a chance spectacles could contact the display, can scratches result? (Section 3.9.3)

2.2.15 If there are small exit pupils, is the eyepiece elevation angle reasonable? (Section 6.1.3)

2.2.16 If there are small exit pupils, is the eye height suitable? (Section 6.1.2)

2.3 BIOCULAR DISPLAYS

2.3.1 Are distortions excessive? (Section 3.4.5)

2.3.2 Does the registration between the images to each eye vary excessively as the head changes position within the exit pupil? (Sections 3.7.1, 3.7.4, 3.4.5)

2.3.3 Is the luminance adequate? (Sections 3.2.6, 3.7.1)

2.4 AERIAL IMAGE DISPLAYS WITH SMALL EXIT PUPILS

2.4.1 Is the eye relief for display users wearing spectacles adequate? (Section 3.9.3)

2.4.2 Is face clearance adequate? (Section 3.9.6)

2.4.3 If there is any chance spectacles could contact the display, can scratches result? (Section 3.9.3)

2.4.4 Is the eyepiece elevation angle reasonable? (Section 6.1.3)

2.4.5 Is the eye height suitable? (Section 6.1.2)

2.5 SCREEN DISPLAYS

2.5.1 Is the screen shielded from ambient illumination? (Section 3.2.13, 4.4.2)

2.5.2 Is the screen tilted slightly to prevent the user from seeing a reflection of his face or shirt? (Section 3.2.13)

2.5.3 If reflection may be a problem, is an antireflection screen used? (Section 3.2.13)

2.5.4 Is the distance to the screen appropriate? (Sections 3.6.5, 4.3.10)

2.5.5 Is the focus control adequate? (Section 3.8.4)

2.5.6 Is the screen size appropriate? (Section 3.5)

2.6 ELECTRO-OPTICAL IMAGERY DISPLAYS

2.6.1 Will the resolution of the camera remain at adequate levels if moving imagery is viewed? (Sections 4.3.7, 4.4.2)

2.6.2 Have adequate precautions been taken to protect the camera from damage by intense light sources?

2.6.3 Have adequate precautions been taken to protect the camera and the CRT from excessive electron beam currents?

2.6.4 Has the range of the camera's linear response to luminance been matched to the range of luminances expected in its operating environment?

2.6.5 Are the color response characteristics of the camera matched with its intended use if color imagery is to be generated?

2.6.6 Is a three-or a four-tube color camera necessary to maintain resolution in color imagery? (Sections 4.0, 4.1)

2.6.7 Is the matrixing of the color signals matched to the intended use of the imagery? (Sections 4.0, 4.1)

2.6.8 Have the quantizing levels been selected to match the intended use of the imagery? (Sections 4.0, 4.3.6, 4.4.2)

2.6.9 Is the deflection angle of the CRT the minimum which can be used? (Sections 4.0, 4.1)

2.6.10 Is there a possibility of better utilization of available bandwidth through the use of higher order line or line/dot interlace techniques? (Sections 4.0, 4.2)

2.6.11 What display aspect ratio should be used? (Sections 4.0, 4.4.2)

2.6.12 Does the face of the CRT need to be protected from ambient illumination? (Sections 4.0, 4.4.2)

2.6.13 Is the luminance produced by the display linear with respect to the strength of the imput signal over the operational range of signal strengths? (Section 4.4.1)

2.6.14 Do high luminance levels in one part of the display area significantly degrade the contrast in adjacent low-luminance areas? (Sections 4.0, 4.4.2)

2.6.15 Do the normal variations in displayed color fall within acceptable limits for the intended application of the system?

2.6.16 If both color and black and white images are to be used, should separate displays be provided? (Sections 4.0, 4.3.8, 4.4.2)

2.6.17 Is the difference in resolution between the center and edges of the display within the limits required by the intended use of the system? (Section 4.0)

2.6.18 Are the geometric distortions of the image within the limits allowed by the intended use of the system?

2.6.19 Has the relationship between line width and line spacing been set with proper consideration for the intended use of the imagery? (Sections 4.4.1, 4.4.2)

2.6.20 Does the design ensure that line pairing will remain within acceptable limits (Sections 4.0, 4.4.2)

2.6.21 Has the effect of raster size and viewing distance on the visibility of the scan lines been taken into account? (Sections 4.0, 4.4.2)

2.6.22 Has the system been designed to have approximately equal horizontal and vertical resolution?

2.6.23 Does the faceplate require special design to prevent the scattering of light through internal reflections? (Section 4.4.2)

2.6.24 Is the variation in luminance between the center and edges of the display within the limits required by the intended use of the system? (Sections 4.0, 4.4.2)

2.6 ELECTRO-OPTICAL IMAGERY DISPLAYS (CONTINUED)

2.6.25 Is the image produced by the display free of unwanted motion?

2.6.26 Will the signal-to-noise ratio of the displayed image be large enough? (Sections 4.0, 4.3.3)

2.6.27 Is there any X-radiation hazard from the display? (Section 6.8.2)

2.6.28 Has the point spread function for the optical line-scan image generator been selected to provide maximum intepretability from the finished image? (Applies to line-scan image generators) (Section 4.3.12)

2.6.29 Is the level of jitter in the printer within acceptable limits? (Applies to line-scan image generators) (Section 4.3.12)

2.6.30 Is banding within acceptable limits? (Applies to line-scan image generators) (Section 4.3.12)

2.7 LIGHT TABLES

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2.7.2 Is the film loading access adequate? (Section 7.1.2)

2.7.3 Is the support mechanism for roll film designed for easy use and to minimize the need to support the film reel in an exact position during loading?

2.7.4 Are the minimum and maximum film speeds adequate? (Section 3.10.3)

2.7.5 Is the film translation control adequate? (Section 3.10.4)

2.7.6 Is the general light table configuration suitable? (Sections 6.1.1, 6.1.2)

2.8 TUBE MAGNIFIERS

2.8.1 Is the device sufficiently small and light to be easily used?

2.8.2 Is it possible to change the focus easily? (Section 3.8.2)

2.8.3 Is an adequate focus range provided? (Section 3.8.1)

2.8.4 Is the distortion within reasonable limits? (Section 3.4.5)

2.8.5 Will it scratch the film?

2.9 COMPARATORS

2.9.1 Is image positioning precision adequate? (Sections 5.3.2, 5.3.5, 3.10.5)

2.9.2 Is the maximum image velocity adequate? (Sections 3.10.3, 5.3.2, 5.3.5)

2.9.3 Is the reticle easy to detect when viewed against imagery? (Section 5.3.8)

2.9.4 Is the recticle likely to obscure the edge with which it is being aligned? (Section 5.3.8)

2.9.5 Is there significant parallax that might cause a measurement error? (Sections 5.3, 5.3.8)

2.9.6 If color imagery or a colored recticle is involved, can this introduce any measurement error? (Sections 5.2.6, 5.3.7)

2.10 STEREO DISPLAYS

2.10.1 Are the two optical trains adequately aligned? (Section 3.7.5)

2.10.2 If the operator cannot reposition the image before one eye relative to the other, are the two images properly registered? (Sections 3.7.4, 5.1)

2.10.3 If the two images are separated by different colors, as in an anaglyphic display, will the color difference cause a differential focus problem? (Section 5.1.4)

2.10.4 Can the two images be interchanged as required? (Section 3.10.6)

2.10.5 Can the two images be differentially rotated as required? (Section 3.10.6)

2.10.6 Can the two images be differentially magnified as required? (Section 5.1)

2.10.7 Is the precise positioning capability for setting up stereo adequate? (Sections 5.1, 3.10.4)

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2.11 COLOR DISPLAYS

2.11.1 Is the image luminance adequate? (Sections 3.2.8, 5.2.3, 5.2.4)

2.11.2 Will displacement of image details of different colors cause a problem? (Section 5.2.6)

2.11.3 If colored targets must be detected, will the illuminant spectral distribution yield the best possible target contrast? (Sections 3.2.9, 5.2.3)

2.11.4 If colors must be determined precisely, is the magnification adequate to enlarge the target to an acceptable size? (Section 5.2.4.1)

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2.11.8 If colors must be determined precisely, is the set of matching colors made of the same material as the target, thereby reducing the impact of variations in viewing conditions and differences among observers? (Section 5.2.4)

2.11.9 If colors must be determined precisely, can the target and matching colors be viewed side by side? (Section 5.2.4)

SECTION 3.0
OPTICAL IMAGERY DISPLAYS

3.1 VISUAL PERFORMANCE

3.2 ILLUMINATION

3.3 ANALYSIS OF DISPLAY PARAMETERS

3.4 ABERRATIONS

3.5 DISPLAY FIELD SIZE

3.6 VIEWING DISTANCE

3.7 BINOCULAR VIEWING

3.8 FOCUS MECHANISM

3.9 EYEPIECE DESIGN

3.10 IMAGE TRANSLATION AND ROTATION

3.11 VIBRATION

SECTION 3.0 OPTICAL IMAGERY DISPLAYS

When discussing certain display features, it is helpful to divide imagery displays into two categories, *screen displays* and *aerial image displays*:

- In a *screen display*, the optical element closest to the eye is a diffusing surface, or screen, on which the image is formed, and *viewing distance* is equal to the eye-to-screen separation. Typical screen displays are front and rear projection screens and cathode ray tubes (CRT's).

- In an *aerial image display*, a *refractive* element is nearest the eye. As Figure 3.6-1 explains, the *viewing distance* in an aerial image display is defined only by the rearward projection of the light rays entering the eye to the point in space where they form an image which is usually, though not necessarily, *virtual*. Typical aerial image displays are the microscope, the magnifier, and the cathode ray tube (CRT) or projection screen viewed with a magnifier.

As far as the user is concerned, these two kinds of displays differ in the following ways:

- Viewing distance, or correct eye focus distance, is fixed by the screen distance in a screen display, but varies with focus setting in an aerial image display (Section 3.6).

- For nonstereo *binocular* displays, the images viewed by the two eyes are identical for a screen display but are not necessarily identical for an aerial image display (Section 3.7.4).

- An aerial image display may incorporate a small exit pupil, which fixes head position, while a screen display may not (Sections 3.3.1, 3.7.1).

- Screen displays are by necessity limited to the resolution achievable with the materials that make up the screen; aerial imagery displays are also resolution limited, but the limit is generally not so directly obvious to the display user (see Section 3.3).

Three terms, *object*, *imagery*, and *image*, are used in this handbook in ways which, though correct, are not always followed in common usage. In an optical imagery display the *object* is, by definition, the *imagery* being viewed. The display forms one, or more, *images* of the object (imagery), but the one discussed most frequently here is the image defined by the rearward projection of the light rays entering the eye.

A fourth potentially misleading term is *image quality*. As used in this handbook, it refers specifically to the quality of the display image, with an implicit assumption in most cases that the display and not the imagery is the limiting factor. The term "image quality" is often used elsewhere to refer to the quality of imagery, but it is not used in that sense here.

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3.1 VISUAL PERFORMANCE

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3.1.3	Factors in the Measurement of Visual Performance	3.1-12
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SECTION 3.1 VISUAL PERFORMANCE

An adequate analysis of an imagery display must include a description of the visual ability of the intended display user. The purpose of the present section is to summarize the best available data on this topic. Because so many different factors can influence vision, the test conditions used in collecting each set of data are described in some detail.

A thorough understanding of how the visual system functions would also make a major contribution to the design of imagery displays. However, it is usually not sufficient to substitute a simple description of the visual system. For example, it is seldom helpful to analyze display image quality just in terms of the size of the photoreceptive elements in the retina.

Most of the data in this section describes *threshold* visual performance. That is, it represents the smallest or lowest contrast object that can be seen in a given situation. When applying this data to an imagery interpretation situation, it is necessary to keep in mind that the important features in any piece of imagery are not all very small or very low *contrast*, nor is it probable that the intelligence value of imagery features is uniformly distributed across whatever continua are used to quantify size and contrast. Therefore, although improving a display so that an object 5 percent smaller can be seen will certainly increase the amount of information that the display user can extract from the imagery, it is generally not possible to assign a number to the practical value of this increased information.

The measurement of visual performance has undergone a lengthy evolution, much of which is illustrated by the data summarized in Sections 3.1.3 through 3.1.7.

Until recently, most measurements of visual performance have involved either size or contrast, but not both. With a few exceptions, researchers measured either ability to resolve detail in small, high-contrast targets, or to distinguish contrast in a very low-contrast, relatively large target. The first of these abilities is usually referred to as *visual acuity* and the second as *contrast threshold*. As Figure 3.1-12 illustrates, visual acuity is simply the reciprocal of the size of the smallest resolvable target in arc minutes.

Because the imagery display user must resolve edges that include a range of both sizes and contrasts, information on visual performance when both of these parameters are varied is much more useful to the designer. Many measurements of this type have been made and some of the more useful data are summarized in Section 3.1.4 for noncyclical targets and in Section 3.1.5 for cyclical targets.

Section 3.1.5 includes data on visual performance in which the luminance variation follows a sinusoidal distribution. This type of target significantly simplifies the analysis of a display or visual performance test situation because, although the size and contrast of the target are changed by the optical elements present, the luminance distribution in the image remains sinusoidal.

Visual performance is often measured with cyclical targets such as *gratings*. The two characteristics usually considered important in describing a grating, in addition to the shape of the luminance distribution, are *spatial frequency* and contrast. Recent data, summarized in Section 3.1.6, suggest that for sinusoidal gratings with a low spatial frequency (below about 2 cycles per degree) and containing a total of less than 3 to 5 cycles, the total number of cycles present may be more important than the spatial frequency. This effect is also evident in Section 3.1.7, which illustrates visual performance for targets that can be described in the same terms as cyclical targets but which are much more like the edges in real imagery because they include only one cycle or a fraction of one cycle. The full impact of this type of data on analyses of display parameters such as those discussed in Section 3.3 has not yet occurred.

Strikingly missing from this sequence is an adequate treatment of the impact of photographic and other *noise* on vision (Ref. 1). When the imagery is photographic film, the principal source of noise is grain. (Noise in electronic displays is treated in Section 4.3.3) In grainless imagery, the ability to resolve details in the imagery increases with magnification up to the limits set by the modulation sensitivity of the eye and the modulation transfer characteristics of the display. (See Section 3.3.) However, because the interference due to grain also increases with magnification, the actual performance limit and possibly even the optimum shape for the modulation transfer function (MTF) of the display may be quite different than predicted by an analysis in which grain noise is not considered.

3.1.1 STRUCTURE AND OPTICS OF THE EYE

This section summarizes many of the physical and optical characteristics of the eye important to the display designer. Eye pupil size is treated briefly here, but the more complete coverage is in Section 3.2.3.

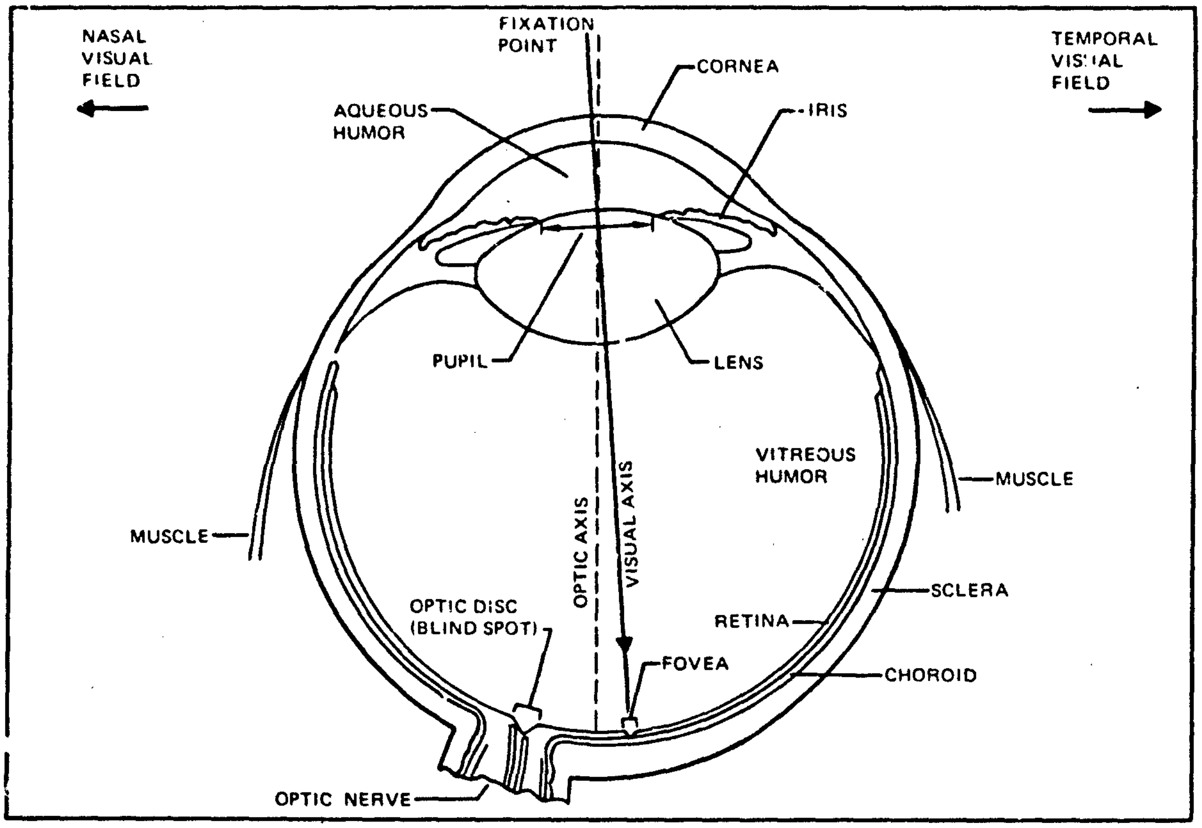


Figure 3.1-1. Structure of the Human Eye. A horizontal cross section through the right eye is shown here (Ref. 2).

Light entering the eye is focused on the *retina* by the two refractive elements of the eye, the *cornea* and the *lens*. The spaces between these elements and the retina are filled with nominally clear fluids (Ref. 3) known as *aqueous* and *vitreous humor*. The area through which the light can enter the eye, the *pupil*, is limited by a membrane known as the *iris*, which lies on the surface of the lens. The iris changes the size of the pupil in response to several variables, including illumination (Section 3.2.2).

The retina contains two types of photosensitive receptors, the *cones* and the *rods*. The cones differ from the rods in that they operate at higher illumination levels, provide better spatial resolution and contrast sensitivity, and provide color vision. The rods are more sensitive to light than the cones and contribute to vision primarily at illumination levels much lower than are provided in imagery displays.

The nerve fibers that connect the receptors to the brain lie on the inner surface of the retina and pass out through the retina at the *optic disc*. There are no receptors in the optic disc, resulting in what is referred to as the *blind spot* (Figure 3.5-7). Individuals are seldom aware of its existence.

The *optic axis*, on which lie the optical centers of the cornea and lens, and which is the common axis of both, exists only in theory. This is also true of the *visual axis*, or line joining the fixation point to the fovea. It occurs because in a real eye (unlike the schematic eye in Figure 3.1-4), the cornea and lens do not share a common axis (Ref. 4). As a result, the optic and visual axes can only be estimated. A common estimate of the optic axis is the line perpendicular to the cornea and centered on the entrance pupil of the eye (Ref. 4). A comparable estimate of the visual axis is the line connecting the fixation point to the center of the entrance pupil. Surprisingly, in most individuals the best estimated optic and visual axes differ about as shown here. A typical value is 5 degrees (Ref. 4).

3.1.1 STRUCTURE AND OPTICS OF THE EYE (CONTINUED)

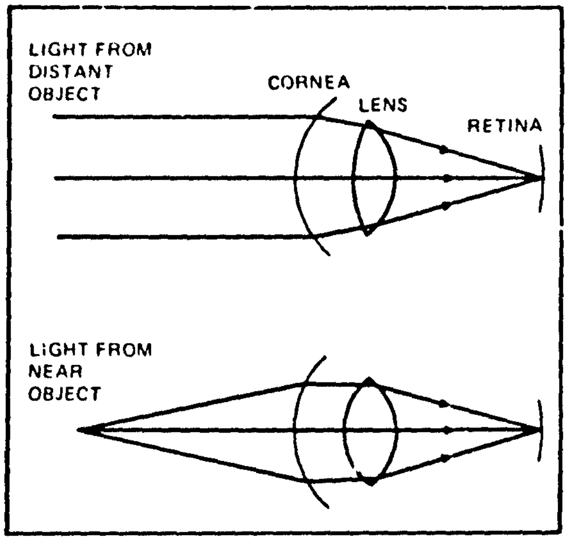


Figure 3.1-2. Accommodation. The distance from the cornea to the retina is essentially fixed. Therefore, in order for bundles of light rays arriving at the eye from different distances to be in focus on the retina, the refractive power of the eye must change. This change in power is caused by a change in the shape of the lens and is known as *accommodation*. The accommodative range of the eye and the reduction in this range as the lens hardens with age are covered in Section 3.6-1.

Accommodation is usually expressed as the change from infinity focus, in *diopters*, which is the same as the inverse of the distance from the eye in meters (1/m). For example, an eye focused on an object at 0.25m (10 in) is said to be accommodated 4 diopters (1/0.25 = 4). An eye focused on an object at infinity is said to be exerting zero accommodation. The resting state of the eye generally involves a diopter or so of accommodation (Section 3.6.2).

3.1.1 STRUCTURE AND OPTICS OF THE EYE (CONTINUED)

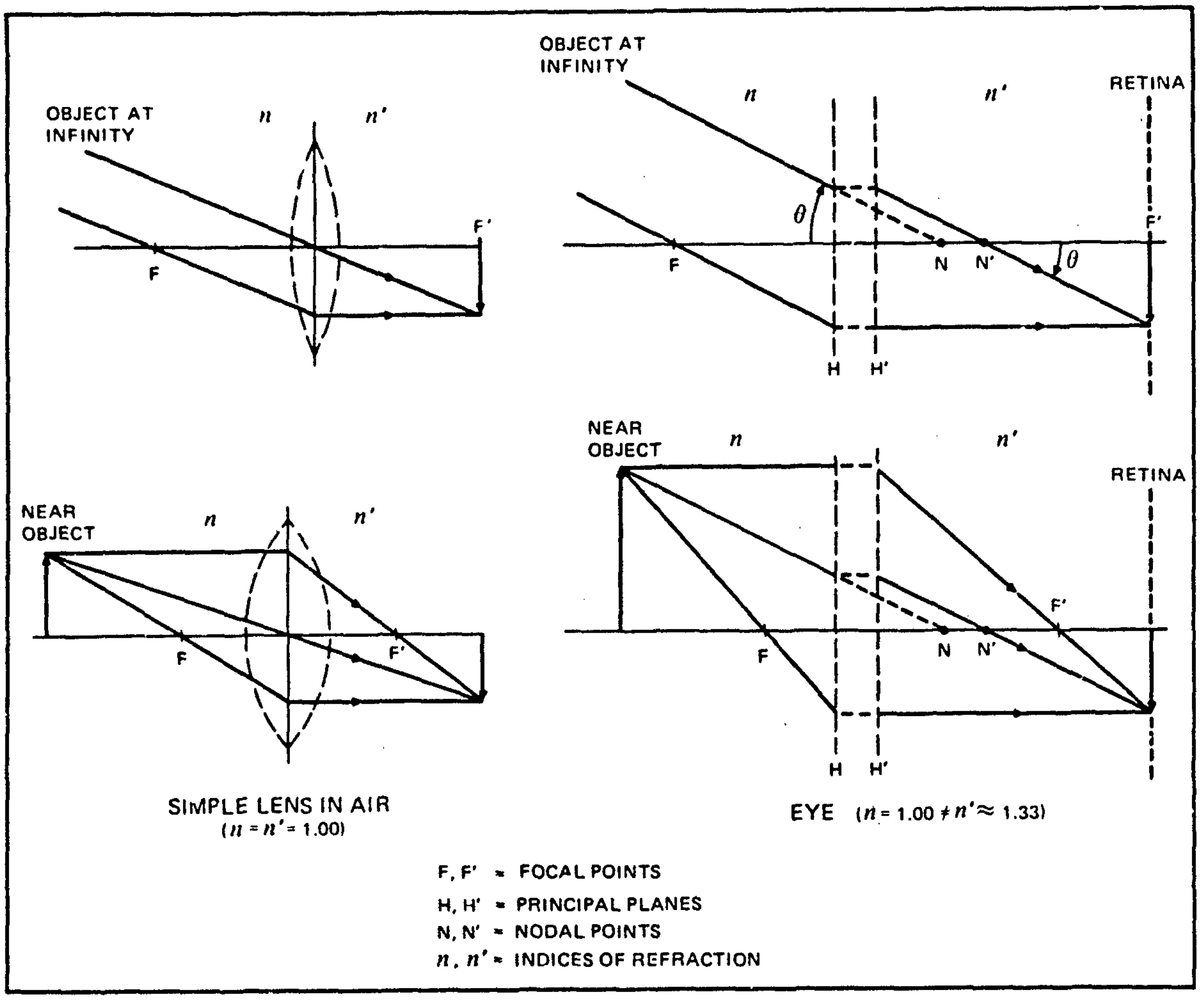
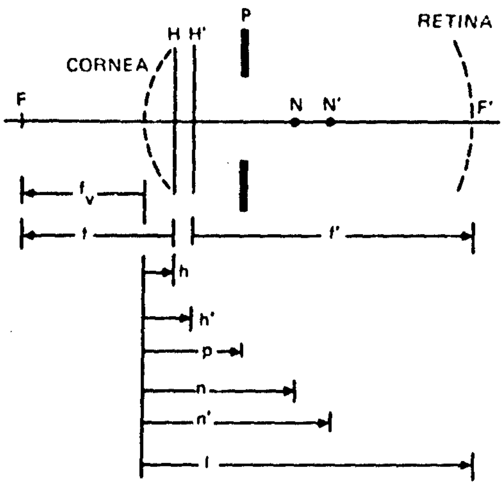


Figure 3.1-3. Review of Ray Tracing in a Simple Lens and in the Eye. This figure is included to illustrate how the basic rules of ray tracing, which can be found in almost any text on optics, apply to the complex optical system of the eye. Tracing the paths of light rays as they enter the eye is more complicated than for a simple lens in air for two reasons. First, the eye must be treated as a *thick*, rather than a *thin lens*, and second, the *index of refraction* of the media inside the eye is not the same as the index of refraction of the air outside the eye. As a result, the schematic, or idealized eye shown in Figure 3.1-4 must contain a separate *principal plane* and *nodal point* for the entering and emerging light rays.

3.1.1 STRUCTURE AND OPTICS OF THE EYE (CONTINUED)



F,F' = FOCAL POINTS
H,H' = PRINCIPAL PLANES
N,N' = NODAL POINTS
P = IRIS, OR REAL PUPIL
f = ANTERIOR FOCAL LENGTH
f' = POSTERIOR FOCAL LENGTH
f_v = ANTERIOR VERTEX FOCAL LENGTH
l = AXIAL LENGTH OF EYE

NOTE: EYE SHOWN FOCUSED AT INFINITY.

	OGLE (Ref. 6)	MIL-141 (Ref. 2)	GULLSTRAND (Ref. 7) FAR	GULLSTRAND (Ref. 7) NEAR
f_v	-15.6	-15.59	-15.31	-12.96
f	-17.0	-17.13	-16.78	-14.66
f'	22.7	22.89	22.42	19.58
h	1.42	1.54	1.47	1.70
h'	1.5	1.86	1.75	2.03
p	–	3.54	3.60	3.20
n	7.1	7.30	7.11	6.62
n'	7.3	7.62	7.39	6.95
l	24.3	24.75*	24.17	–

(all distances in millimeters)

*RANGE IS 21 - 26 mm

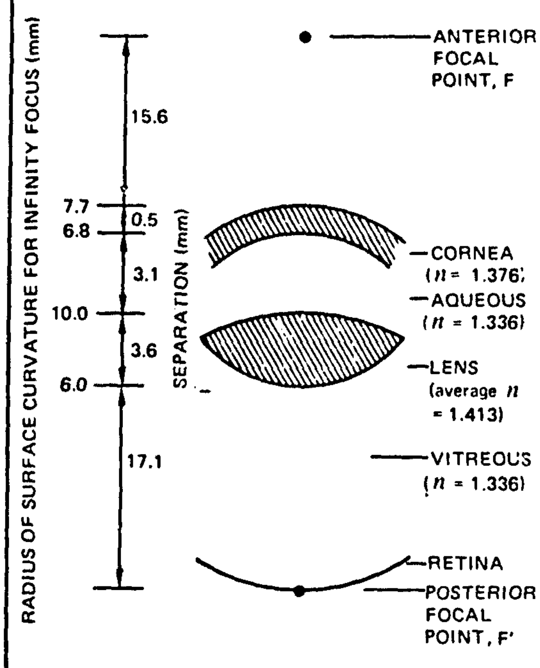


Figure 3.1-4. The Schematic Eye. The parameters for several different *schematic eyes* are illustrated here. The Gullstrand schematic eye No. 2 is one of the earlier versions. It is still the most commonly used. Ogle suggested that data now available on the eye should allow determination of better values for a schematic eye and presented the one listed in the first column. Both it and the schematic eye given in MIL-HDBK-141 (Ref. 2) differ slightly though usually not significantly from the Gullstrand No. 2 eye.

Both the Ogle and MIL-HDBK-141 schematic eyes are for an accommodation distance of infinity. The Gullstrand No. 2 eye includes values for two distances, infinity and a near distance of 8.6 *diopters*.

The lower left-hand part of the figure shows the physical dimensions for the Gullstrand No. 2 eye, focused for infinity. The refractive index of the lens is the effective average value. Actually, the refractive index increases toward the center of the lens.

3.1.1 STRUCTURE AND OPTICS OF THE EYE (CONTINUED)

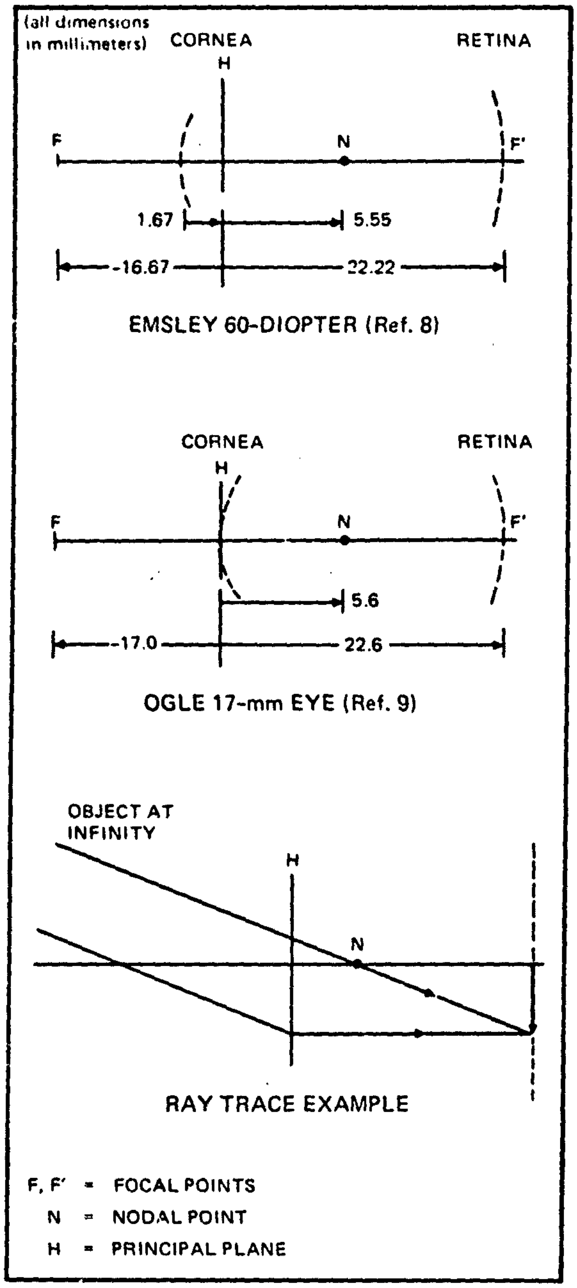


Figure 3.1-5. Reduced Schematic Eyes. Frequently a reduced, or simplified, schematic eye provides adequate computational precision. A typical application is determination of retinal image size. The two examples illustrated here reduce the infinity focused eye to a single refracting surface, the principal plane, H, with a single nodal point, N, at its center of curvature.

Note that these two reduced schematic eyes are nearly identical. The Emsley version, with a refracting power of 60 diopters, has an anterior focal length of 1/60 = 0.01667m, while the Ogle version, with an anterior focal length of 17 mm, has a refracting power of 1/0.017 = 58.8 diopters.

3.1.1 STRUCTURE AND OPTICS OF THE EYE (CONTINUED)

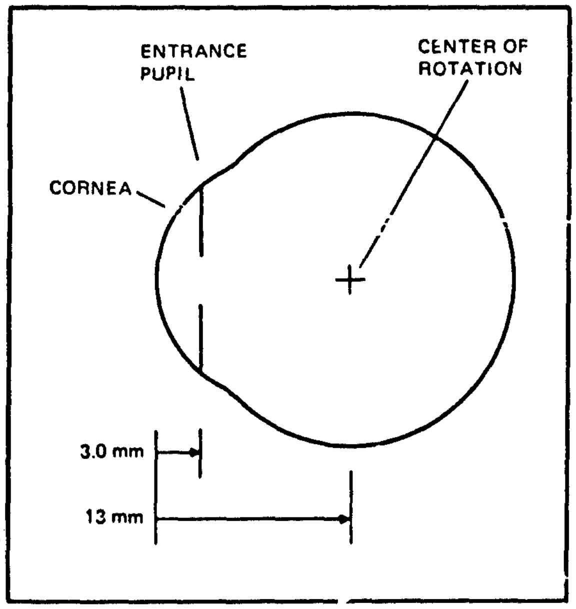


Figure 3.1-6. Eye Center of Rotation. The center of rotation of the eye is approximately 13 mm behind the front surface of the cornea (Ref. 10), which places it approximately 10 mm behind the entrance pupil of the eye. As a result, eye rotation results in movement of the eye pupil. The impact of this movement is treated in Figures 3.5-13 to -15.

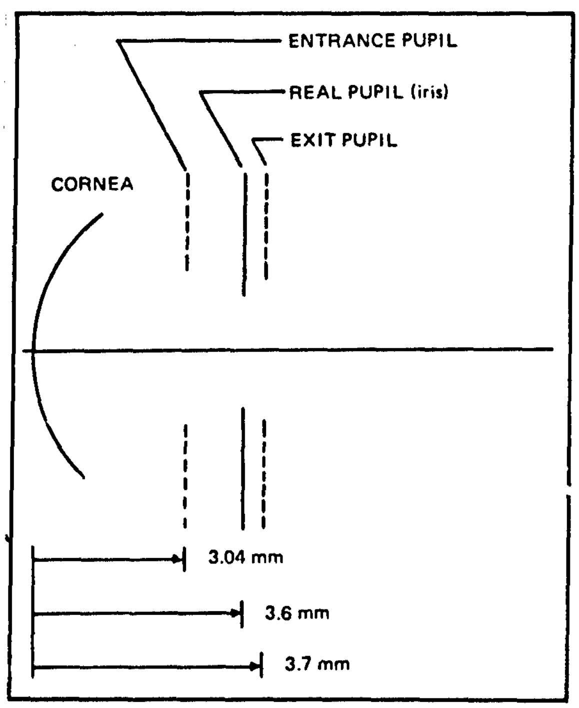


Figure 3.1-7: The Eye Pupil. The display designer must be concerned with the *entrance pupil* of the eye rather than the *real pupil*. The entrance pupil is the dark aperture that can be seen when looking into another person's eye. As this figure illustrates, the entrance pupil is larger and closer to the cornea than the real pupil (Ref. 11). If the diameter of the entrance pupil is x, the diameter of the real pupil is 0.89x, and the diameter of the exit pupil is 0.93x.

With the exception of Figures 3.1-1 and -4, the term "eye pupil" as used in this document implies the eye entrance pupil rather than the real pupil. In particular, the eye pupil data in Sections 3.1.9 and 3.2.3 apply to the eye entrance pupil. Unfortunately, the distinction between real and entrance pupil is not treated in many of the studies used in these sections, and it is necessary in many cases to assume that the authors intended the latter.

3.1.2 UNITS THAT DESCRIBE THE IMAGE

It is customary to characterize the elements that make up an image in terms of their size and *contrast*. This section illustrates some of the more important units that have been used to define these parameters. Subsequent sections utilize as few different units as possible.

A major activity in display development has been the search for a single universal figure of merit that expresses the quality of an image. Recent examples of some importance include the optical power spectrum (OPS) (Ref. 12) and the modulation transfer function area (MTFA) (Ref. 13). While these may be very successful for their intended purpose, there is as yet no data available on these units that serve to define the capabilities of the eye, and therefore they are not included here.

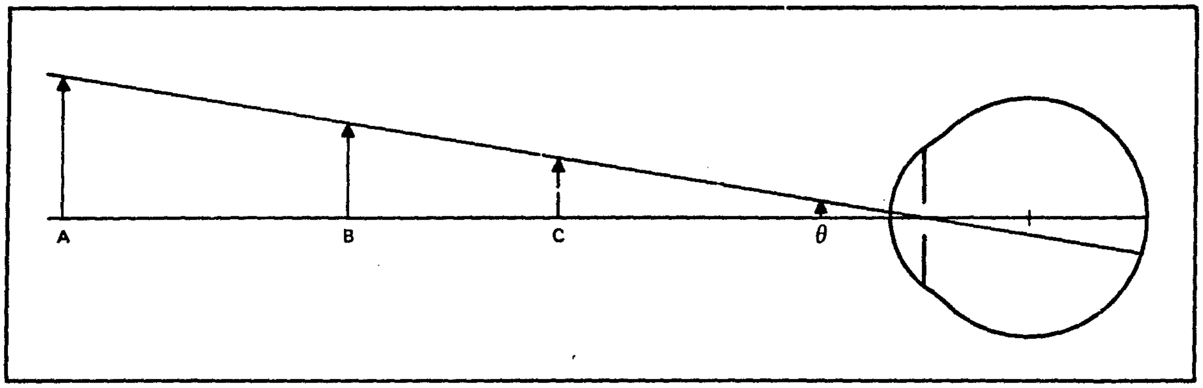


Figure 3.1-8. Visual Angle. From the point of view of the display user, it is most useful to define the size of an object in terms of the *visual angle* it subtends at the user's eye. In the illustration, for example, the three objects, A, B, And C, are different sizes but because their size to distance ratio is constant, they subtend the same visual angle and produce nearly the same size retinal image (Ref. 14). As a result, they are essentially equally visible. The three objects are not, however, completely equivalent. Because they are different distances from the eye they require different amounts of eye accommodation to produce a sharp image on the retina. In addition, because the apparent size of an object depends on several factors in addition to retinal image size, they may be perceived as being different in size (Ref. 15).

3.1.2 UNITS THAT DESCRIBE THE IMAGE (CONTINUED)

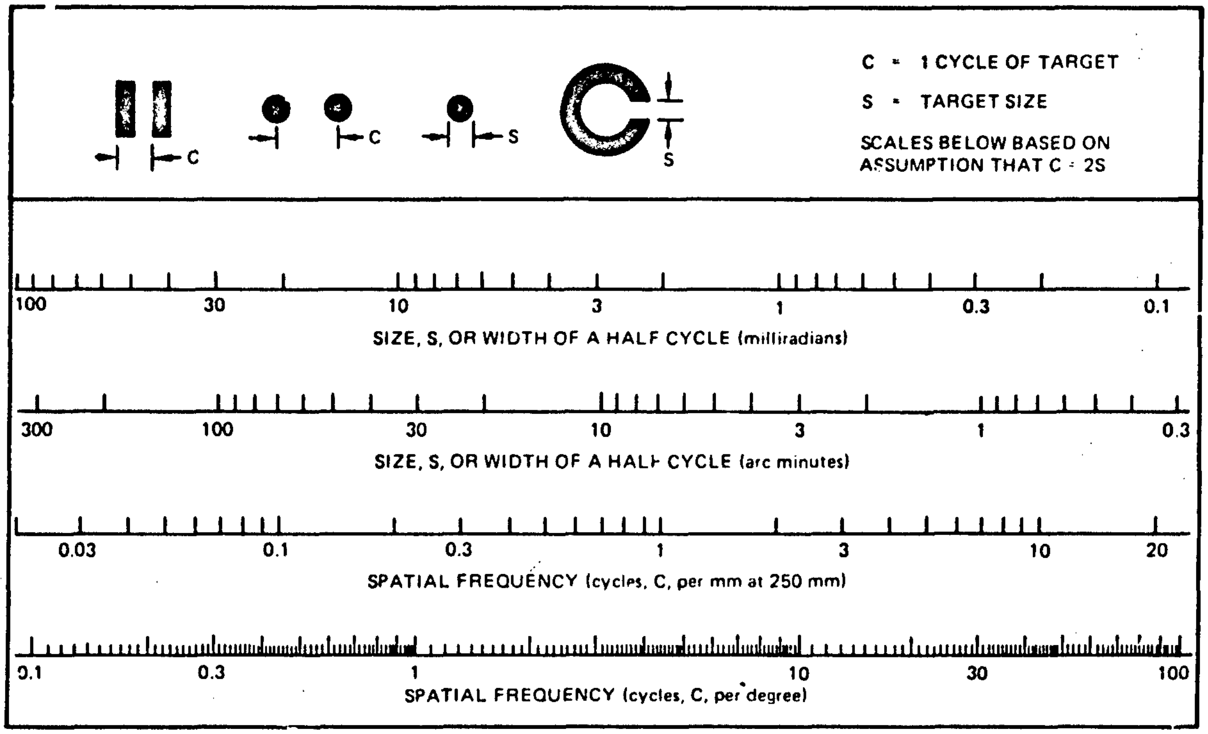


Figure 3.1-9. Size Units. The dimensions conventionally used to define the size of three kinds of targets used to measure visual performance are illustrated here; many more kinds of targets are included in Figure 3.1-11.

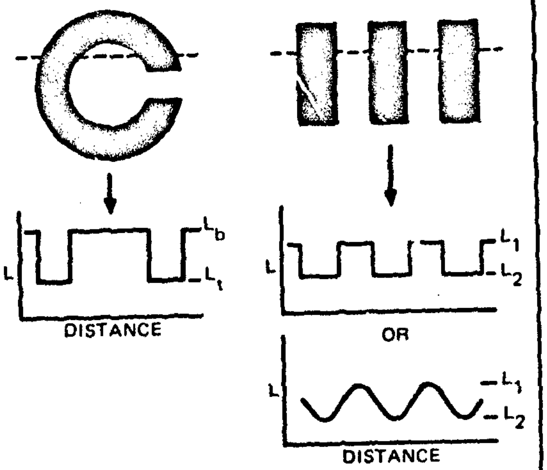
Many different sets of units can be used to characterize the visual angle subtended by these kinds of targets. In this document, spatial frequency in cycles per degree is used for cyclical targets, and size in arc minutes is used for noncyclical targets. Following the convention used in modulation transfer function plots, spatial frequency increases to the right.

In order to facilitate comparisons among different sets of visual performance data, similar scales are used wherever possible in the figures in the remainder of Section 3.1.

The size of a noncyclical target, such as the diameter of a disc or the gap in a Landolt ring, is sometimes treated as if it is equivalent to a half cycle of a cyclical target. There is no adequate theoretical or experimental justification for such an association of data from these two kinds of targets.

However, it happens that much of the visual performance data summarized in this document plots conveniently on a graph in which the limits of the size axis for cyclical and noncyclical targets correspond in just this 2 to 1 fashion. These limits are therefore used, but only for sake of convenience in plotting the data, not because such an association between data from the two kinds of targets has been established.

3.1.2 UNITS THAT DESCRIBE THE IMAGE (CONTINUED)



L_t = TARGET LUMINANCE
L_b = BACKGROUND LUMINANCE
L_1 = MAXIMUM LUMINANCE
L_2 = MINIMUM LUMINANCE
L_0 = AVERAGE LUMINANCE = $(L_1 + L_2)/2$

C_m = CONTRAST AS MODULATION (Ref. 16)
C_d = CONTRAST FOR DARK TARGETS ($L_t < L_b$)
C_l = CONTRAST FOR LIGHT TARGETS ($L_t > L_b$)
C_r = CONTRAST RATIO
ΔD = DELTA DENSITY

$$C_m = \frac{|L_t - L_b|}{L_t + L_b} = \frac{L_1 - L_2}{L_1 + L_2} = \frac{(L_1 - L_2)/2}{L_0}$$

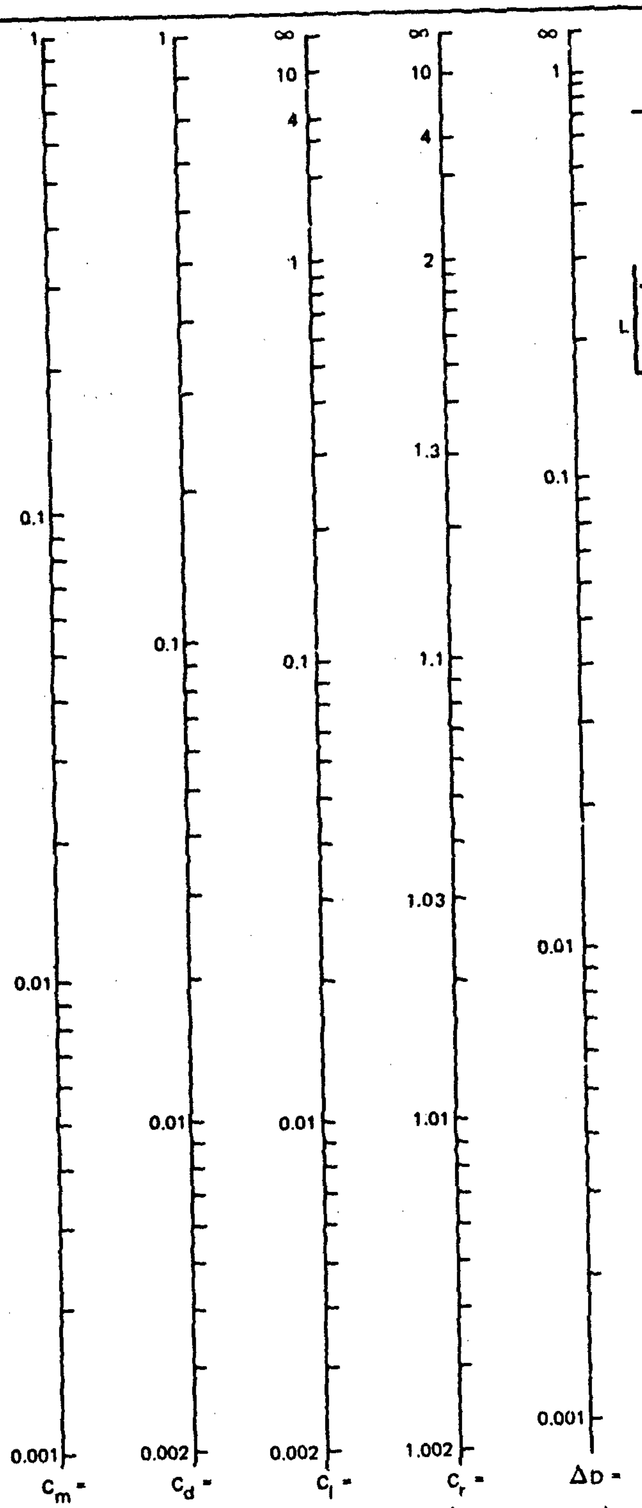
$$C_m = \frac{C_d}{2 - C_d} = \frac{C_l}{2 + C_l} = \frac{C_r - 1}{C_r + 1} = \frac{10^{\Delta D} - 1}{10^{\Delta D} + 1}$$

$$C_d = \frac{2C_m}{1 + C_m}$$

$$C_l = \frac{2C_m}{1 - C_m}$$

$$C_r = \frac{1 + C_m}{1 - C_m}$$

$$\Delta D = \log_{10} \frac{1 + C_m}{1 - C_m}$$



$C_m = \frac{|L_t - L_b|}{L_t + L_b}$ | $C_d = \frac{L_b - L_t}{L_b}$ | $C_l = \frac{L_t - L_b}{L_b}$ | $C_r = \frac{L_t}{L_b}$ | $\Delta D = \log_{10} \frac{L_t}{L_b}$

Note: To obtain percent contrast, multiply by 100. Contrast sensitivity is 1/contrast.

3.1.2 UNITS THAT DESCRIBE THE IMAGE (CONTINUED)

Figure 3.1-10. Contrast Units. When two areas close to each other have different luminances, the visual system discriminates between them on the basis of their relative luminances. Relative luminance, or *contrast*, has been expressed many different ways. A few of these are summarized here. Equations and nomographs are also included to simplify conversions between units.

The contrast of cyclical targets is usually given in terms of C_m, defined as illustrated. Some authors refer to C_m as contrast while others use the term *modulation*. It has been suggested that to be strictly correct the term "modulation" should be applied only to a sinusoidal or quasi-sinusoidal luminance distribution (Ref. 16), but this distinction is generally ignored.

Different equations are given here for contrast with dark as opposed to light targets. This follows the convention used by most authors, which is to avoid the use of negative contrast values.

As this figure illustrates, the conversion from one set of units to the other is straightforward. In order to facilitate making comparisons among the sets of visual performance data in the remainder of Section 3.1, only one contrast unit, C_m has been used wherever possible. This is not meant to suggest that C_m is always the best contrast unit.

A new type of contrast unit, not plotted here, is sometimes used for special targets such as those treated in Section 3.1.7. This is the ratio of the luminance difference to the average scene luminance (Ref. 40). In theory this is an excellent unit for this kind of target. Unfortunately, the value of this contrast unit varies not just with luminance but also with the ratio of target area to scene area, making application to situations where this area ratio does not hold very difficult. If this contrast unit is used more conventional units should be reported also in order to allow the results to be compared with other work.

3.1.3 FACTORS IN THE MEASUREMENT OF VISUAL PERFORMANCE

Many different methods have been used to measure visual performance and to describe the measurement results. This section describes some of the more common methods.

One important aspect of these different methods is the kind of test target used. Typical kinds are described in the figures that follow.

Another aspect is the success criterion or means used to determine whether the target is visible. The two principal categories are as follows:

- Subjective – The target is always present, though not necessarily visible, and the test subject decides whether the test object, or some critical detail in it, is visible.
- Objective – The subject is not certain of the status of the target and must make some response, such as stating its location or orientation to prove that he can see it.

The advantage of the subjective technique is that more data can be collected in a limited amount of time. The relative values obtained by a particular subject are generally valid, but the absolute values depend heavily on his personal definition of "visible." Differences between individuals are therefore large, except when they have practiced together in order to establish similar definitions of "visible." Comparisons from one laboratory to the next are necessarily difficult with this technique.

The advantage of the objective technique is that it does not depend on the subject's personal definition of "visible," increasing the likelihood that different subjects will give comparable results. In addition to facilitating comparisons among different studies, this makes it easier to use the data in analyzing an imagery display. However, performance differences among individuals can still be large, and experienced individuals will usually perform better than naive ones.

Figure 3.1-11. Vision Test Targets. Some of the many targets that have been used to measure visual performance are illustrated here, along with the dimensions commonly used to define their size. As is discussed in Figure 3.1-9, size, S, of a noncyclical target is sometimes taken as being equivalent to a half cycle of a cyclical target, but there is no demonstrated basis for such a correspondence.

Not only do the differences in shape lead to different values of visual performance for these targets, but so do differences in the success criteria used for each. For example, the criterion for a point target is the ability to detect it. For a light target below a certain size, this is independent of target size. For the two-point target, the task is to determine if one or two points are present. The separation, S, required for the viewer to report two points rather than one depends on his knowledge of the target. The separation will be less if he knows that the only possibilities are one or two points rather than if he is simply shown a scene and told to report what is present.

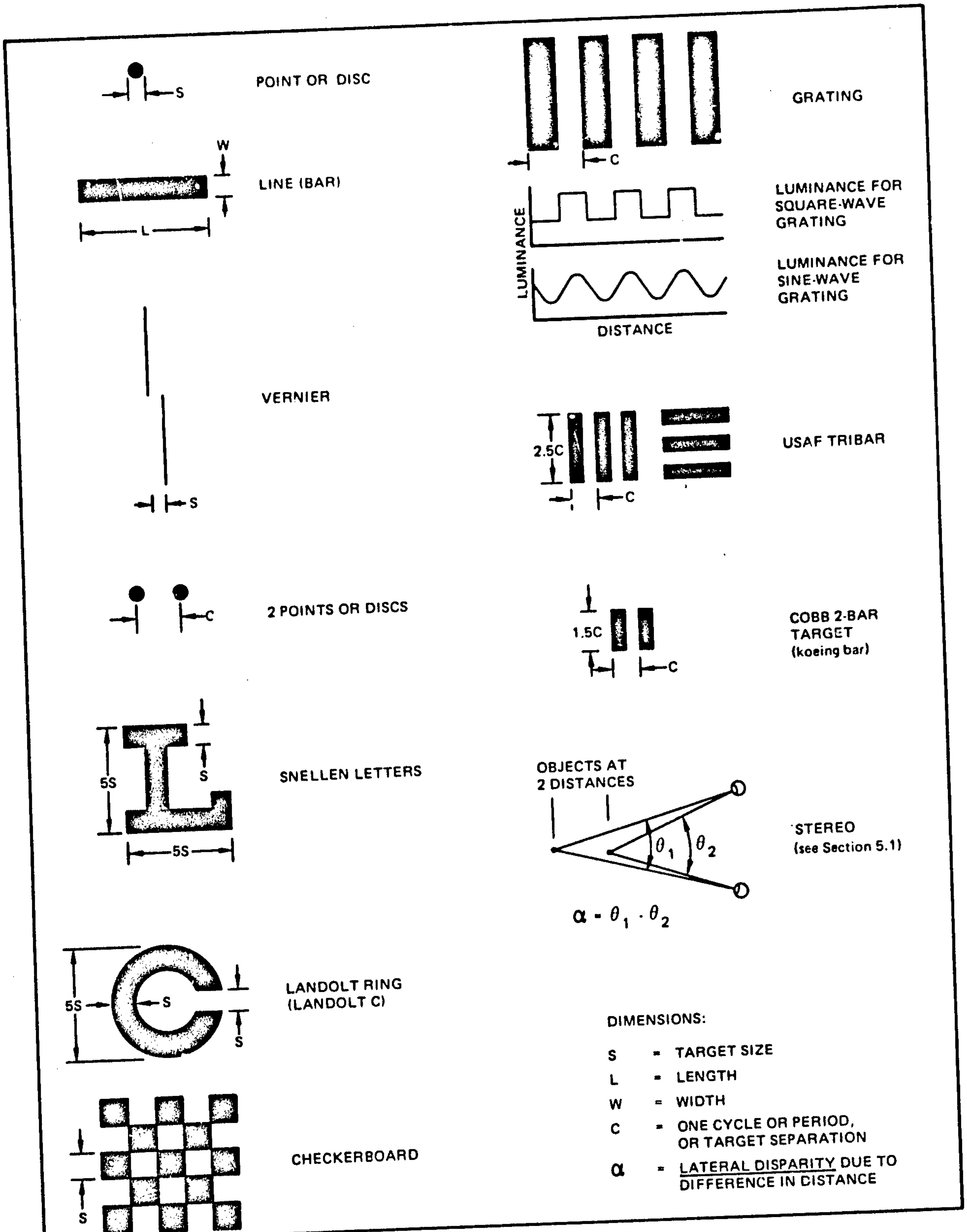
For the line, the Landolt ring, and the several kinds of cyclical (grating) targets, the criterion may be to indicate the orientation of the target or it may simply be to determine whether the grating is present. For the Snellen letters the usual task is to report which letters are present. For the vernier target the task is to align the two lines and for stereo acuity it is usually to adjust the two objects, typically vertical bars, until they are at the same distance. Checkerboard targets are generally presented in sets of four with equal overall size but with one of the four incorporating larger elements. The subject's task with this target is to name which of the four has the larger sized elements.

The situation with the Landolt ring is similar in the usual application where the ring is known to have one of four orientations and a forced-choice procedure is used in which the observer must state which orientation is most likely. A practiced observer may be able to name the orientation consistently, even when the ring is much too small to be seen as a ring and appears only as a fuzzy blob with one side slightly flattened.

The highest spatial frequency grating that can be seen in a display is often referred to as the resolution, or resolving power, of the display. One of the most commonly used gratings is the USAF tri-bar target (Ref. 17). It consists of a series of three-bar targets of the type illustrated here, with each horizontal/vertical pair smaller by a factor of $2^{1/6}$, or about 12 percent. A basic problem with this type of target is that it requires the user to judge which is the smallest set of three bars that can be resolved. Besides the obvious problem of possible differences in visual ability among observers, there is the difficulty of establishing a criterion, or definition, of resolvable. The best accepted criterion is that the space must be visible for the entire distance between the bars. A criterion that yields higher resolution values is that three bars must be visible. If the tri-bar readings are to represent the effect of display astigmatism (Section 3.4.3), an additional restriction is that both horizontal and vertical bars must be viewed at the same focus setting.

The variation among individual observers in tri-bar readings is often large. Values in excess of two steps, or about 26 percent, are common (Ref. 18). Training can reduce this variation considerably. Training in this case apparently means that the group of observers develops a common visibility criterion, which may not be shared by observers in a different group. If one group is buying the display and the other group is selling it, this difference can lead to problems.

3.1.3 FACTORS IN THE MEASUREMENT OF VISUAL PERFORMANCE (CONTINUED)



3.1.3 FACTORS IN THE MEASUREMENT OF VISUAL PERFORMANCE (CONTINUED)

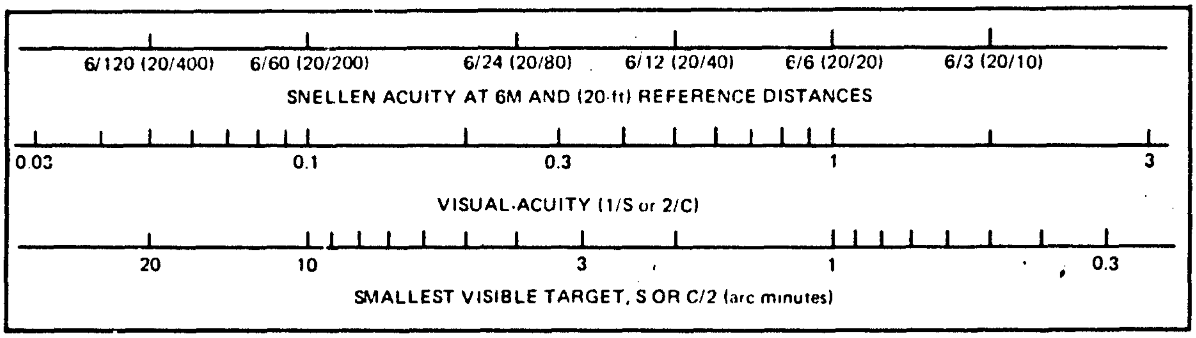


Figure 3.1-12. Visual Acuity Units. The preferred way to describe the minimum size target that can be seen is in terms of the visual angle it subtends at the viewer's eye in units such as arc minutes (Ref. 19). Unfortunately many other units are also in use. One is *visual acuity*, which is usually defined as the reciprocal of the target size (S or C/2 in Figure 3.1-11) in arc minutes. One implication of the visual acuity unit is that normal vision corresponds to 1 arc minute. This is not generally true.

In clinical practice it is common to use the Snellen fraction. This is supposed to be the ratio of the viewing distance used in the test situations to the viewing distance at which the smallest target the patient can see subtends an angle of 1 arc minute. The numerator of this fraction is often taken as 20, even though the test distance is 6m, or even 14 in, rather than 20 ft. This unit should not be used in vision research (Ref. 19).

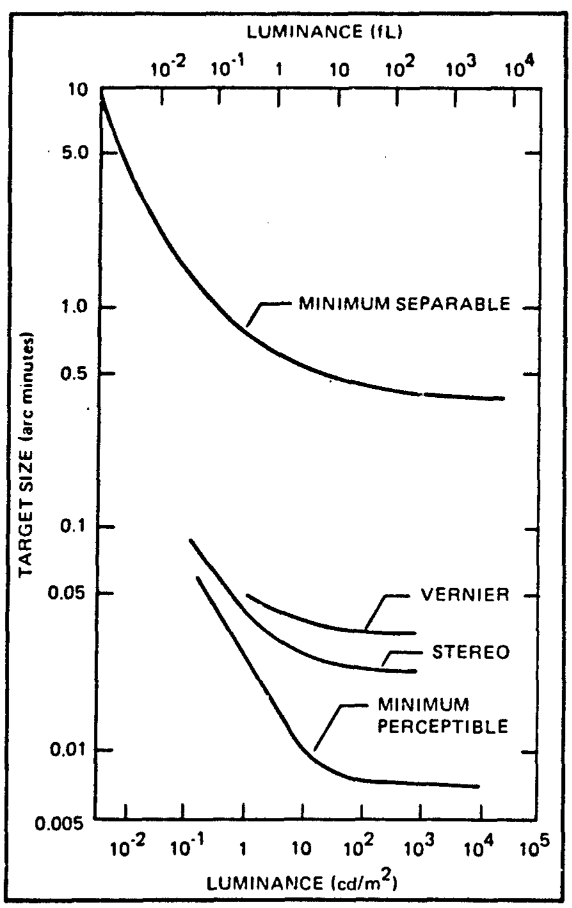


Figure 3.1-13. Comparison of Acuity Measures. This figure illustrates, though with considerable oversimplification, the very large differences that exist among some of the measures that define the ability of the eye to resolve small targets (Ref. 20, X). Minimum separable acuity is based on the gap size in a Landolt ring target as shown in Figure 3.1-11. Vernier and stereo acuity are also defined in Figure 3.1-11. Minimum perceptible acuity is the smallest width dark line that can be resolved.

3.1.3 FACTORS IN THE MEASUREMENT OF VISUAL PERFORMANCE (CONTINUED)

TARGET DESCRIPTION		TARGET SIZE (arc minutes)	
		DETAIL	OVERALL
•	DISC	3.9	3.9
C	LANDOLT RING	4.0	20.0
ıı	COBB 2-BAR	4.0	12.0
|	LINE	1.2	20.8
(dot pattern)	DOT PATTERN	1.0	42.5
(grating)	GRATING	3.9	42.7
e	PRINTED e	2.2	15.8
ℓ	SCRIPT	3.2	35
U P S E R	TEST CHART LETTERS	4.0	20.1

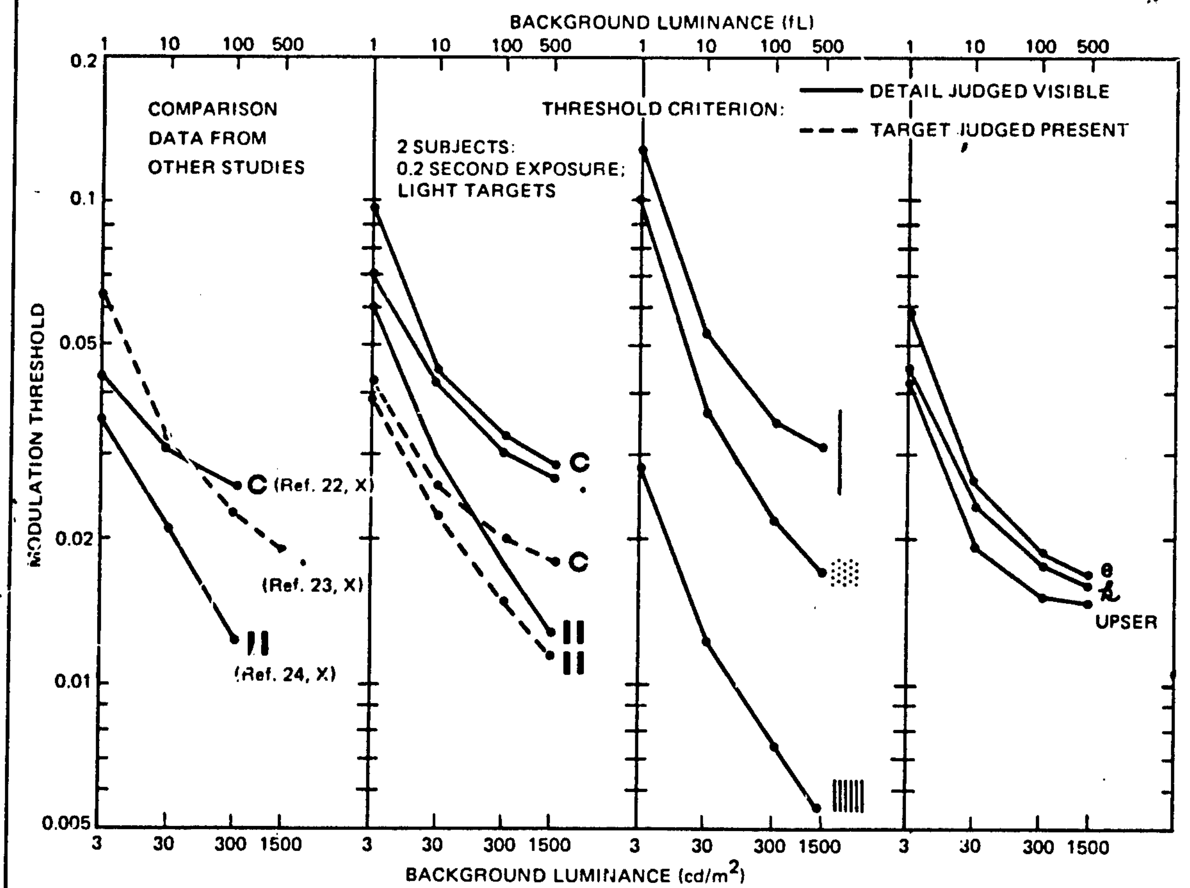


Figure 3.1-14. Visual Performance with Different Target Shapes. The effect of target shape on the minimum modulation at which nominally equal size targets are judged visible is illustrated in the three right-hand portions of this figure (Ref. 21, B). Most of the differences do not exceed a modulation ratio of 2 to 1.

Comparison data for similar results from three other studies are included in the left-hand part of the figure.

3.1.3 FACTORS IN THE MEASUREMENT OF VISUAL PERFORMANCE (CONTINUED)

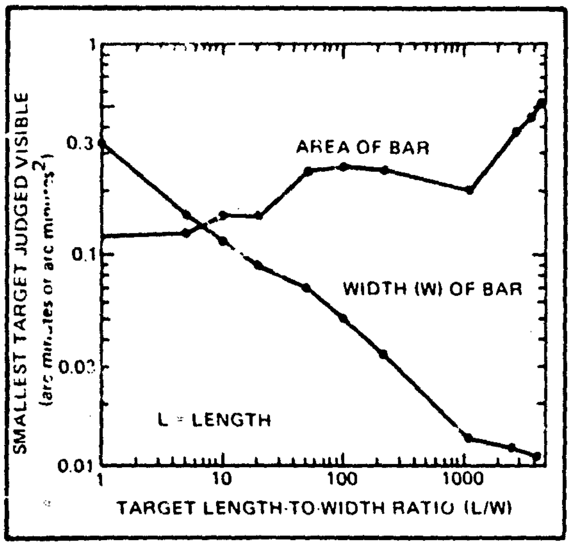


Figure 3.1-15. Effect of Target Shape. It would be useful to have a method of describing target size that would indicate whether a target should be visible regardless of its shape. These test data illustrate the kind of problem that occurs (Ref. 25, C). Subjects adjusted the size of a single dark bar until it was barely visible. As length-to-width ratio increased, threshold expressed as bar width dropped sharply, but expressed as bar area, it remained relatively constant, implying that area is the preferable way of describing target size. Other research suggests that area and perimeter combined provide an even better description of target size, at least for simple shapes such as single bars (Ref. 26). Unfortunately, this approach has not yet been successfully applied to the more complex target shapes involved in image interpretation.

3.1.4 NONCYCLICAL TARGETS

This section summarizes selected visual performance data for two common types of noncyclical targets.

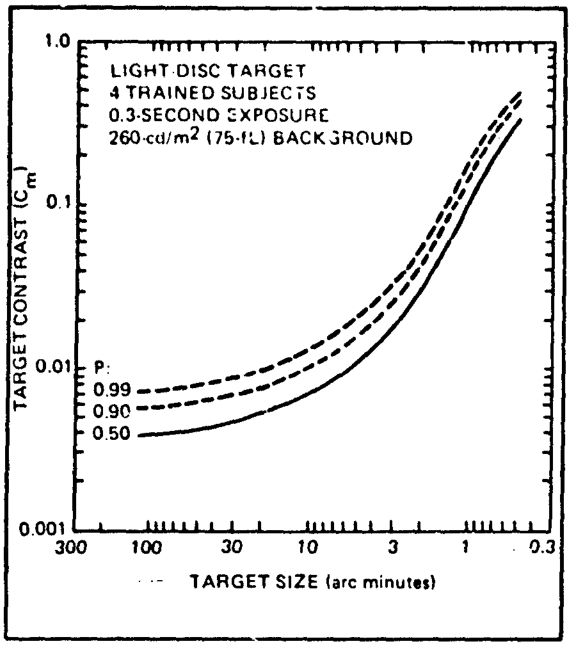


Figure 3.1-16. Contrast Sensitivity for Disc Targets of Different Sizes. In the study summarized here, highly trained subjects were required to state which of four time intervals was most likely to have contained a light disc target (Ref. 27, B). Exact target location was known. The evenly illuminated background was very large. Viewing was binocular. The three curves represent different values of P, which is the probability of target detection, corrected for chance.

Additional data from this lab summarized in Figures 3.1-42 and 3.2-30 illustrate how target detection success improves with increased target exposure time and with background luminance.

Nearly 500,000 contrast threshold measurements have been made using this experimental procedure. There is no known report of variability in performance either within or between subjects (Ref. 28). Such information is important when estimating the significance of the visual performance change that results from a variation in viewing conditions. At present, the only available variability data are those summarized in Figure 3.1-17.

3.1.4 NONCYCLICAL TARGETS (CONTINUED)

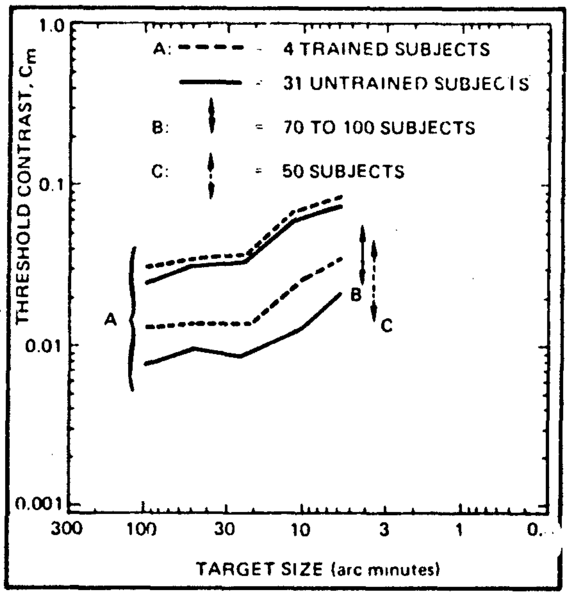


Figure 3.1-17. Variability in Contrast Sensitivity for Disc Targets. Three studies, identified here as A, B, and C, provide the very limited data available on variations in contrast thresholds for viewing situations such as those represented in Figures 3.1-16, 3.1-19, and 3.2-30.

All the results summarized here illustrate the threshold range for approximately the middle 90 percent of the population. In addition, they all are based in part on curves fit visually to the data, and they all include both between subject and within subject variation. The variation between subjects is usually much larger than the variation within a single subject. All three studies involved binocular viewing.

In study A, contrast was increased until the subject could state the location of a square dot target, or the orientation of a Landolt ring (Ref. 29,C). Because the differences were small, data for the two target shapes, and for both light and dark targets, were combined. The background subtended 17 degrees and, for the data shown here, had a luminance of 4 cd/m^2 (1.2 fL). These are the data used to obtain the population range estimate shown by the two broken curves in Figure 3.1-19.

In studies B and C, the target was a light 4-arc-minute disc that appeared for 0.2 second in a known location and at a known time in a large 340-cd/m^2 (100-fL) display field. Hence, these conditions are very similar to those in Figure 3.1-16. In study B, which was conducted in the same lab as the study in Figure 3.1-16, the subject adjusted the luminance of the disc to the point where it was barely visible (Ref. 30,C). In study C, the luminance of the disc was increased by the experimenter until the subject reported that he saw the target (Ref. 31,C). Neither study included trials in which the validity of the subject's responses was checked by presenting a disc of zero contrast.

These three studies all suggest that contrast sensitivity between and within subjects will vary by a ratio of at least 2.5 to 1. It is also striking that for the two studies conducted in the same lab, study B and the study summarized in Figure 3.1-16, the lowest contrast at which any of the subjects in study B considered the disc barely visible yielded a 90- to 99-percent chance of detection when the subjects were forced to guess when the target occurred.

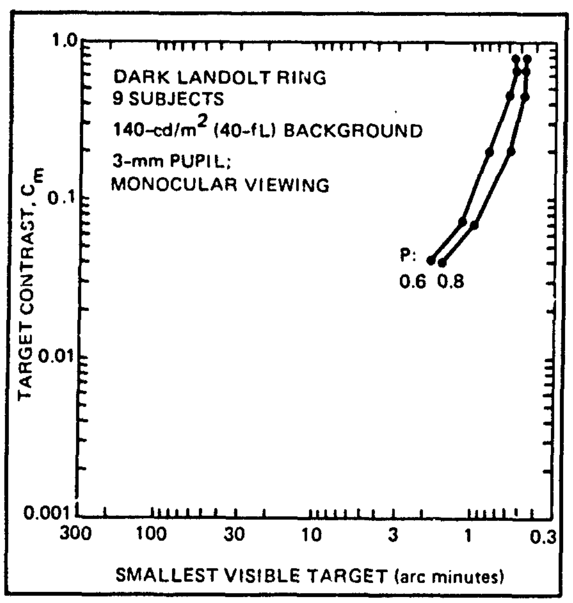


Figure 3.1-18. Visual Performance Measured with Landolt Rings (Ref. 31a, B). In this study, Landolt rings were displayed to subjects at six different modulations, and the minimum detectable gap size was measured. P is the probability of naming the orientation of the gap, corrected for chance. The axes of the graph are the same as in the previous figures in order to facilitate comparisons.

3.1.5 CYCLICAL TARGETS

This section summarizes the best available visual performance data for cyclical targets.

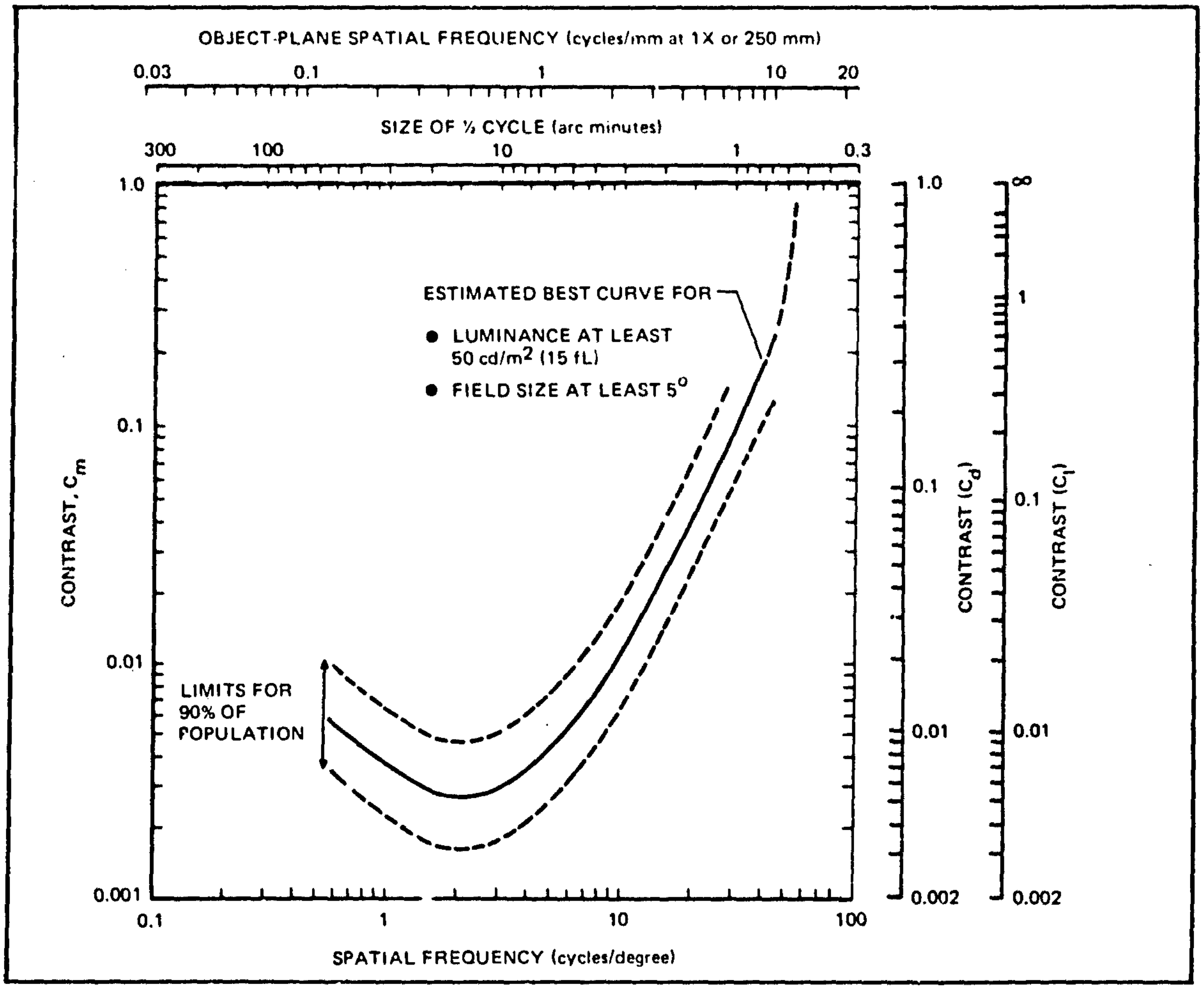


Figure 3.1-19. An Average Contrast Sensitivity Curve for the Eye. This curve, sometimes referred to as the J Curve, is the best currently available summary of the ability of the eye to resolve cyclical targets in terms of both contrast and spatial frequency (Ref. 32). It is a very approximate visual fit to the better visual performance data summarized in Figures 3.1-20 through -28. As many of the figures in Sections 3.1 and 3.2 illustrate, there are many factors that can prevent achieving this performance level, particularly in the region below a modulation value of 0.01.

In order to provide a better basis for making comparisons among different sets of visual performance data, the "population limits" portion of this curve is included wherever possible in other figures in this document.

The population performance range illustrated is derived from the only known study in which visual performance was measured in terms of both target size and modulation for a large group of subjects (Ref. 29, C). The target used in this study was a disc, rather than a grating. The test results are summarized in Figure 3.1-17.

3.1.5 CYCLICAL TARGETS (CONTINUED)

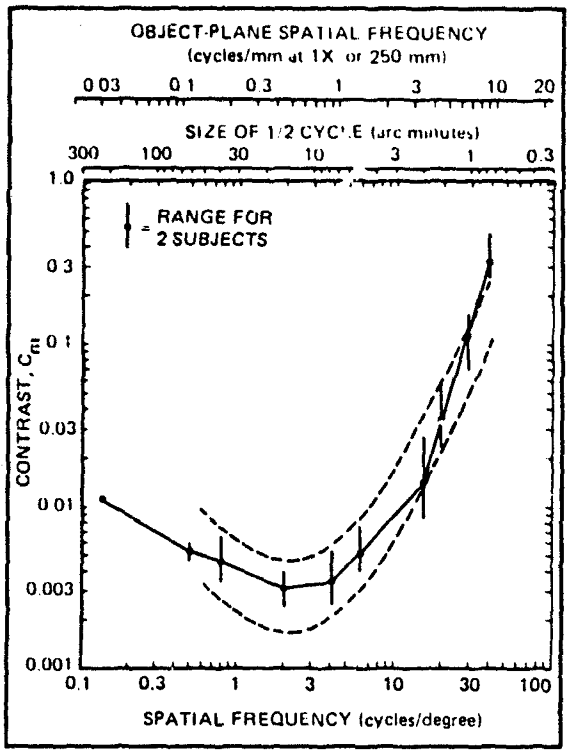


Figure 3.1-20. Contrast Sensitivity (Ref. 33,B).
The test conditions were:

- Sinusoidal grating; vertical or horizontal
- Up to 17-degree-wide by 11-degree-high field (minimum of 10 cycles)
- Incandescent illumination
- 10 cd/m^2 (3 fL)
- Surround not defined
- Binocular viewing
- Criterion – Subject had to state orientation.
- Two subjects

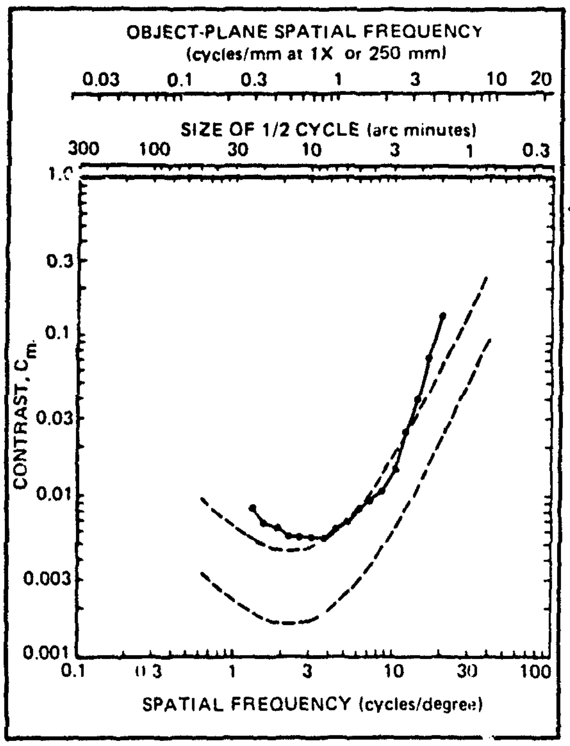


Figure 3.1-21. Contrast Sensitivity (Ref. 34,C).
The test conditions were:

- Vertical sinusoidal grating
- 4-degree-wide by 3 degree-high field
- CRT display
- 4.8 cd/m^2 (1.4 fL)
- Dark surround
- Binocular viewing
- Criterion—Subject had to adjust contrast to just visible.
- One subject

3.1.5 CYCLICAL TARGETS (CONTINUED)

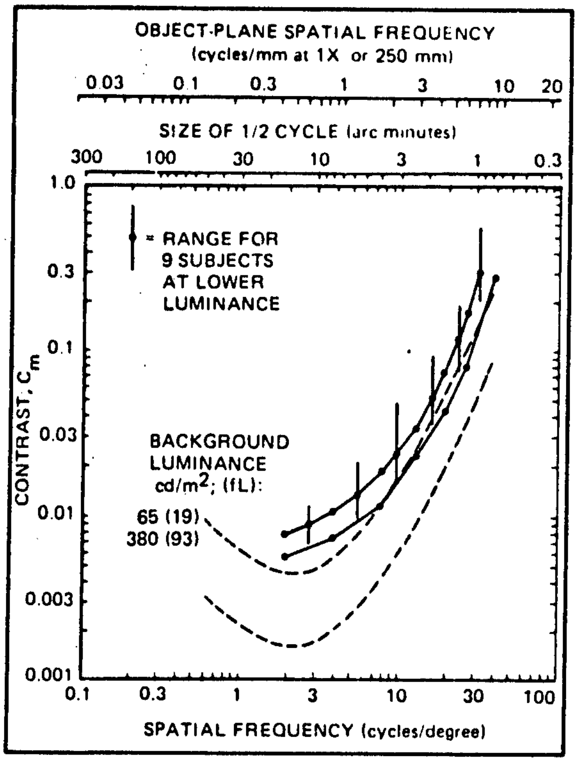


Figure 3.1-22. Contrast Sensitivity at Different Luminances (Ref. 35,B). The test conditions were:

- Square-wave 2-bar Cobb target; dark bars
- Incandescent illumination
- Luminance shown on figure
- Binocular viewing
- 0.17-second exposure time
- Criterion – Subject stated target orientation; curves show probability of right minus probability of wrong answers equal to 50 percent.
- Nine subjects

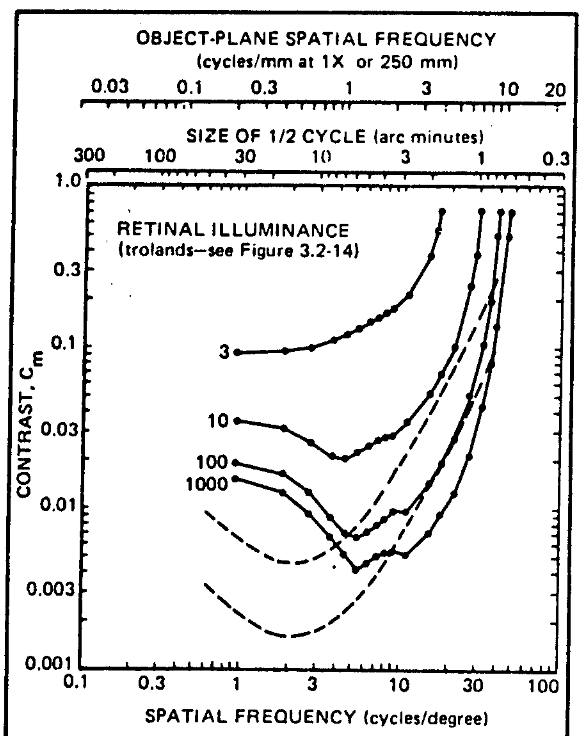


Figure 3.1-23. Contrast Sensitivity at Different Luminances (Ref. 36,C). The test conditions were:

- Sinusoidal grating
- 2-degree-diameter field
- Green CRT, P31 phosphor
- Luminance varied; see figure labeling (3 to 1000 trolands corresponds to a luminance range of 0.25 to 110 cd/m^2 or 0.07 to 33 fL, viewed with a natural pupil)
- 30-degree equiluminous surround
- Single eye, 2-mm pupil
- Criterion – Contrast increased until subject said he could see grating.
- Data reported for one subject

3.1.5 CYCLICAL TARGETS (CONTINUED)

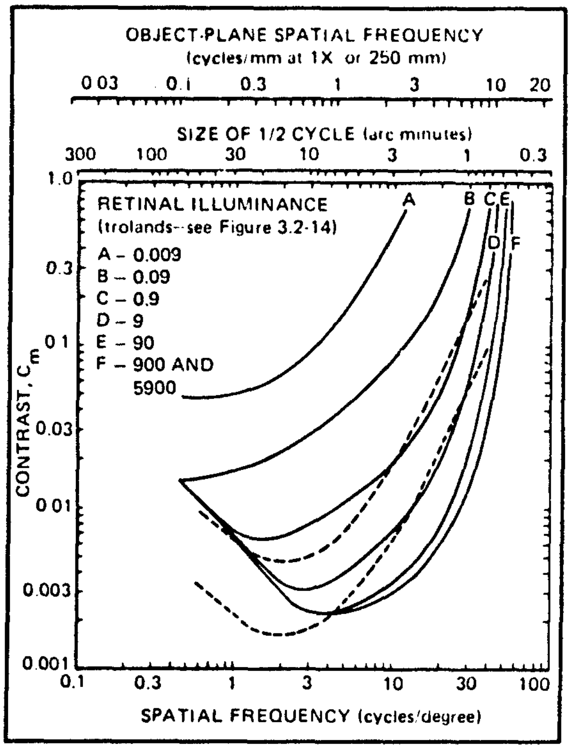


Figure 3.1-24. Contrast Sensitivity at Different Luminances (Ref. 37,C). The test conditions were:

- Sinusoidal grating
- 4.5-degree-wide by 8.2-degree-high field
- Monochromatic green illumination, 525 nm
- Luminance varied; see figure labeling [the luminances required to produce the test conditions with a natural pupil, in cd/m^2 and (fL) are: D–0.5(0.15), E–6(1.8), F–1C0(30) and 1200(350)
- Dark surround
- Single eye, 2-mm pupil, projected into eye
- Criterion – Subject varied contrast to bracket level at which grating was just perceptible.
- One subject

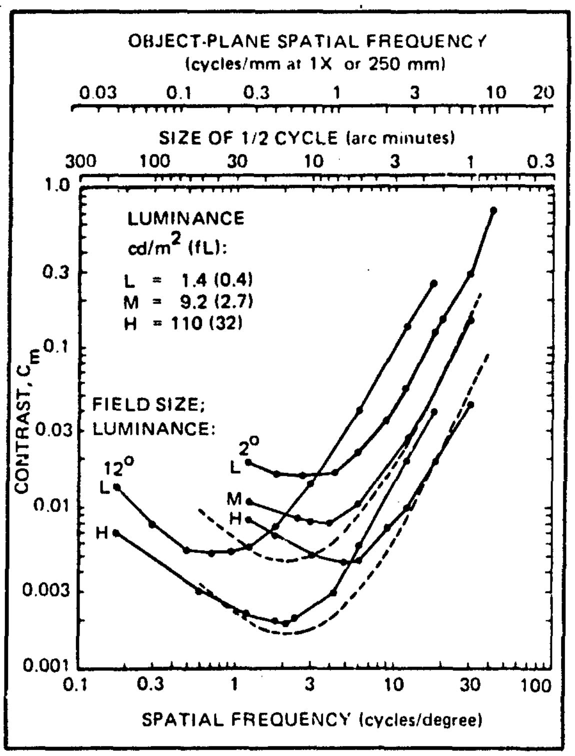


Figure 3.1-25. Contrast Sensitivity at Different Luminances and Field Sizes (Ref. 38,C). The test conditions were:

- Square-wave grating
- 2- by 2-degree field at 7m (23 ft) or 12- by 12-degree field at 1m (3 ft)
- Incandescent illumination
- Three luminance levels
- 18- by 18-degree surround, probably equiluminous
- Binocular viewing
- Criterion – Subject reduced contrast to minimum where he still could see the lines.
- One subject

3.1.5 CYCLICAL TARGETS (CONTINUED)

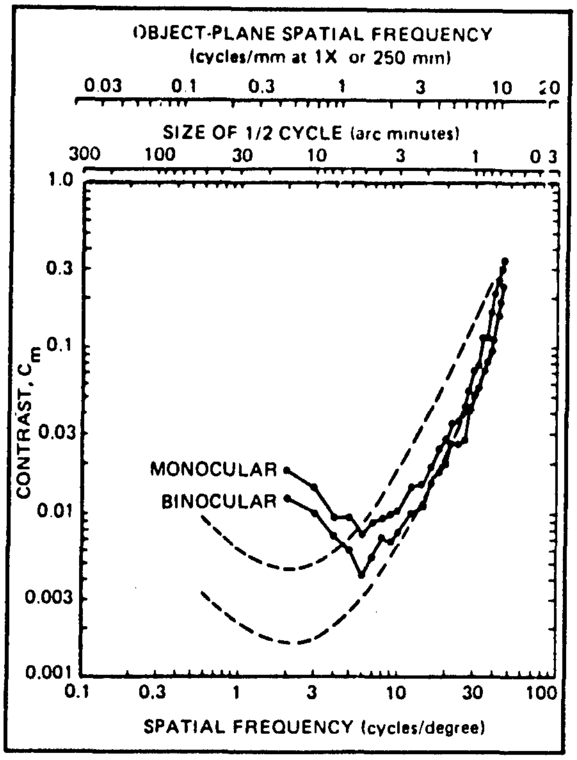


Figure 3.1-26. Contrast Sensitivity for Monocular and Binocular Viewing (Ref. 39,C). The test conditions were:

- Sinusoidal grating
- 2- by 1.3-degree field
- CRT display
- 80 cd/m^2 (25 fL)
- 12-degree equiluminous surround
- 2.8-mm pupil; accommodation fixed with atropine
- Criterion – Subject adjusted contrast to just resolve grating.
- One subject

The ratio of the monocular to binocular threshold modulation was approximately 1.414.

To evaluate the impact of using a display that would split the illumination between the two eyes, the contrast sensitivity for one eye was measured at two illumination levels and a single spatial frequency, 30 cycles/degree. The contrast threshold at 40 cd/m^2 was 1.17 times the threshold at 80 cd/m^2, indicating that binocular viewing is advantageous even if the illumination is limited.

3.1.5 CYCLICAL TARGETS (CONTINUED)

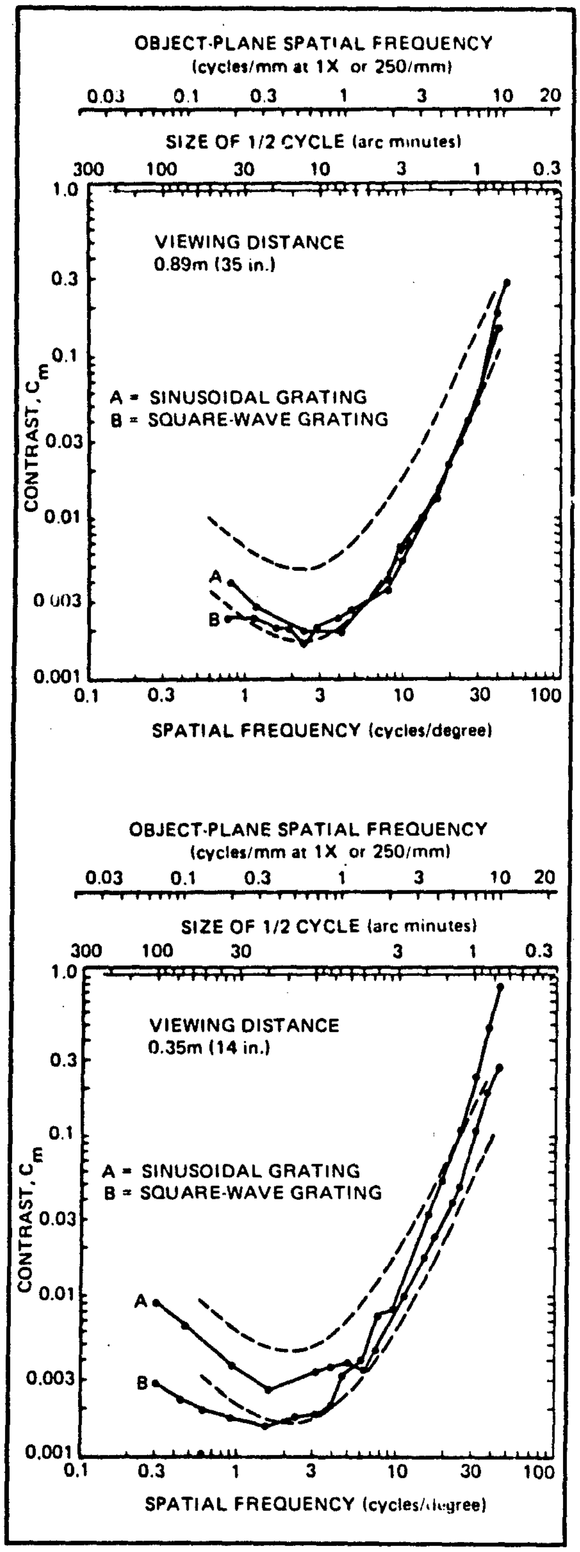


Figure 3.1-27. Sine-Wave and Square-Wave Contrast Sensitivity (Ref. 40,B). The test conditions were:

- Sinusoidal and square-wave gratings (see figure labeling)
- 6- by 6-degree field
- Incandescent illumination
- 70 cd/m^2 (20 fL)
- Equiluminous surround; size not specified
- Binocular viewing
- Criterion – Contrast reduced until subject reported grating disappeared.
- Probably one subject

Contrast sensitivity for the two kinds of gratings is very similar except at spatial frequencies below 2 cycles/degree, where the sinusoidal grating is less visible than the square-wave grating.

3.1.5 CYCLICAL TARGETS (CONTINUED)

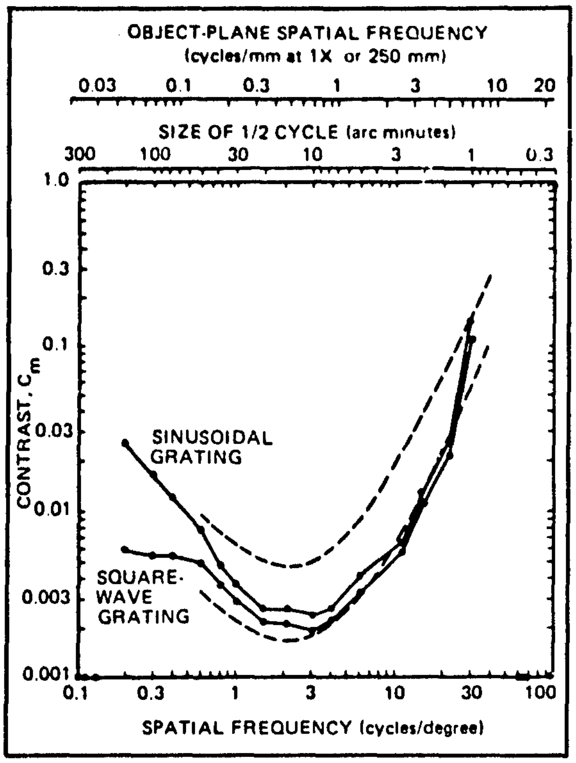


Figure 3.1-28. Sine-Wave and Square-Wave Contrast Sensitivity (Ref. 41,B). The test conditions were:

- Sinusoidal or square-wave grating, switched on and off at 0.5 Hz
- 10- by 10-degree field
- Two viewing distances, 2.8m and 0.6m (9 ft and 2 ft) used to obtain an adequate spatial frequency range
- White CRT display
- 500 cd/m^2 (145 fL)
- 30-degree equiluminous surround
- One-eye viewing; 2.5-mm pupil; atropine used to fix accommodation
- Criterion—Subject adjusted contrast so that grating was barely visible.
- Two subjects

As in the previous figure, contrast sensitivity for sinusoidal and square-wave gratings is very similar except at spatial frequencies below a few cycles per degree, where the sinusoidal grating is relatively less visible.

3.1.6 NUMBER OF TARGET CYCLES VISIBLE

Several studies demonstrate that if the number of cycles visible in a target is less than some critical number, visual performance is reduced. The data are not yet adequate to establish what the critical number of cycles is, but 10 is certainly a safe value.

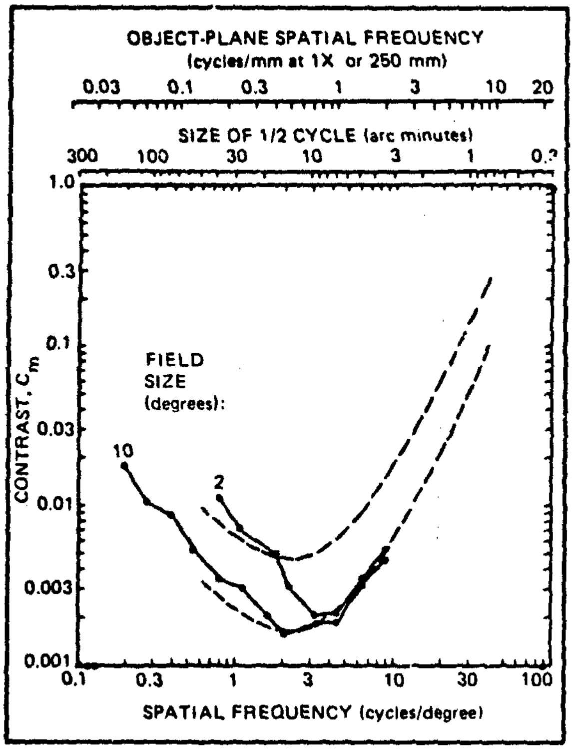


Figure 3.1-29. Effect of Field Size (Ref. 41,C). In this study, the number of target cycles visible was controlled by fixing the size of the field. These data came from the same study as the data in Figure 3.1-28. The test conditions were:

- Sinusoidal grating switched on and off at 0.5 Hz
- Square field; size on figure
- White CRT display
- 500 cd/m^2 (145 fL)
- 30-degree equiluminous surround
- One-eye viewing; 2.5-mm pupil; atropine used to fixed accommodation
- Criterion – Subject adjusted contrast so that grating was barely visible.
- One subject

3.1.6 NUMBER OF TARGET CYCLES VISIBLE (CONTINUED)

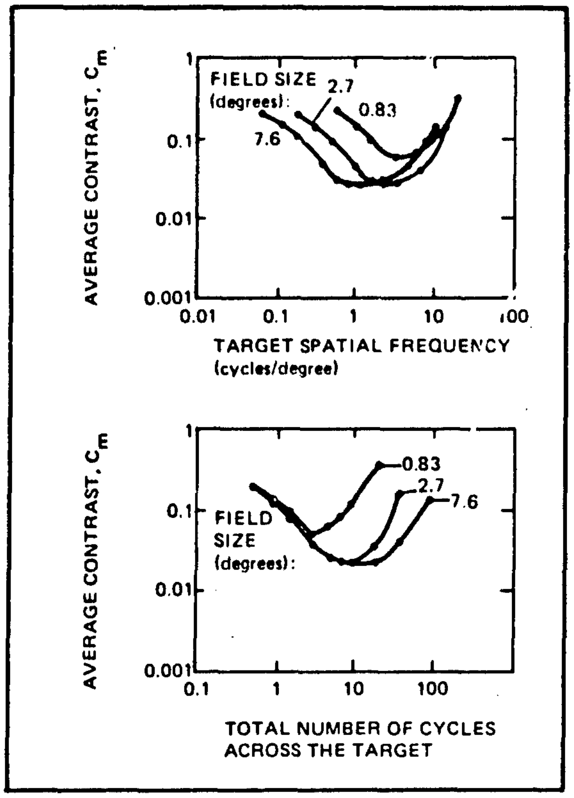


Figure 3.1-30. Relative Effect of Number of Cycles and Spatial Frequency (Ref. 42,C). These graphs illustrate test data averaged over two subjects and four test conditions, as follows:

- Vertical sinusoidal grating
- Three field sizes, as shown
- CRT display
- 9.3 cd/m^2 (2.7 fL)
- Dark surround in conditions B and D; equiluminous surround in A and C
- Monocular viewing with natural pupil
- Criterion—In conditions A and B, the subject switched manually between the grating and a uniformly luminous display and adjusted the grating contrast to the minimum value that could be distinguished from the uniform field. In conditions C and D, the subject switched between the test grating and a standard grating that had a contrast, C_m, of 0.1 and filled the field with 1.5 cycles. In this case, he adjusted the test grating contrast until it was subjectively equal to the contrast of the standard grating.

Because the data shown here were averaged over four very different sets of test conditions, they cannot be compared on an absolute basis with other studies. Separate contrast sensitivity curves for the four test conditions were reported for one of the two subjects. These were very similar in shape to each other, and to the curves shown here, but were shifted vertically so that the lowest contrast, Cm, values were as follows:

A – 0.01
B – 0.02
C – 0.03
D – 0.02

The two graphs show contrast sensitivity first as a function of spatial frequency and then as a function of the number of cycles present. The curves for the three field sizes appear to fall close together in the high spatial frequency region in the first graph, and in the low number of cycles region of the second. This suggests that although at high spatial frequencies it is the spatial frequency that determines visibility, when less than about 3 cycles of the target are present, visibility becomes highly dependent on the number of cycles. Interpretation of these data is complicated by the fact that the target was switched on and off, making it similar to a flicker task.

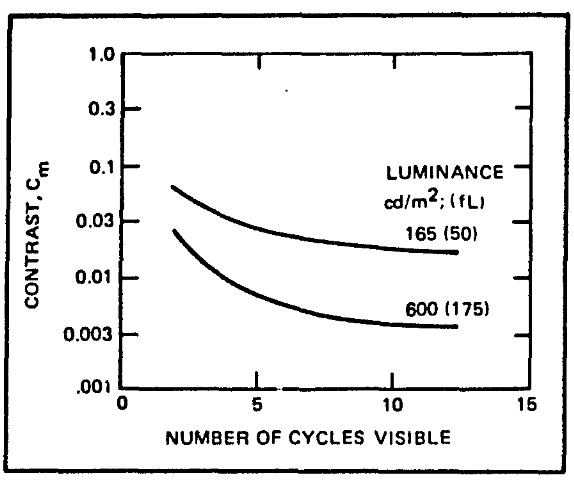


Figure 3.1-31. Effect of Number of Cycles in Target (Ref. 43,B). Two test subjects were used to measure the minimum contrast, Cm, at which a vertically oriented sinusoidal grating containing a variable number of cycles was visible. The grating was displayed on a CRT and had a minimum height of 1 degree. Spatial frequency values of 2 to 7 cycles/degree are included in the upper curve and 1 to 5 cycles per degree in the lower curve. According to the report, contrast threshold did not vary with spatial frequency over this frequency range. Performance did vary with the number of cycles visible, reaching a maximum somewhere between 5 and 10 cycles.

3.1.6 NUMBER OF TARGET CYCLES VISIBLE (CONTINUED)

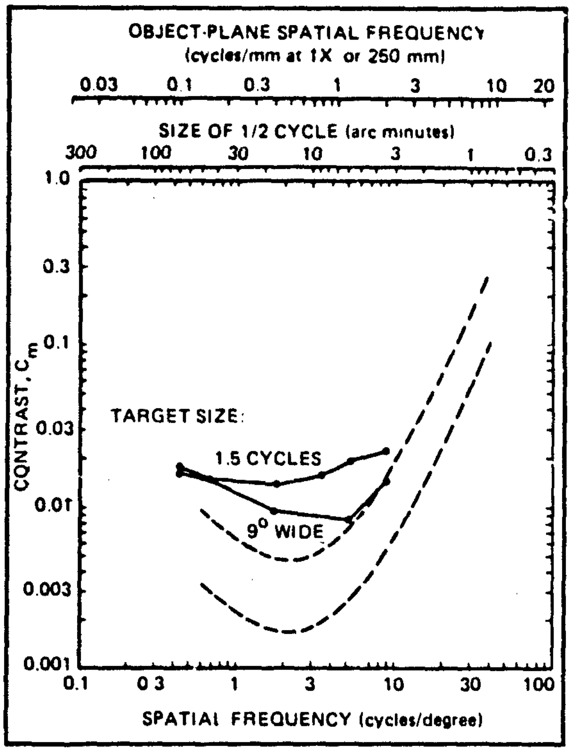


Figure 3.1-32. Effect of Number of Cycles in Target (Ref. 44,C). In this study, the target consisted of either two bars or a row of bars that filled the 9-degree display field. The other test conditions were:

- Square-wave grating containing light bars 3.8 degrees long, oriented 45 degrees left or right of horizontal
- 32-cd/m^2 (9-fL) background
- 0.5-second exposure
- Criterion – Subject said he could see the bars on half the trials.
- One subject

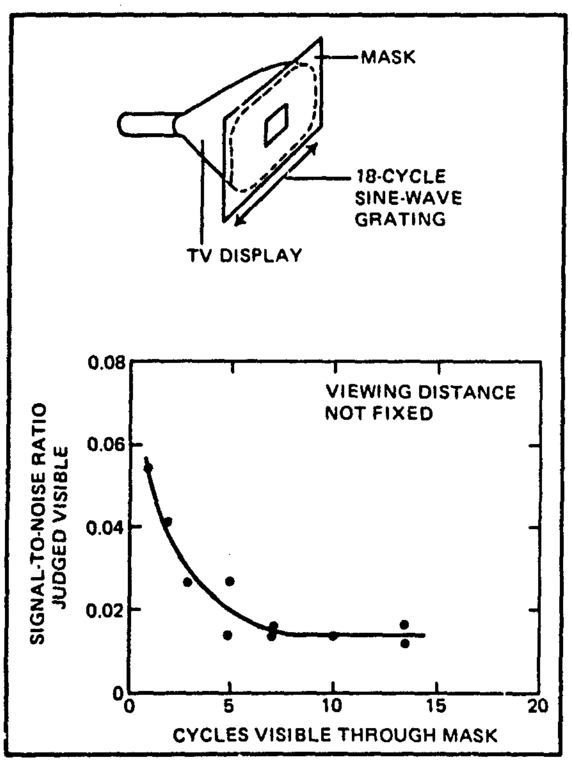


Figure 3.1-33. Effect of Number of Cycles in Target (Ref. 45,D). In this study, an 18-cycle sinusoidal grating was displayed on a CRT, and the number of grating cycles was varied with a mask. Viewing distance was not controlled, and the scene luminance and number of test subjects were not reported. Visibility was measured in terms of the signal-to-noise ratio required to obtain consistent reports from the subjects that the target was visible.

3.1.7 SPECIAL TARGET SHAPES

Although the targets used in the experiments described in Sections 3.1.3 through 3.1.6 have considerable application in the theoretical analysis and testing of imagery displays, objects with a luminance distribution exactly like any of these targets are rarely encountered by the display user. Several recent studies utilizing targets much more similar to the edges that an imagery display user might actually be viewing are summarized here.

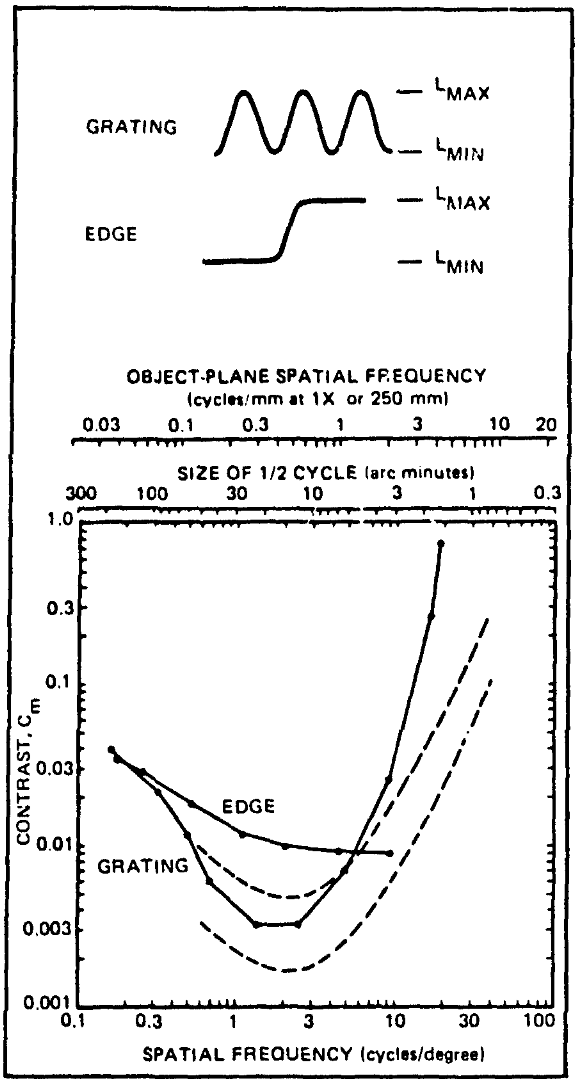


Figure 3.1-34. Effect of Target Shape (Ref. 46,C). The test conditions were:

- Vertically oriented sinusoidal grating or edge.
- 2.9-degree-wide by 1.4-degree-high field
- Incandescent illumination
- 75 cd/m^2 (22 fL)
- Large equiluminous surround
- Single eye viewing; artificial pupil, size not reported, projected into eye
- Criterion – Subject adjusted contrast until target was barely visible.
- One subject

The spatial frequency of the edge target was taken as the spatial frequency of a grating with an equal luminance gradient. The upper illustration shows, to scale, the luminance distribution of two targets with numerically equal contrast and spatial frequency.

3.1.7 SPECIAL TARGET SHAPES (CONTINUED)

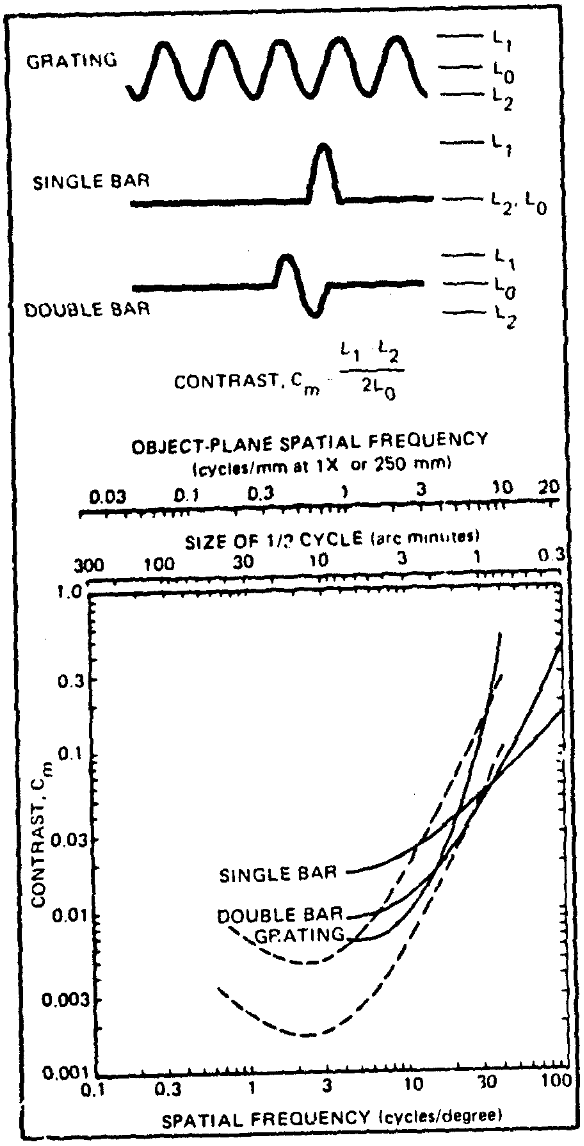


Figure 3.1-35. Effect of Target Shape (Ref. 47,C). The test conditions were:

- Vertical sinusoidal grating containing 0.5, 1.0, or multiple cycles; luminance distribution is illustrated; pattern was switched on and off at 0.5 Hz
- 1-degree-diameter field
- CRT display
- Luminance not specified
- 5- by 5-degree equiluminous white surround
- Binocular viewing
- Criterion—Subject adjusted contrast to make pattern barely visible; results were the same for 50-percent probability of seeing measured objectively at selected spatial frequencies.
- Three subjects

Unfortunately this report does not include a clear statement of how the contrast of each type of target was calculated. The upper illustration, which is drawn to scale, shows the most likely relative luminance distribution for the three types of targets when they have numerically equal contrast and spatial frequency.

3.1.7 SPECIAL TARGET SHAPES (CONTINUED)

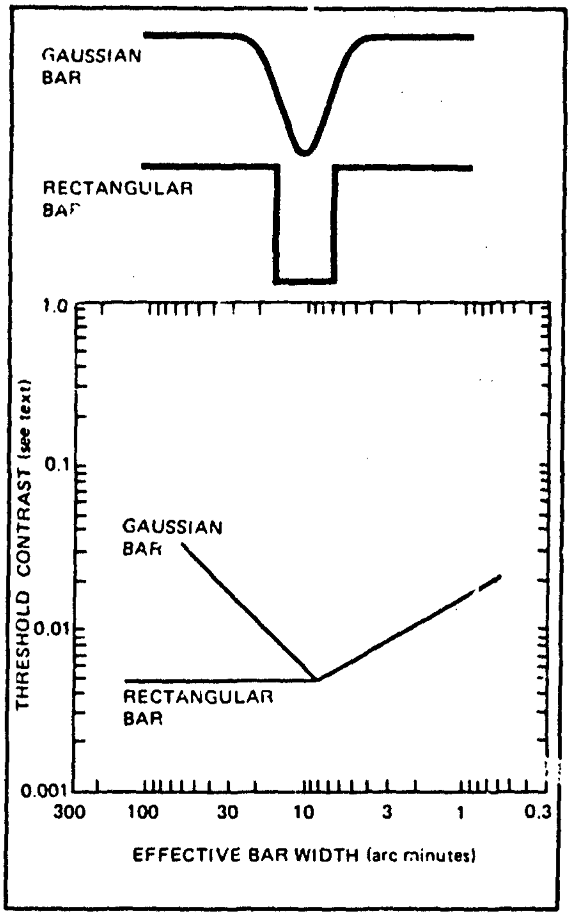


Figure 3.1-36. Effect of Target Shape (Ref. 48,C). The test conditions were:

- Dark vertical bar with a rectangular or Gaussian luminance distribution (Ref. 49)
- 5.5-degree-diameter field
- CRT display
- 100 cd/m^2 (30 fL)
- Surround not reported
- Binocular viewing
- Criterion – Subject adjusted contrast to make bar barely visible.
- Two subjects; figure illustrates an approximate visual fit to the data.

The upper illustration, which is drawn to scale, shows the relative luminance distribution of the two targets when they have numerically equal contrast and spatial frequency. Contrast is defined here as the luminance difference across the target divided by twice the luminance averaged over the entire display field. When the contrast is low and the bar fills only a small portion of the display, contrast is approximately equal to C_m as used elsewhere in this document. An exact conversion to contrast units used by other authors is very difficult (Ref. 50).

3.1.8 TARGET ORIENTATION

A number of studies have demonstrated that targets oriented horizontally or vertically relative to the observer are easier to see than targets oriented obliquely (Ref. 50). Two typical studies are summarized here.

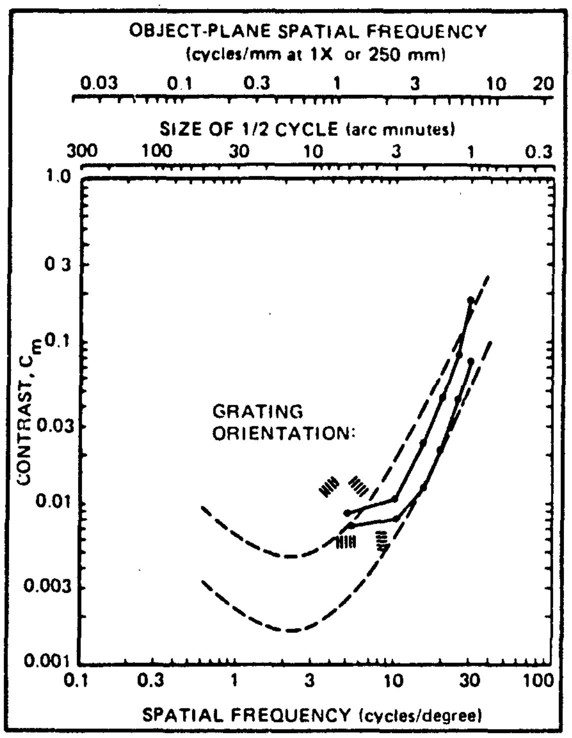


Figure 3.1-37. Contrast Sensitivity as a Function of Target Orientation (Ref. 52,B). Test conditions were:

- Sinusoidal grating
- CRT display
- Single eye viewing; 2.8-mm pupil
- Criterion - Subject adjusted contrast to threshold level.
- Three subjects

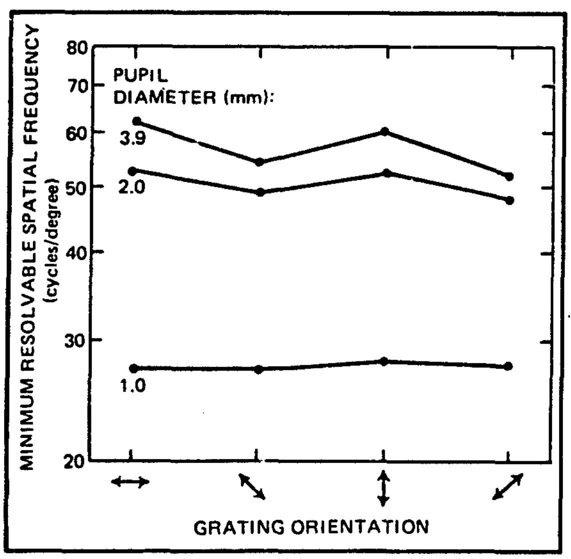


Figure 3.1-38. Minimum Visible Size (Ref. 53,B). The test conditions were:

- Square-wave grating filling display field
- 4-degree-diameter field
- Incandescent illumination
- Retinal illuminance of 100 trolands (equivalent to viewing a 7-cd/m^2 or 2-fL surface with a natural pupil)
- Single eye viewing; pupil projected into eye
- Criterion — minimum size at which subject could correctly report the grating orientation
- Two subjects

3.1.9 VISUAL PERFORMANCE AND EYE PUPIL SIZE

A vital part of the analysis of an imagery display depends on the relationship between visual performance and eye pupil size. (See Section 3.3.) When the eye pupil is small, vision is limited by diffraction effects, and when the pupil is large, it is limited by the optical quality of the eye and the capability of the retina. The most useful data on this topic are summarized below. Considering the importance of this relationship to the design of displays optimally matched to the eye, there is surprisingly little test data available.

In the analysis of an optical display, visual performance as a function of pupil size is usually expressed as the smallest resolvable target size multiplied by the diameter of the pupil. This unit is known as *specific resolution* or as the coefficient of specific resolution.

Visual performance varies both with pupil size, as is illustrated here, and with scene illumination, a topic that is reviewed in Section 3.2. As scene luminance decreases, pupil size increases, thereby partially compensating for the reduction in available light. There is a very small amount of evidence that the normal variation in pupil size with illumination follows a function that yields the best compromise between the amount of light reaching the retina and the aperture effect of the pupil, thereby resulting in the best possible vision at any scene luminance level (Ref. 54,D).

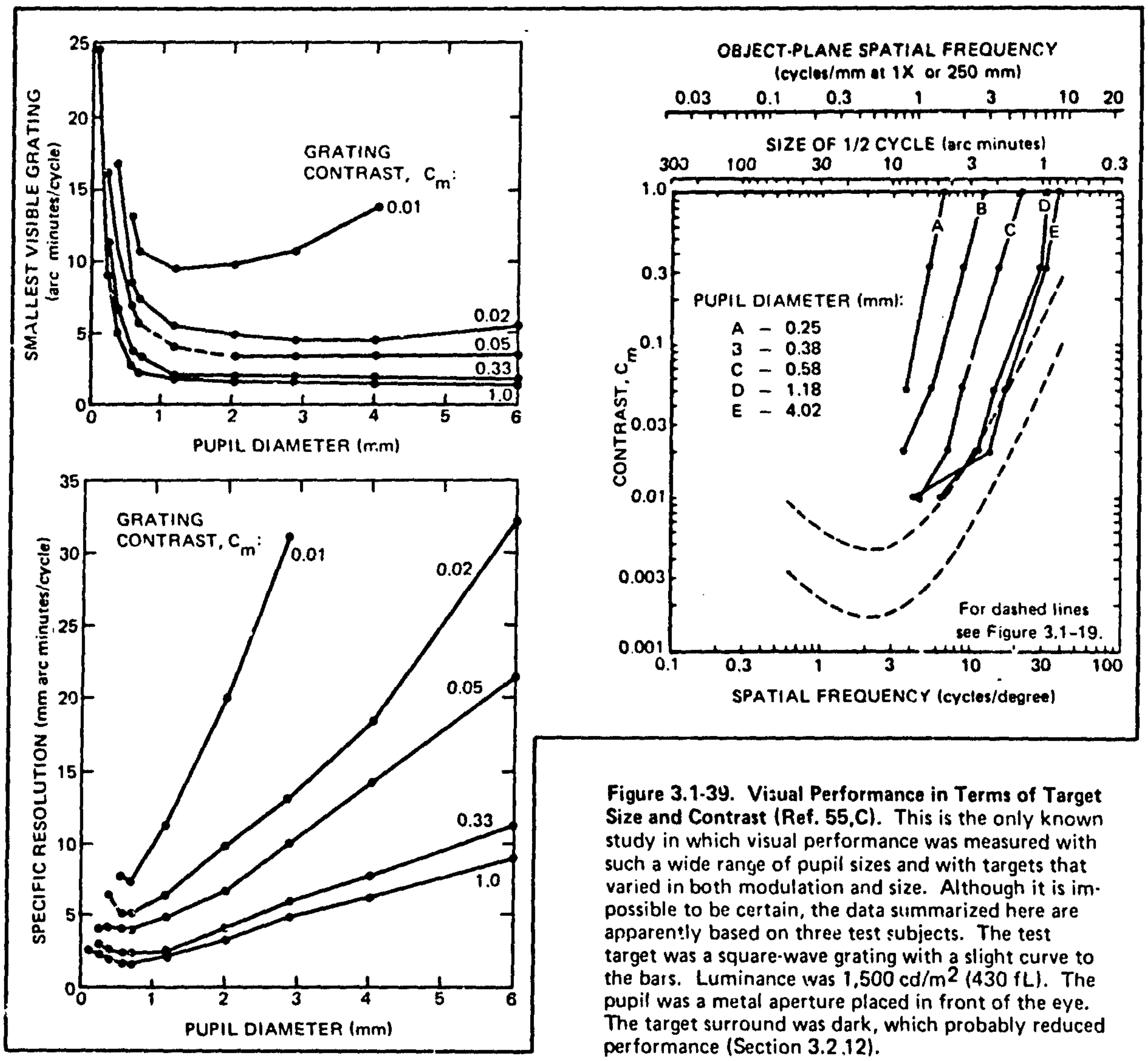


Figure 3.1-39. Visual Performance in Terms of Target Size and Contrast (Ref. 55,C). This is the only known study in which visual performance was measured with such a wide range of pupil sizes and with targets that varied in both modulation and size. Although it is impossible to be certain, the data summarized here are apparently based on three test subjects. The test target was a square-wave grating with a slight curve to the bars. Luminance was 1,500 cd/m^2 (430 fL). The pupil was a metal aperture placed in front of the eye. The target surround was dark, which probably reduced performance (Section 3.2.12).

3.1.9 VISUAL PERFORMANCE AND EYE PUPIL SIZE (CONTINUED)

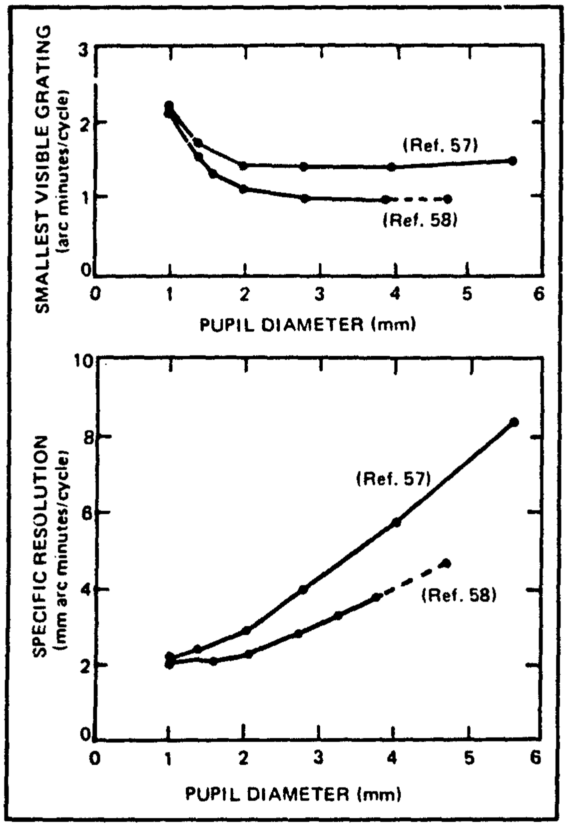


Figure 3.1-40. Visual Performance in Terms of Target Size. The two studies summarized here used high-contrast test targets. The relative effect of pupil size on vision was nearly identical in the two studies here, and in two others that used comparable test conditions but less adequate control of the amount of light that reached the retina with different pupil sizes (Ref. 56).

The test conditions for the study summarized in the upper curve in each figure were (Ref. 57,B):

- Two light bars (Cobb target) with a square-wave luminance distribution
- Incandescent illumination
- Retinal illuminance of 150 trolands (equivalent to viewing a 10-cd/m^2 or 3-fL surface with a natural pupil)
- Metal pupil 15 mm in front of eye pupil
- Criterion – Subject adjusted target size to make bar separation just visible.
- Three subjects

The test conditions for the study summarized in the lower curve in each figure were (Ref. 58,B):

- Square-wave grating filling display field
- 4-degree-diameter field
- Incandescent illumination
- Retinal illuminance of 1,000 trolands (equivalent to viewing a 110-cd/m^2 or 32-fL surface with a natural pupil)
- Surround probably dark
- Single eye viewing; pupil projected into eye
- Criterion - minimum size at which the subject could correctly report the grating orientation
- Two subjects, except only one for the largest pupil condition (indicated with a dashed line)

A luminance level 10 times lower reduced performance but had little if any impact on the relationship between performance and pupil size.

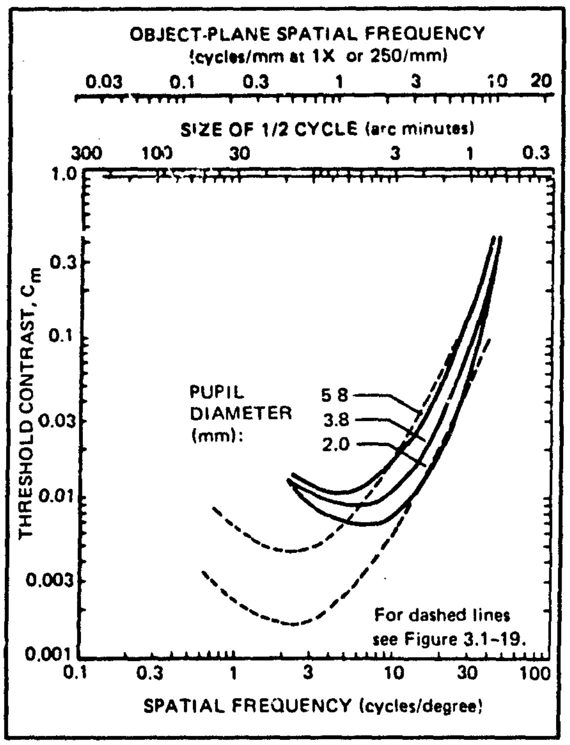


Figure 3.1-41. Effect of Pupil Size on Contrast Sensitivity (Ref. 59,C). The test conditions were:

- Sinusoidal grating
- 2- by 1.3-degree field
- CRT display with green phosphor, P1
- 100 cd/m^2 (30 fL)
- Equiluminous surround
- Accommodation fixed and natural pupil dilated with drugs; artificial pupil sizes as shown
- Criterion–Subject adjusted contrast to just resolve grating.
- One subject

3.1.10 FACTORS THAT REDUCE VISUAL PERFORMANCE

CAUTION: The data in Sections 3.1.4 through 3.1.9 may overestimate visual ability in applied situations.

Most of the data presented in Sections 3.1.4 through 3.1.9 were collected under ideal laboratory conditions. That is, the background was uniformly luminous, the subjects were familiar with the appearance of the target and knew where and when it would appear, and viewing time was usually not severely restricted. Imagery viewing conditions are seldom so favorable, and the minimum target size or contrast that can be seen, the time required to perform a visual task, or the number of targets missed are accordingly increased. This section lists a few of the factors that can cause such an increase and summarizes the available test data. The total reduction in vision associated with a particular set of viewing conditions, relative to vision under ideal conditions, is sometimes referred to as the field factor (Ref. 60).

The following viewing conditions and situations generally result in, or at least are associated with, a reduction in visual ability:

- Reduction in luminance -Typical reductions in visual ability with a reduction in luminance are shown in Figure 3.1-42 and in several figures in Sections 3.1.6 and 3.2.6.

- Reduction in time available to look at or search for the target- One study showing the reduction in visual ability with reduced target exposure time is summarized in Figure 3.1-42. The impact of time on this kind of very simple visual task is likely to be considerably less than in a complex imagery search situation. Figure 3.5-2 shows representative data for search performance as a function of time.

- Introduction of a nonuniform background-If the luminance in the area around the target is not uniform, the target will be more difficult to see; if a search task is involved, the target will be more difficult to find. Unfortunately there are no known data that provide a direct comparison between visual thresholds for uniform and nonuniform backgrounds. However, Figures 3.1-44, -45, and -46 below provide limited information about visual performance with a nonuniform background, as does Reference 62. The reduction in search performance with a nonuniform background is at least partially due to the fact that time is lost looking at objects visually similar to the target being sought (Ref. 63).

- Introduction of noise Noise, such as grain in a photograph or electronic noise in an electro-optical display, creates a nonuniform background, and in addition can obscure the target directly. The effects of noise in electro-optical displays are covered in Section 4.3.3.

- Lack of experience with the viewing situation- Subjects required to state whether or not a disc target was visible required 2.0 times as much contrast on initial trials as they required when experienced (Ref. 63,X). Unfortunately the author of this statement did not indicate in the report of his follow-on research, summarized as study B in Figure 3.1-17, whether the subjects in the latter study fell into the experienced or inexperienced category.

- Lack of knowledge about the target shape and orientation-In the study summarized in Figure 3.5-3, subjects were more successful in locating a target when they knew its orientation than when they did not. Orientation information would probably be less important for extremely familiar objects. Familiar objects should also be easier to find, or visible at lower contrasts, than unfamiliar ones. There is some discussion of this in Figure 3.1-11.

- Reduction in information about when a target will appear-Elimination of the signal warning that a target was about to appear in a study, such as described in Figures 4.2-17 and -42, increased the contrast threshold by a factor of 1.4 (Ref. 64,D).

- Displacement of the target from the fixation point- As Figures 3.5-10, -11, and -12 illustrate, visual ability in the peripheral visual field is worse than at the fixation point. Contrast thresholds for disc targets 1.5 degrees from the fixation point were 2.6 times the value at the fixation point in a study similar to

3.1.10 FACTORS THAT REDUCE VISUAL PERFORMANCE (CONTINUED)

those described in Figures 3.1-16 and -42 (Ref. 65,X). At 2° from the fixation point, the increase was 4 times the value at the fixation point. (These data are probably from the study illustrated in the upper graph of Figure 3.5-12.)

- Reduction in the information about target location – In most of the experiments described previously in Section 3.1, the subjects knew the exact location of the target. Contrast thresholds increased by a factor of 1.3 when the disc target appeared 3 to 4 degrees on either side of the fixation point in studies such as those summarized in Figures 3.1-16 and -42 (Ref. 64,X). Target exposure duration in this study was not reported, but it must have had an effect on the results. Additional studies on this topic in which visual search was involved are summarized in Figures 3.1-43 and -44 below.

- Reduction of the rate at which targets appear – Presenting disc targets in a situation like that described in Figures 3.1-16 and -42 at an average rate of one per 15 minutes, rather than one per 10 to 30 seconds, increased contrast thresholds 1.2 times (Ref. 64,D). An extremely low target rate makes the visual task a vigilance task as well. The many factors that affect vigilance have been extensively studied (Ref. 66). The rate at which new targets are found in most imagery search situations is very low.

- Reduction in the reward for a correct response, relative to the penalty for reporting the wrong object as a target – The probability that a particular object that looks sort of like a target will be reported as a target depends heavily on the relative values of the rewards and penalties for making a correct or incorrect report of a target, or for missing a target. For example, if all correct responses are rewarded and there is no penalty for wrong responses, the subject will be more likely to guess and hence will have a lower threshold than if he is penalized for reporting objects that are not targets. Because each individual assigns different relative values to tangible things, like money, and to intangible things like criticism or the knowledge that a particular test response was correct, these rewards and penalties are never fully under the control of the experimenter or employer. In simple experimental situations, it is sometimes possible to reduce the impact of this variable on the results by forcing the test subject to make a choice between several alternatives. For example, in the study in Figure 3.1-16, the subjects had to choose which of four time intervals contained a target, while in studies B and C in Figure 3.1-17, they judged when the target was visible.

3.1.10 FACTORS THAT REDUCE VISUAL PERFORMANCE (CONTINUED)

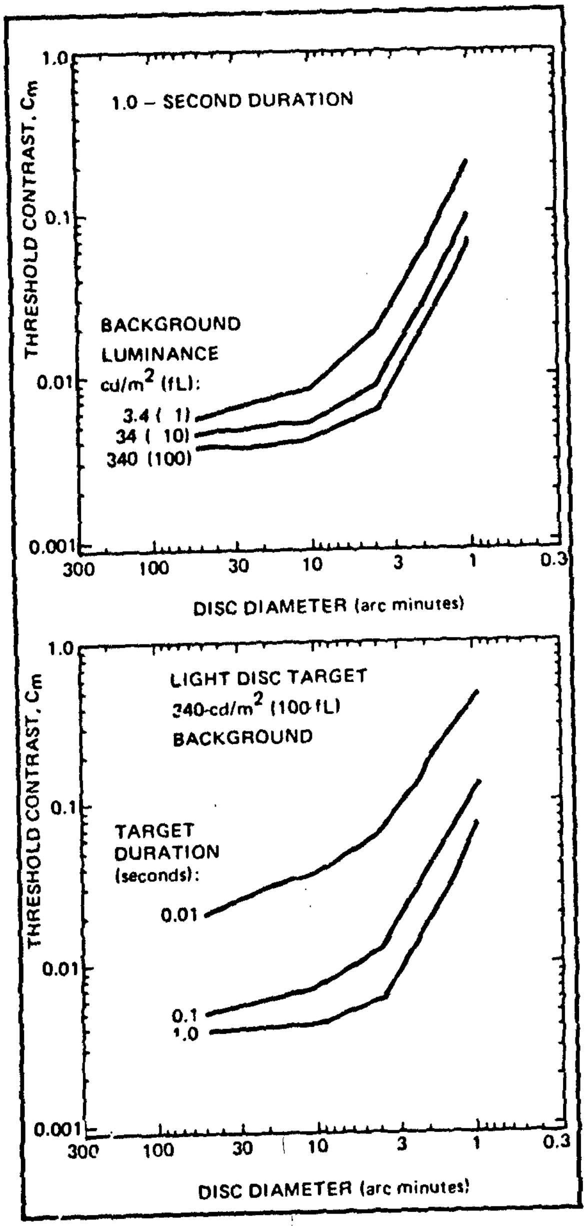


Figure 3.1-42. Effect of Luminance and Time on Contrast Sensitivity. In this study, which is from the same lab as Figure 3.1-16, subjects attempted to determine which of four time intervals contained a luminous disc of the indicated size and duration (Ref. 67,B). Performance was worse at lower background luminances (Section 3.2.6) and with shorter target exposure durations.

The data shown here are probably based on a success probability, corrected for chance, of 0.5. However, this is not certain from the available reports.

3.1.10 FACTORS THAT REDUCE VISUAL PERFORMANCE (CONTINUED)

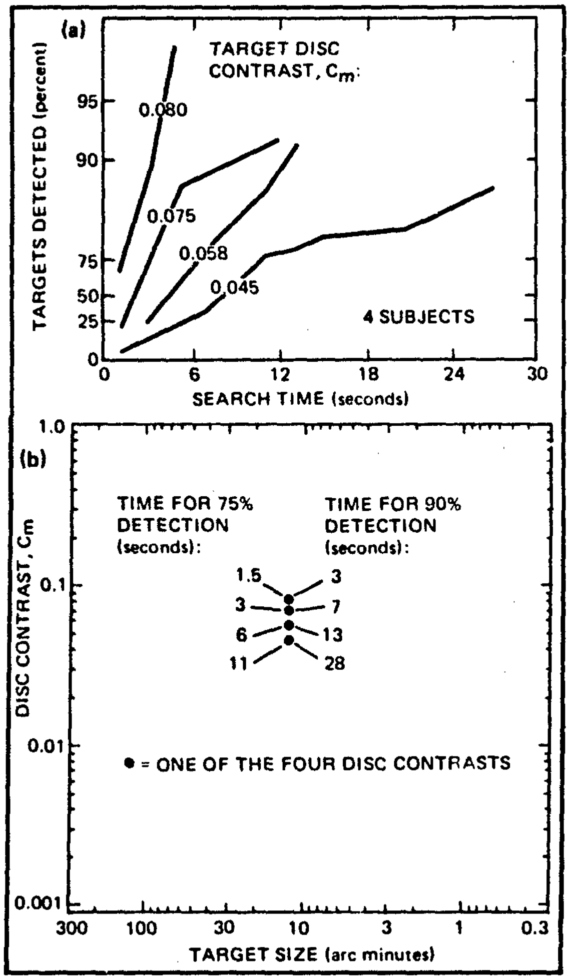


Figure 3.1-43. Contrast Sensitivity in a Search Situation. In this study, subjects searched a 32-degree-diameter field with a uniform luminance of 42 cd/m^2 (12.4 fL) for a single 13-arc-minute-diameter light circular disc (Ref. 68,C). As part (a) illustrates, the higher contrast discs were found rapidly, while an appreciable number of lower contrast discs had still not been found after 30 seconds of searching. The vertical scale in this figure matches a complex probability function and has no 100-percent value.

In part (b), the disc size and contrasts are shown on the same coordinate system used in Figure 3.1-16. The study described in that figure used a similar disc target, but the subjects knew exactly where it would appear and only had to decide within which of four time intervals it occurred. In the study described here, the requirement to search for the target disc made the disc much harder to find. Other data from this study, not illustrated here, showed that increasing the size of the field, or decreasing its luminance, also made the disc more difficult to find.

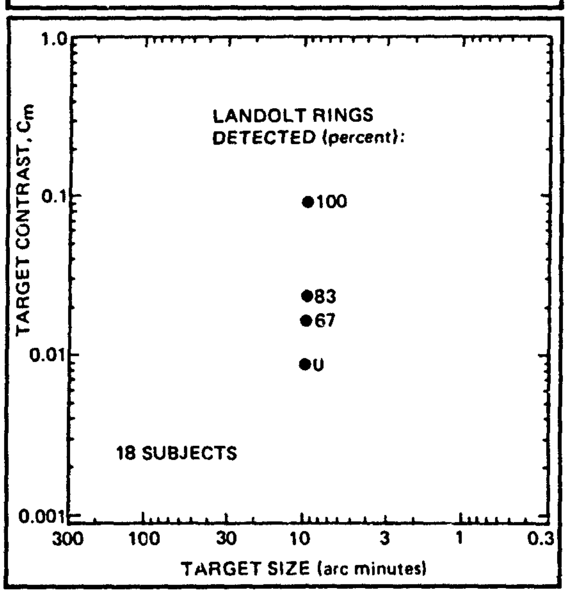


Figure 3.1-44. Effect of Background Clutter. In this study, subjects searched for a single dark Landolt ring located in a uniform density area of at least a degree or so in a photograph of an aerial map (Ref. 69,X). The overall diameter of the ring was 10 arc minutes. The subjects were not required to state the ring orientation. The illumination on the photograph was nominally 1200 lux (110 footcandles). The density variations in the photograph were not constant across different ring contrast conditions, since lower ring contrasts were obtained by compressing the total density range. This should have made the lower contrast rings easier to find than if the full range of densities had been retained. The search area was 27 degrees square.

In order to simplify the comparison of these data with the results of other studies, success in finding each size and contrast target with 120 seconds of search is shown here on the same coordinates used in Figure 3.1-16. Most target rings were located in much less than 120 seconds. The report does not make it clear whether search was allowed to continue beyond 120 seconds.

The data shown in this figure are the same as the free-search condition in Figure 5.4-2.

3.1.10 FACTORS THAT REDUCE VISUAL PERFORMANCE (CONTINUED)

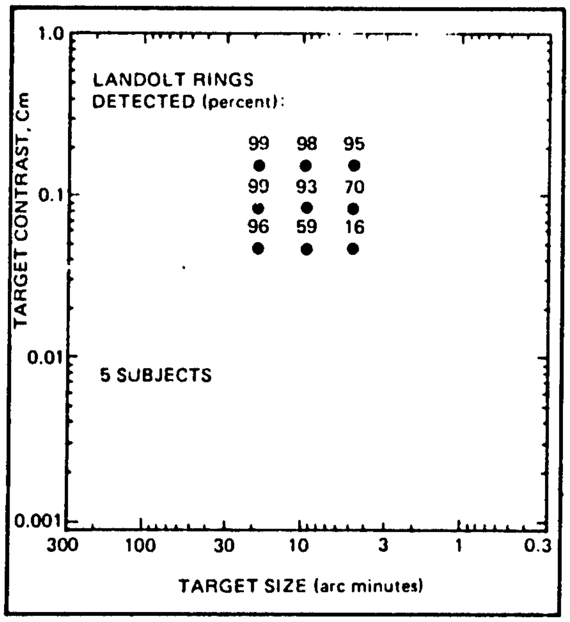


Figure 3.1-45. Forced Search in Background Clutter. This figure is based on the same general test conditions as Figure 3.1-44, except that the 27-degree-square test field was broken into 144 2.3-degree squares and the subject was given 0.65 second to view each (Ref. 69,D). (Figure 5.4-2 is based on the same study.) Thirty-six of the 144 squares contained rings. Three sizes of rings, 5, 10, and 20 arc minutes in diameter, were used. Under these conditions, the reduction in performance was even greater than in Figure 3.1-44.

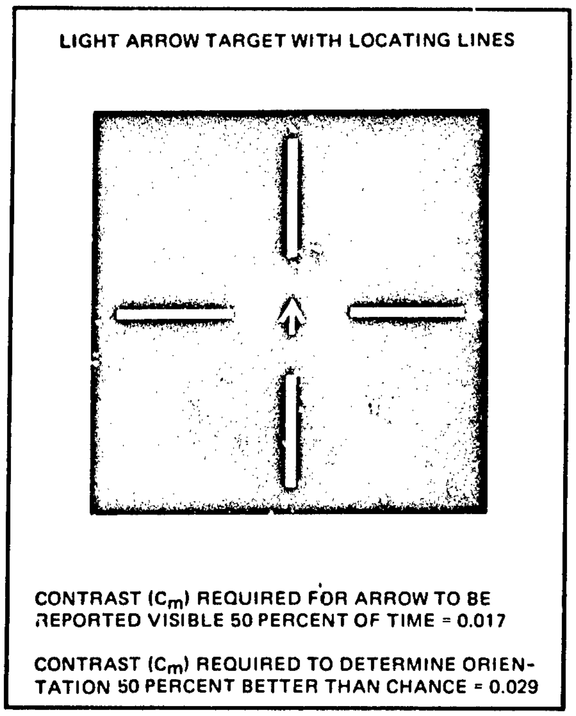


Figure 3.1-46. Contrast Sensitivity in a Photographic Image. In this study, a light arrow was projected onto 1 of 32 uniform density areas on the projections of six black and white amateur-type snapshots (Ref. 70,C). The approximate shape of the 0.5-degree-wide arrow is shown here. To help the subjects find the arrow, it was located in the open center of a cross formed by four lines. The projection screen luminance with no film present was 34 cd/m^2 (10 fL). The 32 uniform density areas ranged in luminance from about 0.1 to 28 cd/m^2 (0.03 to 8 fL). The luminance increment of the lines was constant at 3.4 cd/m^2 (1.0 fL), while the luminance of the arrow was set at different levels to cover the threshold range.

The arrow and lines appeared for 2 seconds, which reportedly gave the subjects about 1 second to find the four lines and 1 second to study the arrow. The subjects first indicated whether they could see the arrow and then gave their best estimate of its orientation. Preliminary testing was used to establish the ratio between the threshold contrast for seeing the target and for establishing its orientation. After this, only orientation responses were required and these were used to calculate the threshold for seeing the target.

The thresholds given here were approximately constant over a background luminance range of about 1 to 28 cd/m^2 (0.3 to 8 fL). A further reduction in background luminance to 0.1 cd/m^2 (0.03 fL) increased the required contrast by a factor of 10 times.

3.1.10 FACTORS THAT REDUCE VISUAL PERFORMANCE (CONTINUED)

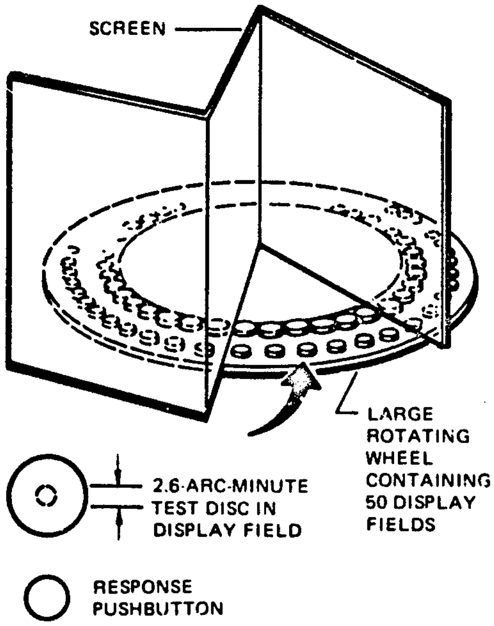


Figure 3.1-47. Contrast Sensitivity in a Simulated Work Task. This study illustrates an attempt to estimate contrast thresholds for tasks more similar to normal work situations than the typical laboratory experiment (Ref. 71,C). Subjects attempted to detect light 2.6-arc-minute discs centered in uniformly luminous circular display fields as these moved past the subject's workstation. Display field size was not given, but was probably several degrees. Subjects responded by depressing a pushbutton below each display. This part of the task reportedly did not limit performance.

New display fields appeared at a rate of either 1 or 2.5 per second, which gave the subject an average time of either 1 or 0.4 second to study each field. Contrast thresholds obtained in this manner were compared with values using the same size disc and the same exposure times, either 1 of 0.4 seconds, but with the target disc appearing during one of four intervals as in Figure 3.1-16.

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2. Adapted from Hopkins, R. E., *Visual Optics*. Chapter 4 in *Optical Design*, MIL-HDBK-141, Standardization Division, U.S. Defense Supply Agency, Washington, D.C., 1962.

3. The aqueous and vitreous humor normally contain small particles of foreign material. Under proper conditions, such as when looking at a uniformly luminous scene such as the sky, or when looking into a microscope, these particles can be seen moving across the visual field. They are generally known as "floaters" and are discussed under the heading "entoptic phenomena" in books on vision.

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    Donaldson, K. C. and Gough, H. O. *The Determination of a Set of Alphanumeric Characters of Equal Recognizability*. B.A. thesis, Rochester Institute of Technology, 1968. This study indicates that one of the reasons for between-rate disagreement on tri-bar readings is that observers differ in their criteria of what constitutes a just-acceptable image.

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SECTION 3.2 ILLUMINATION

Adequate illumination is essential if the user is to take full advantage of an imagery display. Proper specification of illumination must include quantity, spectral distribution, and spatial distribution. The available information on user requirements in each of these areas is treated in Sections 3.2.6 through 3.2.13 below.

The requirement to specify illumination implies a need to be able to properly describe and measure it. Because a certain amount of confusion exists in these areas, Sections 3.2.1 through 3.2.4 are devoted to a brief summary of photometric concepts and techniques. The following aids are of particular importance when display luminance must be measured:

- Charts for converting scene luminance to retinal illuminance (Figures 3.2-14, -15, and -16).
- A discussion of photometry as it applies to imagery displays (Sections 3.2.3 and 3.2.4, and particularly Figures 3.2-21 and -22).

3.2.1 PHOTOMETRIC CONCEPTS

Light can be described as *radiant energy* traveling in the form of electromagnetic waves and having a *wavelength* proper for evoking a visual sensation (Ref. 1). In this document the spectral range for light is taken as 400 to 700 nm, even though if the energy level is sufficient, wavelengths adjacent to this region will also evoke a visual sensation (Ref. 2).

The term *radiometry* applies to the measurement of *radiant energy* and the term *photometry* to similar measurements when the spectral region measured has been weighted according to the sensitivity of the eye to energy at each point along the spectrum, using the curve shown in Figure 3.2-2. With the exception of the treatment of *infrared* and *ultraviolet* energy in Section 6.8, this document is concerned only with photometry.

Techniques for measuring and describing light are described in numerous sources (Ref. 3). This section is therefore limited to two factors of particular importance in the photometry of imagery displays, the spectral response of the sensor and the geometric limitations on the energy it accepts. For the special problem of electro-optical displays a third factor, the temporal response of the sensor, is also important (Section 4.2).

The most important radiometric and photometric terms used in this document are listed below.

- *Radiant power*, also called *radiant flux*, is the time rate of flow of radiant energy. Typical units are joules/second or watts.
- *Luminous power*, also called *luminous flux*, is radiant power weighted according to the spectral sensitivity of the eye. The basic unit is the lumen.
- *Illuminance*, formerly called illumination, is the luminous power per unit area (density) incident upon a surface. Units are lux and footcandles.
- *Luminance* is the luminous power per unit solid angle leaving, passing through, or arriving at a unit surface area in a specified direction. The surface area is defined in terms of the apparent area as viewed from the specified direction. Common units are candelas per square meter (cd/m^2) and footlamberts (fL). Conversions among the several luminance units in use are included in Figures 3.2-14, -15, and -16.

Luminance is the most frequently used of these quantities in imagery displays. Like the response of the eye to a luminous surface, the definition of luminance involves:

- The apparent size of the luminous surface
- The angular size of the bundle of light rays reaching the sensor from a single point on the surface
- The direction in which the light is traveling

The term *brightness* has been used to refer both to luminance and to the visual sensation associated with a given luminance. Preferred usage at present is to restrict the term "brightness' to the latter meaning.

Luminance measurement is complicated in some situations because the size of the bundle of light rays that reaches the sensor of the eye, the retina, is controlled by the size of the eye pupil, which varies with luminance. The impact of this on display luminance measurement is discussed in Section 3.2.4.

3.2.1 PHOTOMETRIC CONCEPTS (CONTINUED)

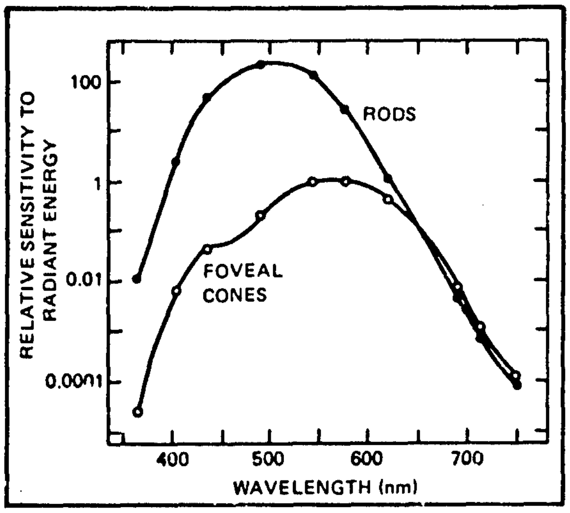


Figure 3.2-1. Spectral Sensitivity of Retinal Receptors. As this figure illustrates, the dark adapted *rods* are much more sensitive to radiant energy than the *cones* over most of the *visual spectrum*, and have their peak sensitivity at a slightly shorter wavelength (Ref. 4). The cones outside the fovea have a very similar spectral sensitivity.

The range of luminance over which the eye functions is normally broken into three regions (Ref. 5):

- *Photopic*—Luminance more than 10 cd/m^2 (3 fL); vision primarily with cones, although the rods may contribute in the periphery.
- *Mesopic*—Luminance of 10^{-3} to 10 cd/m^2 (3 x 10^{-4} to 3 fL); vision with both rods and cones
- *Scotopic*—Luminance less than 10^{-3} cd/m^2 (3 x 10^{-4} fL); vision with rods only

Vision with imagery displays depends almost exclusively on the cones, although at some luminance levels the rods may contribute in the periphery.

The distribution of rods and cones across the retina is treated in Section 3.5.2.

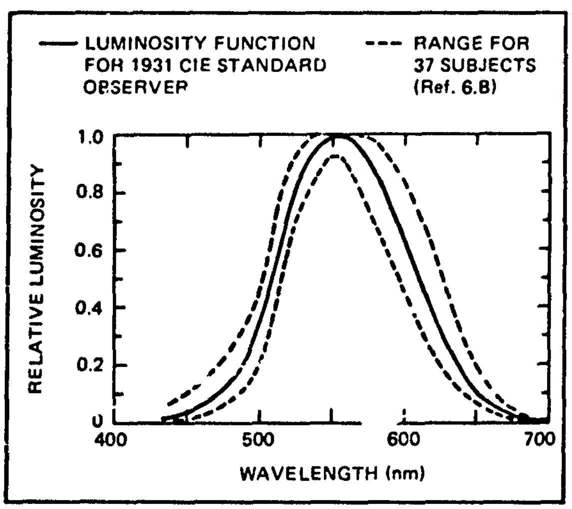


Figure 3.2-2. Relative Contribution of Different Wavelengths to Luminance—the Luminosity Function. The contribution of radiant energy at each wavelength in the visual spectrum to the sensation of brightness is known as *relative luminosity* and is generally defined in terms of a *standard observer.* The most commonly used standard, the 1931 CIE Standard Observer, is described by the solid curve in this figure. It was adopted by the *CIE* in 1931 and is based on data from several subjects with normal color vision and a 2-degree target size (Ref. 7). The 1931 CIE Standard Observer is described more fully in Section 5.2.1.3 and in most books on color (Ref. 8). The values plotted here are generally identified as $\bar{y}_\lambda$ *tristimulus values* for an equal energy spectrum in such sources and in Figure 5.2-7. Since this curve describes the relative contribution of different parts of the spectrum to the sensation of brightness, it also describes the correct relative sensitivity across the spectrum for a sensor used to measure luminance.

The range of relative luminosity values obtained for a different group of 37 similar subjects is shown by the broken curves and provides an indication of the amount of variation that can be expected among individuals.

3.2.1 PHOTOMETRIC CONCEPTS (CONTINUED)

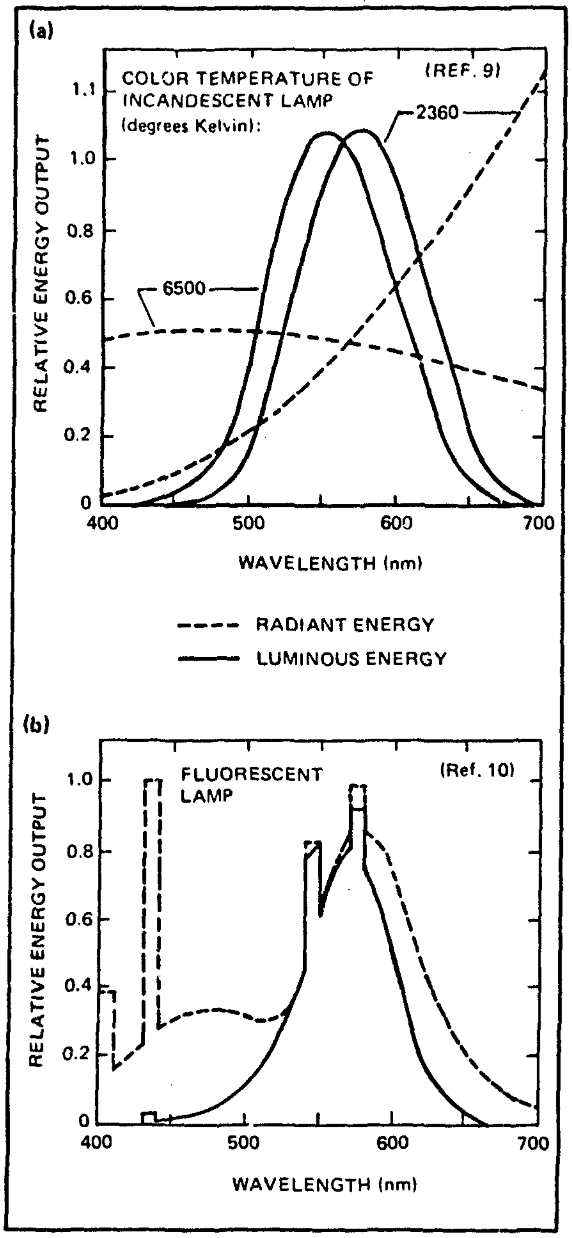
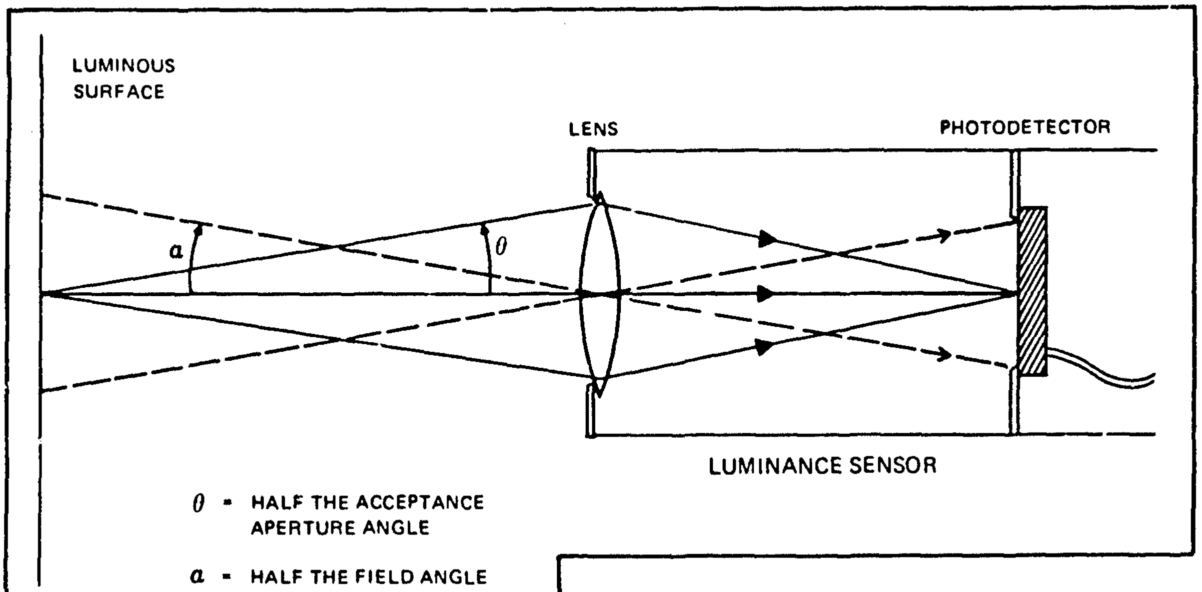


Figure 3.2-3. Relationship of Radiant and Luminous Energy. This figure shows how spectral plots of radiant and luminous energy can give a very different indication of the relative importance of energy in portions of the visual spectrum.

The spectral output of a lamp is usually expressed in terms of relative radiant energy at each wavelength across the visual spectrum. The contribution to image luminance of the energy radiated in different parts of the spectrum is better illustrated by the relative luminous energy output at each wavelength. This is obtained by weighting the radiant energy output by the luminosity curve for the eye illustrated in Figure 3.2-2. Part (a) of this figure shows relative radiant energy and *luminous energy* produced by an incandescent lamp at two *color temperatures*. Part (b) shows similar data for a fluorescent lamp.

The solid curves in these illustrations represent only relative luminosity, not color; adequate representation of color requires weighting of the radiant energy by two additional curves, as is described in Section 5.2.1.3.

3.2.1 PHOTOMETRIC CONCEPTS (CONTINUED)



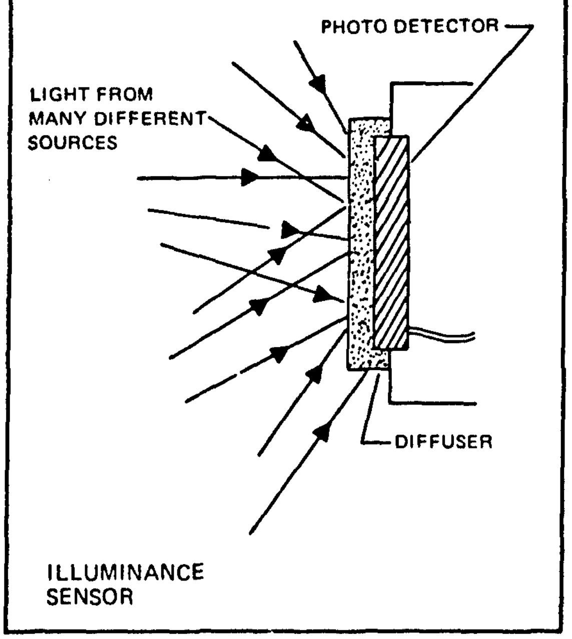


Figure 3.2-4. Luminance Sensor Configuration. Luminance measurements must be made with a sensor such as the one in the upper part of the illustration that accepts light only from a limited area that is traveling in a limited range of directions. This can be contrasted with the *illuminance sensor* illustrated on the left that accepts essentially all the light that reaches a given surface area, regardless of the direction from which it approaches.

A luminance sensor is characterized geometrically by two factors, θ and a, defined as illustrated. So long as the photometer is operated with the luminous surface being measured in focus on the photodetector aperture, these are directly equivalent to the angular field size and entrance aperture of a display device. It is convenient to define the entrance aperture of the photometer in the same units as for a display: numerical aperture (NA) = sin θ (Figure 3.2-18).

There are many common situations, such as when the luminance of a large uniformly luminous surface of very low collimation (Figure 3.2-52) is being measured, in which the focus of the luminance sensor has little noticeable effect on the luminance reading obtained. (Reference 11 treats the problem of focus in luminance sensors.) However, in the display luminance measurement situation described in Figure 3.2-22, correct sensor focusing is critical.

3.2.2 PASSAGE OF LIGHT INTO THE EYE

The eye pupil constricts with increasing scene luminance, reducing both the angular size of the bundle of rays entering the eye and the illuminance on the *retina*. This effect must be considered in display design because in some cases the eye pupil is limiting and in other cases it is the display exit pupil that is limiting. This difficulty also occurs with the data on visual performance at different luminance levels in Section 3.2.6.

Retinal illuminance (E) is expressed in terms of the *troland* (Td). This is defined as the scene luminance (L) in metric units (cd/m^2), multiplied by the pupil area (A) in square millimeters. Expressed as an equation, $E = AL$. As an example, a retinal illuminance of 1 Td would be produced by a pupil area of 1 mm^2 and a scene luminance of 1 cd/m^2, or by a pupil area of 10 mm^2 and a scene luminance of 0.1 cd/m^2.

Knowledge of pupil size is a prerequisite for calculating retinal illuminance. The best available data on the size of summarized in Figures 3.2-5 and -11 below. Charts are also included to convert directly between scene luminance and retinal illuminance. If an artificial pupil is in use, the retinal illuminance is calculated directly from the equation $E = AL$.

There are many variables, in addition to luminance, that affect eye pupil size. Figures 3.2-7 and 3.2-8 show typical data for two of these variables.

Light that enters the marginal portion of the eye pupil is less effective in evoking a sensation of brightness than the light that enters at the center. There is some indication that this phenomenon, known as the *Stiles-Crawford effect*, is related to the directionality of the cones in the retina (Ref. 12). For pupil diameters larger than 2 or 3 mm, the effective retinal illuminance is reduced sufficiently that the loss must be considered in precise work. Figure 3.2-10 shows the appropriate correction when using the equation $E = AL$, and Figures 3.2-11 through -16 include the best available correction when the natural eye pupil, rather than an artificial pupil, is the limiting aperture.

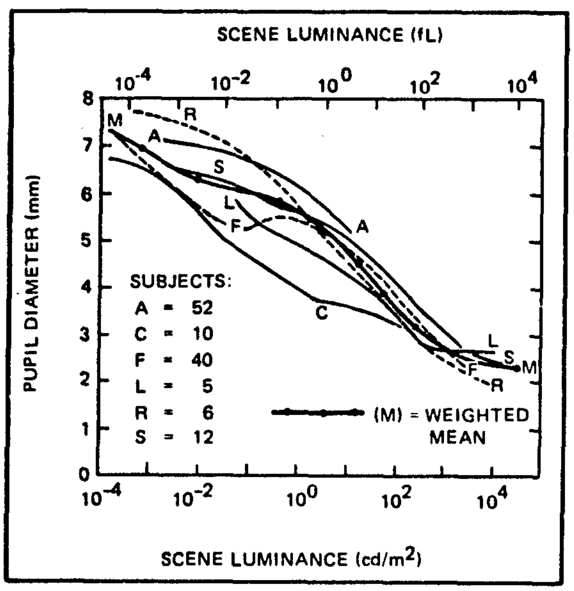


Figure 3.2-5. Change in Pupil Diameter With Scene Luminance. Considerable new data on the variation in eye pupil size with scene luminance have become available since the last summary curve was published in 1955 (Ref. 13). Average values reported by six different experimenters are illustrated here (Ref. 14,X). All six sets of data were collected using an extended visual field and at least five subjects.

The mean curve, M, was fit to these data visually. The averaging was performed at each integral value of scene luminance expressed as log cd/m^2, with each set of test data contributing according to the number of subjects tested. Curve M is shown in large scale in Figure 3.2-11 (Ref. 15).

These data are based on young and middle-aged adults. Older individuals will show less increase in pupil size with a decrease in luminance (Ref. 42).

3.2.2 PASSAGE OF LIGHT INTO THE EYE (CONTINUED)

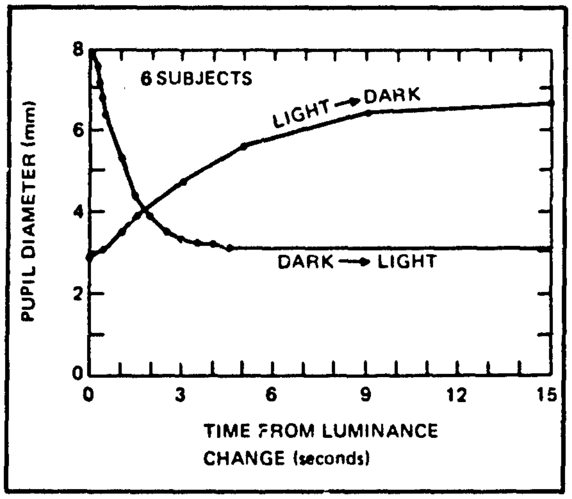


Figure 3.2-6. Rate of Pupil Size Changes. The eye pupil requires several seconds after a change in scene luminance to reach its final size (Ref. 16,B). The change is faster when the light level is increased than when it is decreased.

More recent data suggest that in some situations pupil size does not change as smoothly as is illustrated here. In one study the pupil initially went through a period of alternate dilation and contraction before reaching its final size (Ref. 17,X).

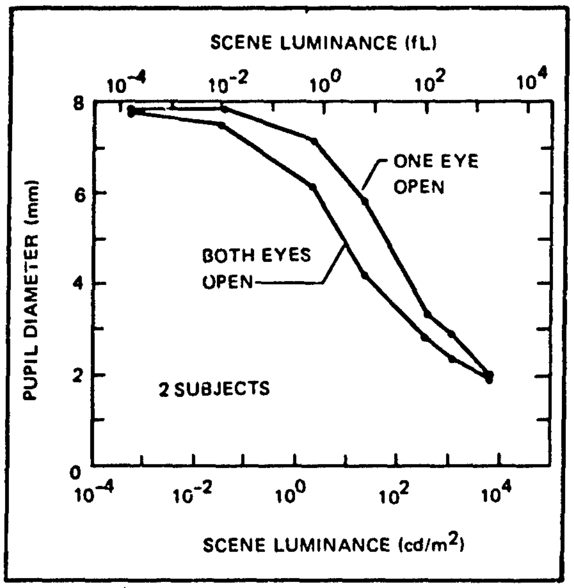


Figure 3.2-7. Monocular Versus Binocular Pupil Diameter. Over a considerable range of scene luminance levels, the eye pupil diameter is less when both eyes are illuminated than when only one is illuminated (Ref. 16,B).

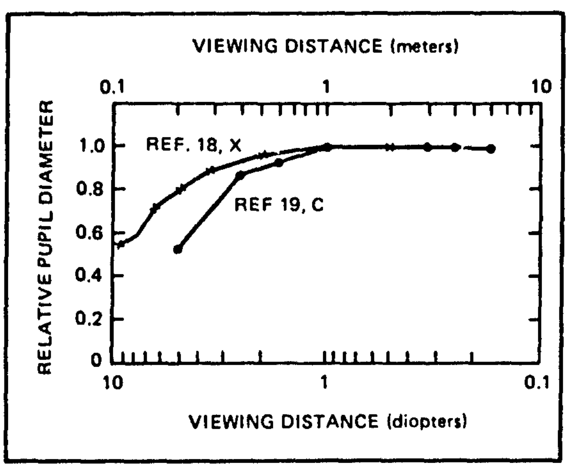


Figure 3.2-8. Effect of Target Distance. The pupil of the eye contracts as the target being viewed moves closer. This is apparently due to the *accommodation* of the eye, although convergence may also be involved.

3.2.2 PASSAGE OF LIGHT INTO THE EYE (CONTINUED)

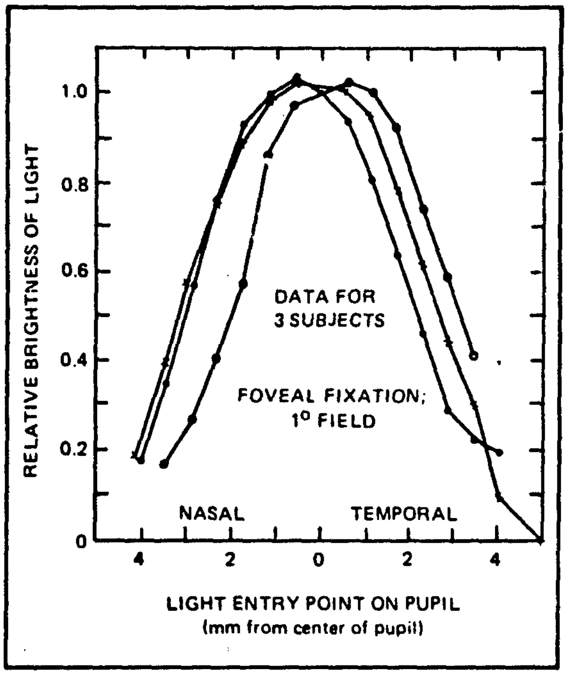


Figure 3.2-9. The Stiles-Crawford Effect. The relative contribution of light entering various parts of the pupil in evoking a sensation of brightness is illustrated (Ref. 20). This is commonly called the Stiles-Crawford effect after its discoverers. Retinal illuminance in the test situation was 45 Td.

This decrease in sensitivity of the eye occurs in the cones and not in the rods (Ref. 21). It is therefore appropriate to correct for it only when cone vision is involved.

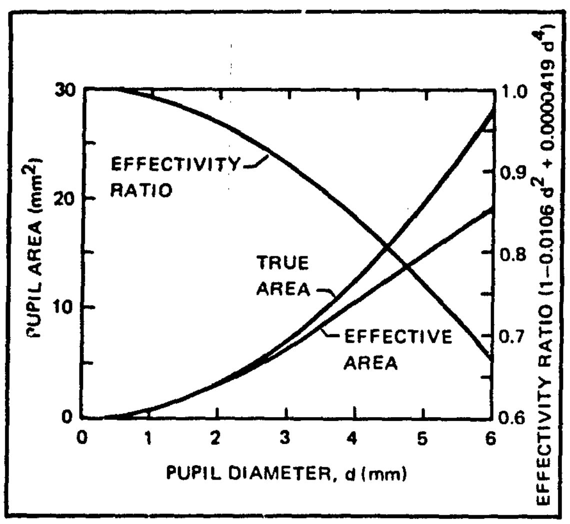


Figure 3.2-10. Correction for Stiles-Crawford. Because of the Stiles-Crawford phenomenon (previous figure), the true pupil area should be replaced by the effective pupil area when calculating retinal illuminance. The best available expression for the ratio between effective and true area, sometimes called the *effectivity ratio*, is (Ref. 22,C):

$$1 - 0.0106\,d^2 + 0.0000419\,d^4,$$

where d is pupil diameter in millimeters.

3.2.2 PASSAGE OF LIGHT INTO THE EYE (CONTINUED)

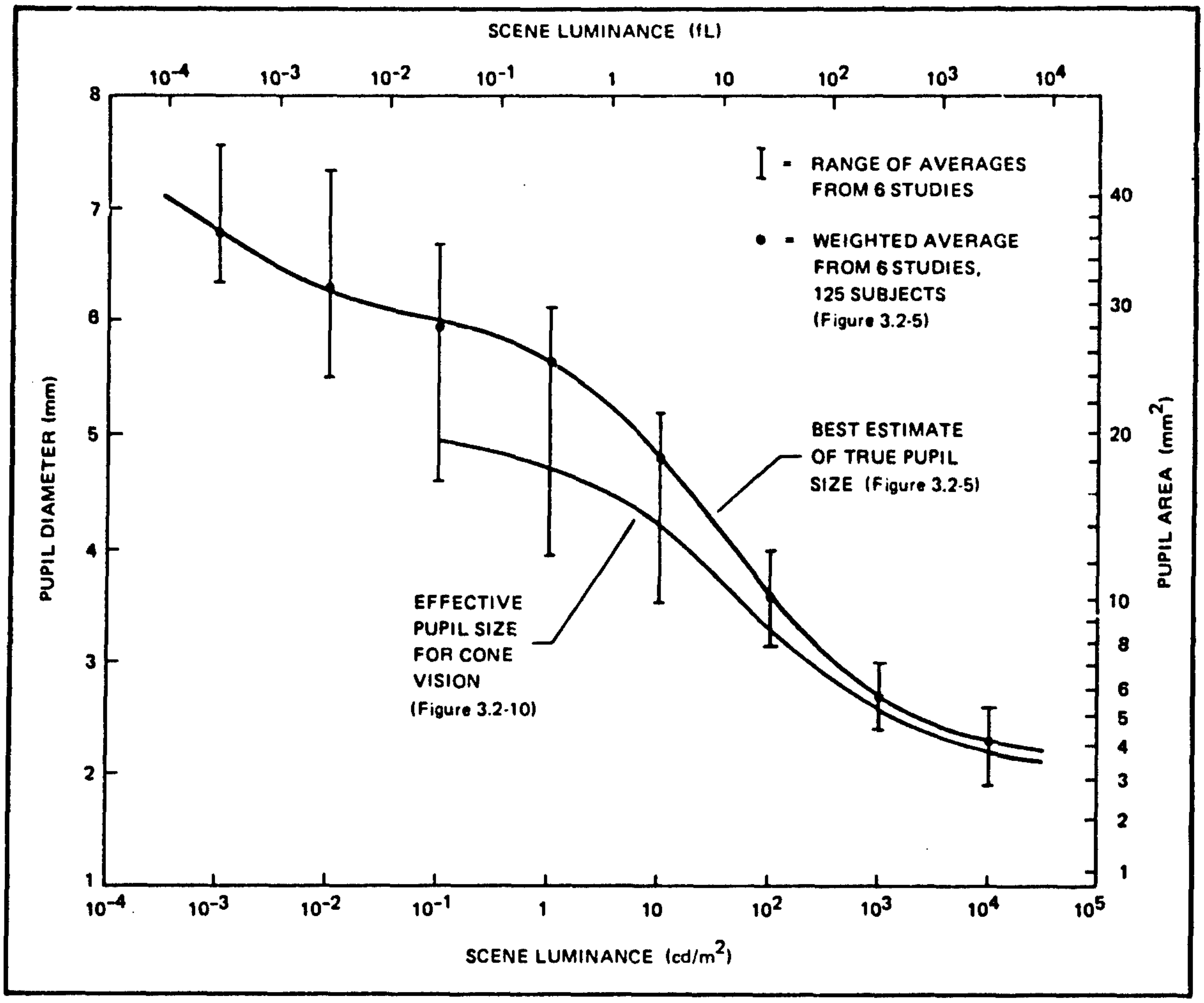


Figure 3.2-11. Eye Pupil Size as a Function of Scene Luminance. The pupil size function of Figure 3.2-5 is illustrated here (Ref. 15). Both true size and effective size corrected for the Stiles-Crawford effect, as described in Figure 3.2-10, are included. Because the Stiles-Crawford phenomenon occurs only in cones, it is not appropriate to apply a correction for it much below approximately 0.1 cd/m² (0.03 fL).

3.2.2 PASSAGE OF LIGHT INTO THE EYE (CONTINUED)

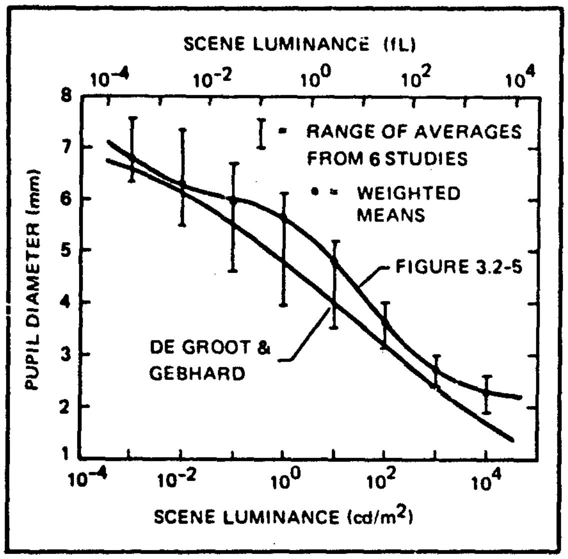


Figure 3.2-12. Comparison of Alternative Pupil Size Functions. The best previously available summary curve describing the relationship between eye pupil size and scene luminance was published by de Groot and Gebhard in 1952 (Ref. 13). It was based on eight studies but only 35 test subjects. It is compared here with the curve from Figure 3.2-5, which is based on a total of 125 test subjects.

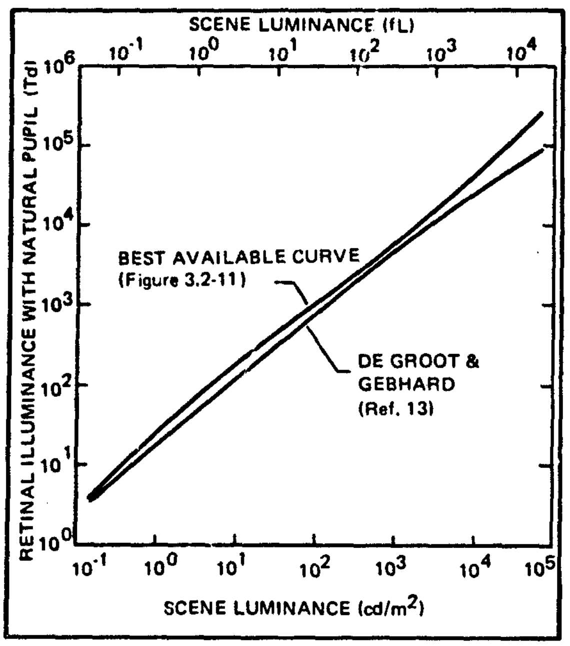


Figure 3.2-13. Impact of Alternative Pupil Size Functions on Retinal Illuminance. The relationship between retinal illuminance and scene luminance using the de Groot and Gebhard pupil size function and the pupil size function from Figure 3.2-11 are compared here. Both curves are based on true rather than effective pupil area.

The upper curve in this figure is the same as the upper curve in Figures 3.2-15 and -16.

3.2.2 PASSAGE OF LIGHT INTO THE EYE (CONTINUED)

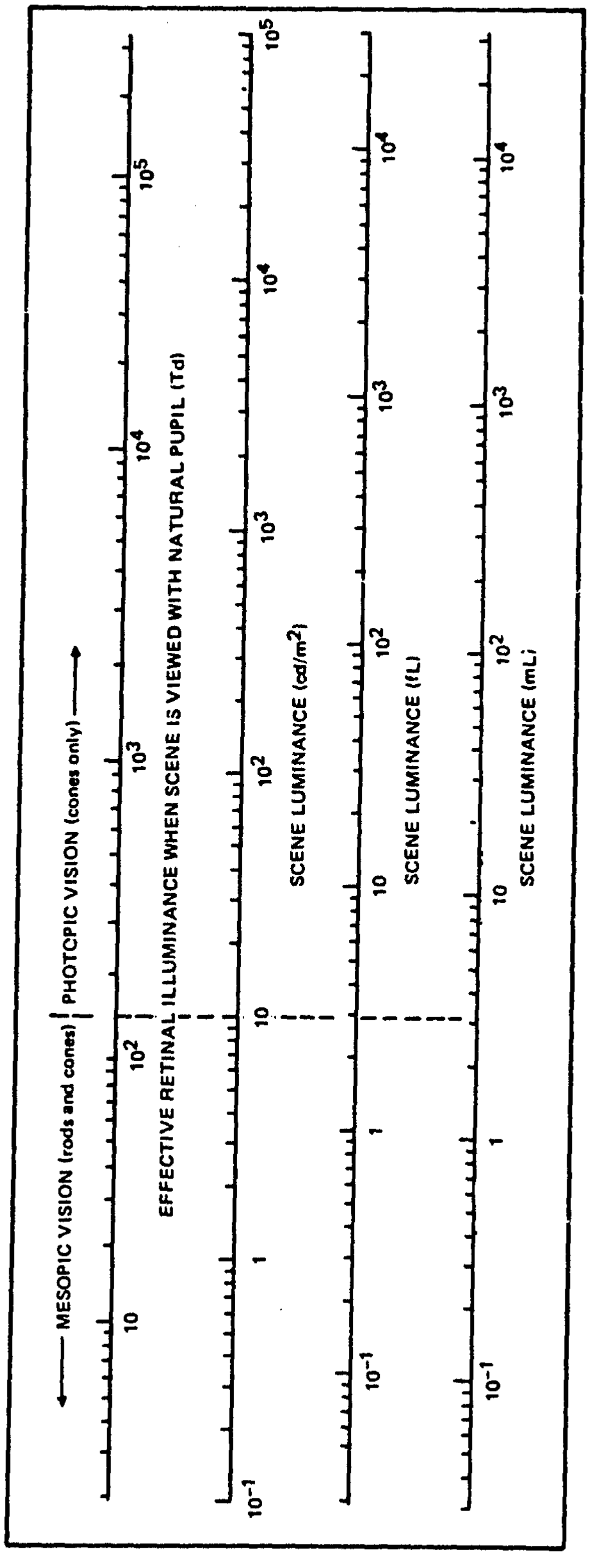


Figure 3.2-14. Conversion of Three Scene Luminance Units to Effective Retinal Illuminance. The relationship among the three luminance units is:

$$1 \text{ cd/m}^2 = 0.292 \text{ fL} = 0.314 \text{ mL}$$
$$1 \text{ fL} = 3.426 \text{ cd/m}^2 = 1.076 \text{ mL}$$
$$1 \text{ mL} = 0.929 \text{ fL} = 3.183 \text{ cd/m}^2$$

Retinal illuminance is scene luminance in cd/m^2, multiplied by eye pupil area in mm^2. Effective pupil area, corrected for the Stiles-Crawford effect, is used here (Figure 3.2-11).

3.2.2 PASSAGE OF LIGHT INTO THE EYE (CONTINUED)

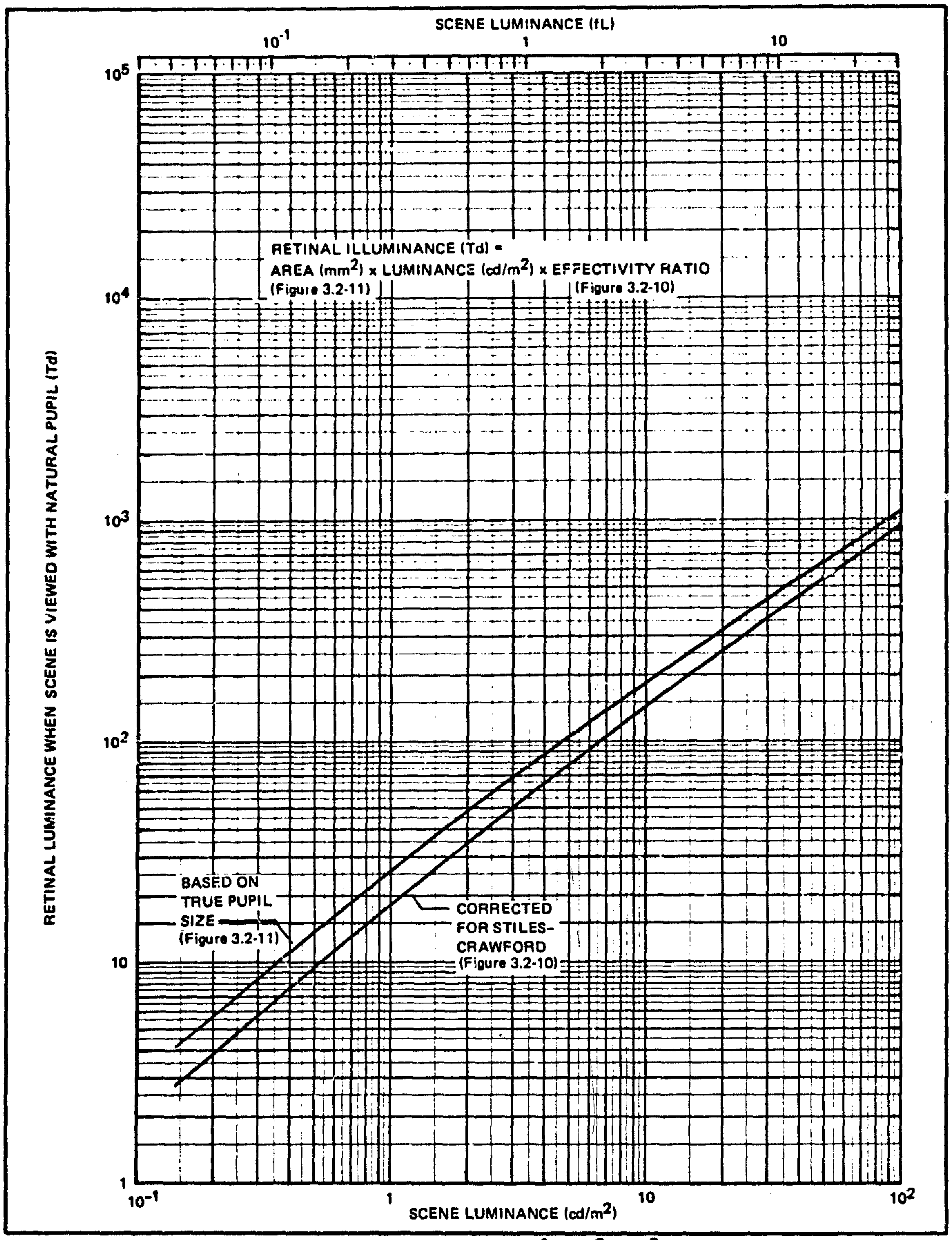


Figure 3.2-15. Conversion of Scene Luminances of 10^{-1} to 10^2 cd/m² to Retinal Illuminance

3.2.2 PASSAGE OF LIGHT INTO THE EYE (CONTINUED)

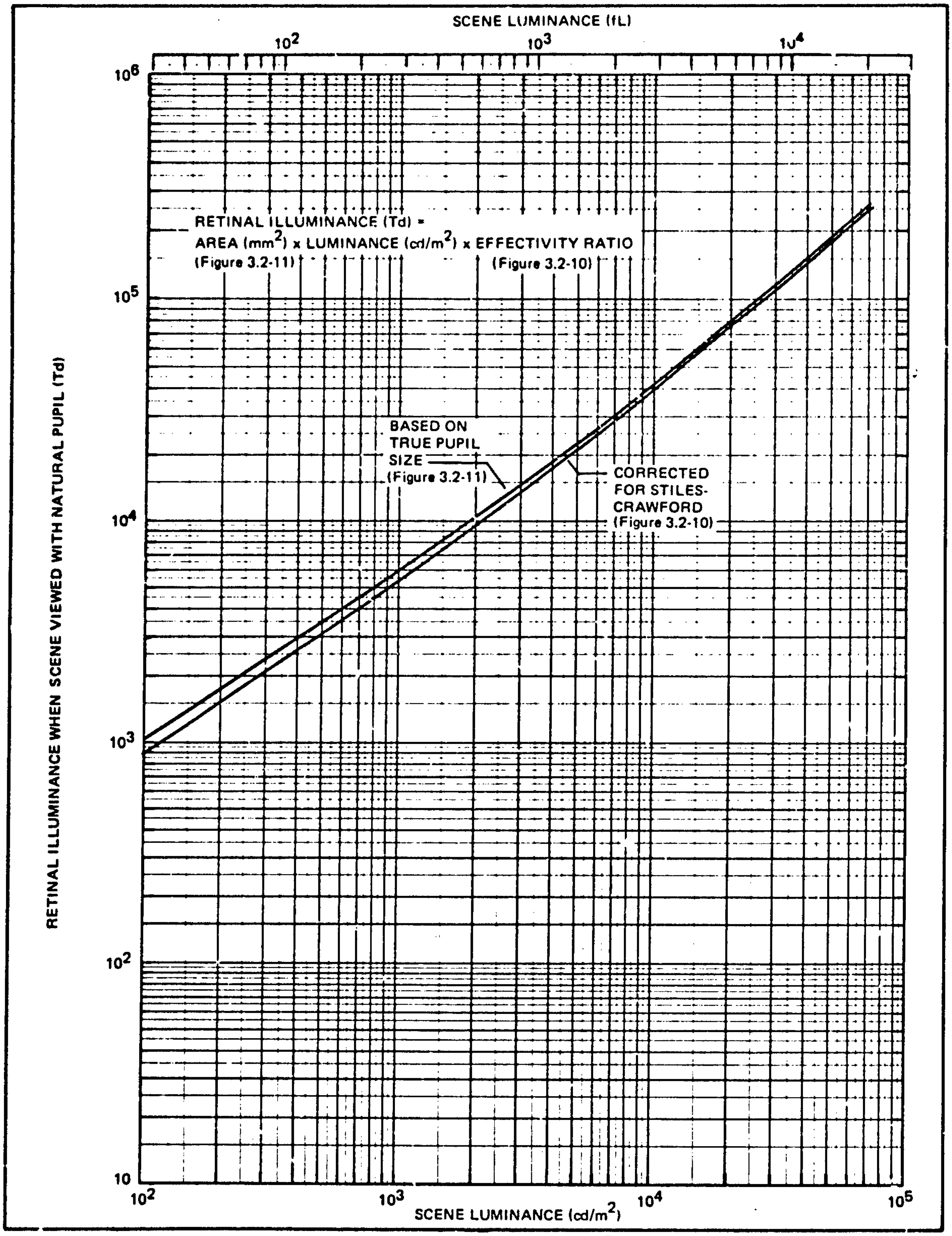


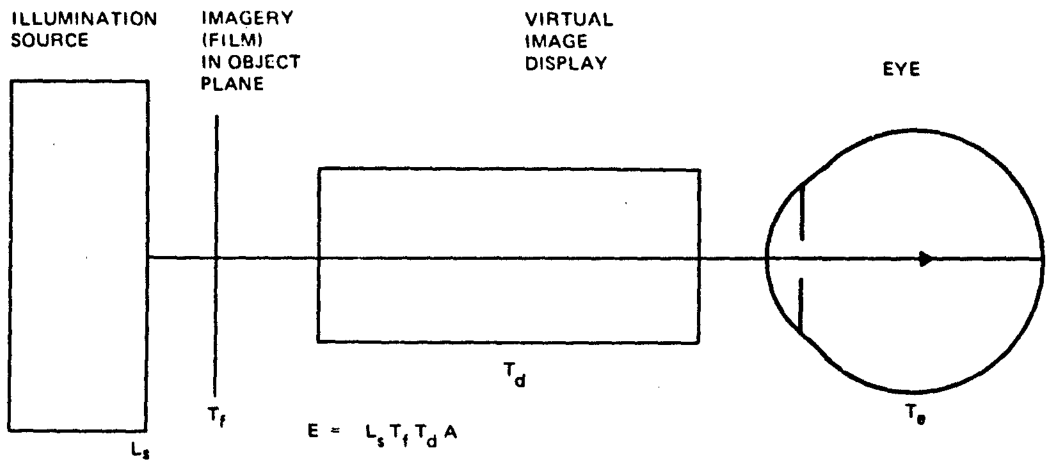
Figure 3.2-16. Conversion of Scene Luminances of 10^2 to 10^5 cd/m^2 to Retinal Illuminance

SECTION 3.2 ILLUMINATION

3.2.3 IMAGE LUMINANCE IN DISPLAYS

This section describes the several factors that determine image luminance in an imagery display. An understanding of these factors is particularly important for an aerial image display such as a microscope if one desires to predict the image luminance that will result when a particular light source and microscope are combined.

The derivation of the equations used in this section is available in several sources and will not be repeated here (Ref. 23).



$E = L_s T_f T_d A$

$L_d = L_s T_f T_d$:

E = RETINAL ILLUMINANCE (Td)

L_d = EQUIVALENT LUMINANCE OF IMAGE IN DISPLAY (cd/m^2)

L_s = LUMINANCE OF SOURCE (cd/m^2)

T_f = TRANSMITTANCE OF IMAGERY (film)

T_d = TRANSMITTANCE OF DISPLAY

T_e = TRANSMITTANCE OF EYE

A = AREA OF LIMITING PUPIL, EITHER THE EXIT PUPIL OF THE DISPLAY OR THE EYE ENTRANCE PUPIL (mm^2) (corrected for Stiles-Crawford if appropriate)

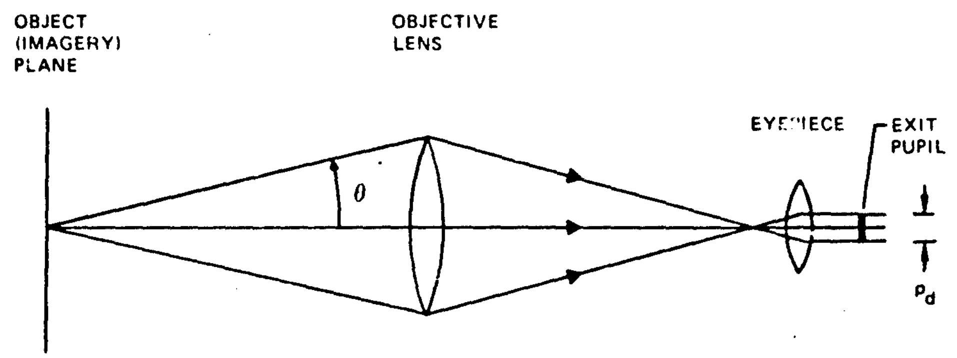
Figure 3.2-17. Elements That Determine Image Luminance. The elements that determine image luminance and retinal illuminance in a virtual image type display are illustrated here. As is explained further in the next two figures, if the eye pupil limits the amount of light entering the eye, it is appropriate to calculate display image luminance, L_d, directly. If, on the other hand, the display pupil is the smaller, it is necessary to determine retinal illuminance, E, and then use the charts at the end of Section 3.2.2 to convert this value to an equivalent luminance as seen with the natural pupil.

The transmittance of the eye, T_e does not appear in these equations because it is already included in the definition of *troland* (Td) as the unit of retinal illuminance.

The illumination source as treated here includes both the lamp and whatever diffusers and condensers are used to distribute the light across the object plane. The source luminance, L_s, is therefore the luminance of the imagery support surface, rather than the luminance of the lamp filament as is used in some treatments of display illumination. A full description of the illumination source also includes *collimation* and *coherence* (Section 3.2.11) and spectral distribution (Section 3.2.7).

Similar factors operate for a projection screen display. However, such displays are almost always designed as a complete unit, making it adequate for most purposes to simply specify the screen luminance when no imagery is present in the film gate (Ref. 24). Specification in terms of location on the screen is important, particularly for high-gain screens.

3.2.3 IMAGE LUMINANCE IN DISPLAYS (CONTINUED)



$$NA = n \sin \theta = \frac{0.5\, p_d M}{250} = \frac{p_d M}{500}$$

$$M = \frac{500\ NA}{p_d}$$

$$p_d = \frac{500\ NA}{M}$$

NA	=	NUMERICAL APERTURE
θ	=	HALF THE ACCEPTANCE APERTURE ANGLE
p_d	=	DISPLAY EXIT PUPIL DIAMETER (mm)
M	=	DISPLAY MAGNIFICATION
n	=	INDEX OF REFRACTION = 1 FOR MOST IMAGERY DISPLAYS

Figure 3.2-18. Numerical Aperture. The angular size of the bundle of light rays that is accepted by the display objective lens is generally expressed as the *numerical aperture* (NA), defined as illustrated here. Numerical aperture, exit pupil size, and display magnification are related by the equations shown (Ref. 23). These relationships have considerable impact in the figures that follow.

Figure 3.2-19. Equations for Determining Display Image Luminance. The equations shown here can be used to calculate the on-axis luminance of the image in an *aerial image* display with a large (Case II) or small (Case III) exit pupil. (Similar viewing situations appear in Figure 3.2-21.)

Case I is included for comparison and applies to unaided viewing, as occurs when film on a light table is viewed directly, without optical aids. It also applies to viewing a *screen image*, in which case the luminance of the screen image is L_o.

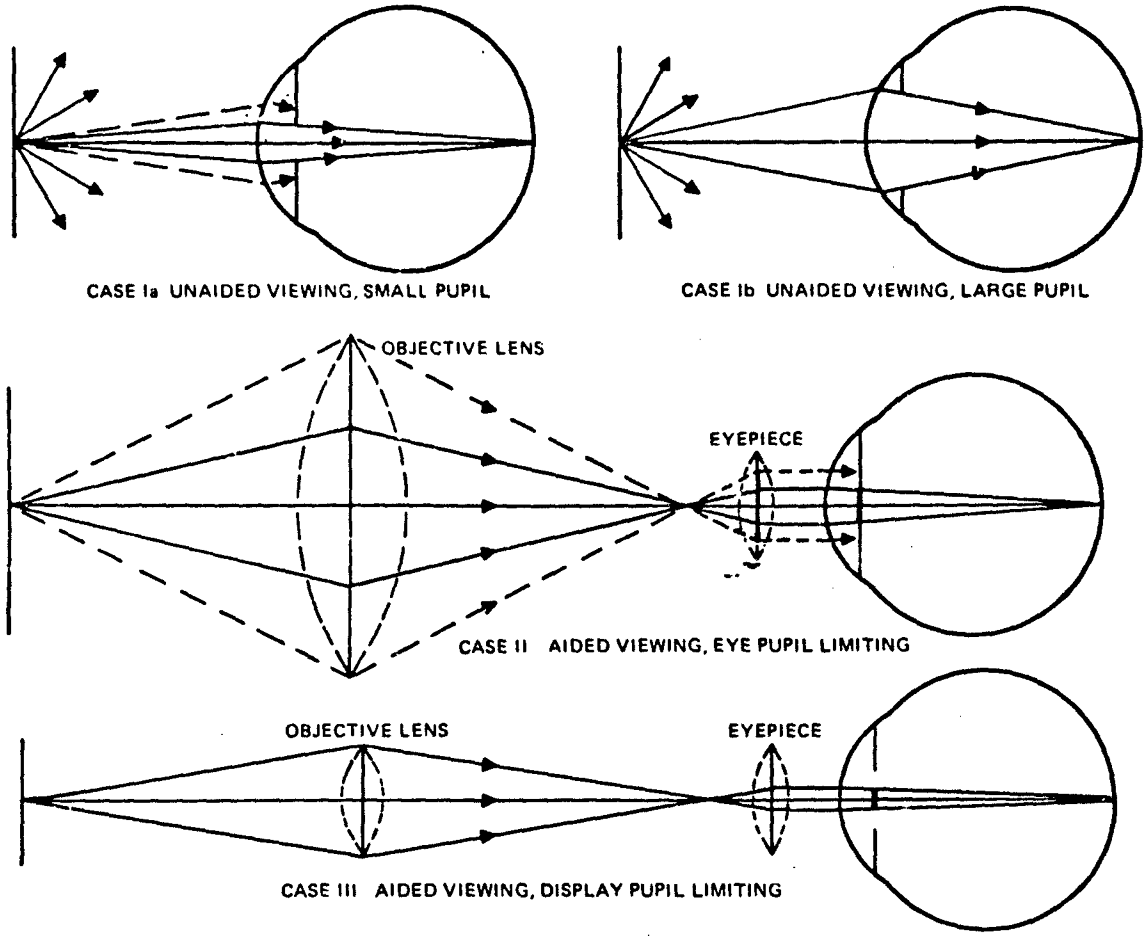
The transmittance of the eye, T_e, must be added to all equations defining retinal illuminance, E, unless E is given in some unit that includes T_e such as trolands (Td).

If the display has an exit pupil larger than the eye, as in Case II, then the eye pupil is limiting and, as a first approximation, the object luminance, L_o, is reduced only by the transmittance of the display, T_d. If T_d is considerably less than unity, there may also be an increase in eye pupil diameter relative to the diameter when viewing the object (imagery) unaided. The result is an increase in the amount of light reaching the retina equal to the ratio of the two pupil areas, p_{ed}^2/p_{eu}^2.

In Case III, the display exit pupil is the limiting aperture, eliminating the effect of variations in eye pupil size on the amount of light reaching the retina. As a result, it is necessary to first determine the amount of light reaching the retina in terms of retinal illuminance, and to then use this quantity to determine the luminance that would produce this same retinal illuminance when the eye pupil is the limiting aperture. This latter conversion can be made most easily with charts such as Figures 3.2-14, -15, or -16.

In Case III, the amount of light reaching the retina is reduced both by the transmittance of the display, T_d, and by decrease in pupil size from p_{eu} to p_d. The display pupil diameter, p_d, can be replaced by the expression 500 NA/M, where NA is numerical aperture and M is magnification (Figure 3.3-2.) As a result, whenever display magnification is increased with no increase in numerical aperture, the image luminance decreases by the square of the magnification.

3.2.3 IMAGE LUMINANCE IN DISPLAYS (CONTINUED)



CASE I: $E_u = \frac{\pi}{4} L_o p_{eu}^2 (K_{sc})$

CASE II: $E_d = \frac{\pi}{4} T_d L_o p_{ed}^2 (K_{sc})$

$\frac{E_d}{E_u} = T_d (p_{ed}/p_{eu})^2$

$L_d = T_d L_o (p_{ed}/p_{eu})^2$

CASE III: $E_d = \frac{\pi}{4} T_d L_o p_d^2 (K_{sc})$

$\frac{E_d}{E_u} = \frac{T_d p_d^2}{p_{eu}^2} = \frac{T_d}{p_{eu}^2} \left(\frac{500\ NA}{M} \right)^2$

L_o MUST BE FOUND FROM FIGURE 3.2-14, -15, OR -16

WHERE:

- E_u = RETINAL ILLUMINANCE UNAIDED (Td)
- E_d = RETINAL ILLUMINANCE WITH DISPLAY (Td)
- T_e = EYE TRANSMITTANCE
- T_d = DISPLAY TRANSMITTANCE
- L_o = OBJECT (imagery) LUMINANCE (cd/m^2)
- L_d = EFFECTIVE DISPLAY IMAGE LUMINANCE (cd/m^2)
- p_{eu} = EYE PUPIL DIAMETER, UNAIDED (mm)
- p_{ed} = EYE PUPIL DIAMETER USING DISPLAY (mm)
- p_d = DISPLAY EXIT PUPIL DIAMETER (mm)
- K_{sc} = CORRECTION FOR STILES-CRAWFORD EFFECT REQUIRED WITH LARGE PUPILS (Figure 3.2-10)
- NA = NUMERICAL APERTURE
- M = DISPLAY MAGNIFICATION

Figure 3.2-19. Equations for Determining Display Image Luminance (text on preceding page)

3.2.4 PHOTOMETRY OF IMAGERY DISPLAYS

A number of special problems occur in the proper measurement of luminance in imagery displays. Techniques for dealing with a few of these are described in this section. A more thorough mathematical treatment of the principles involved can be found in several sources (Ref. 23).

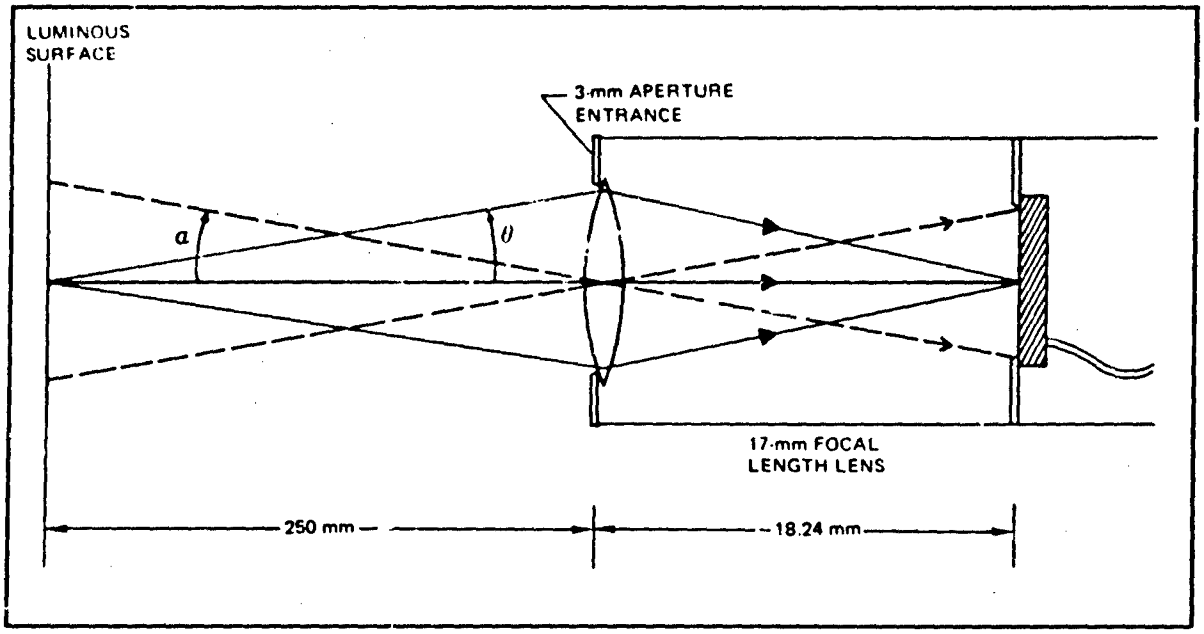


Figure 3.2-20. Artificial Eye Photometer. One of many sensor configurations suitable for measuring display image luminance is illustrated here (Ref. 25). It is convenient, though certainly not essential, that it approximately matches two dimensions of the eye, the eye entrance pupil diameter and the eye focal length. As illustrated here, it is focused for 250 mm (10 in), which means that for the application illustrated in Figure 3.2-22, it would be placed 250 mm from the illumination source. When used to measure image luminance in a microscope-type display, if the uniformly luminous area being measured extends well beyond the field of the sensor, exact matching of sensor focus distance to image distance is generally not critical (Ref. 26). For some applications it may be safest to determine the importance of sensor focus empirically. Exact positioning of the microscope exit pupil within the sensor entrance pupil is essential.

If this type of sensor is calibrated against a standard luminance source, then to determine display image luminance when the exit pupil is smaller than the sensor pupil, it is necessary to correct for the relative areas of the two pupils (Figure 3.2-21).

In theory, one could avoid building such a sensor and simply make a pupil area correction to measurements obtained with the common telescopic luminance sensor supplied with most photometers. Such devices usually have an entrance pupil in excess of 10 mm. Unless this is reduced by the addition of an aperture, the large difference in pupil areas will make the final image luminance value very sensitive to measurement errors. Also, the large variation in sensitivity across the entrance aperture typically found in this kind of sensor will necessitate a correction factor akin to that used to correct for the Stiles-Crawford effect in the eye. That is, as with the eye, light entering through different parts of the entrance pupil of this type of sensor contributes differentially to the meter reading obtained.

3.2.4 PHOTOMETRY OF IMAGERY DISPLAYS (CONTINUED)

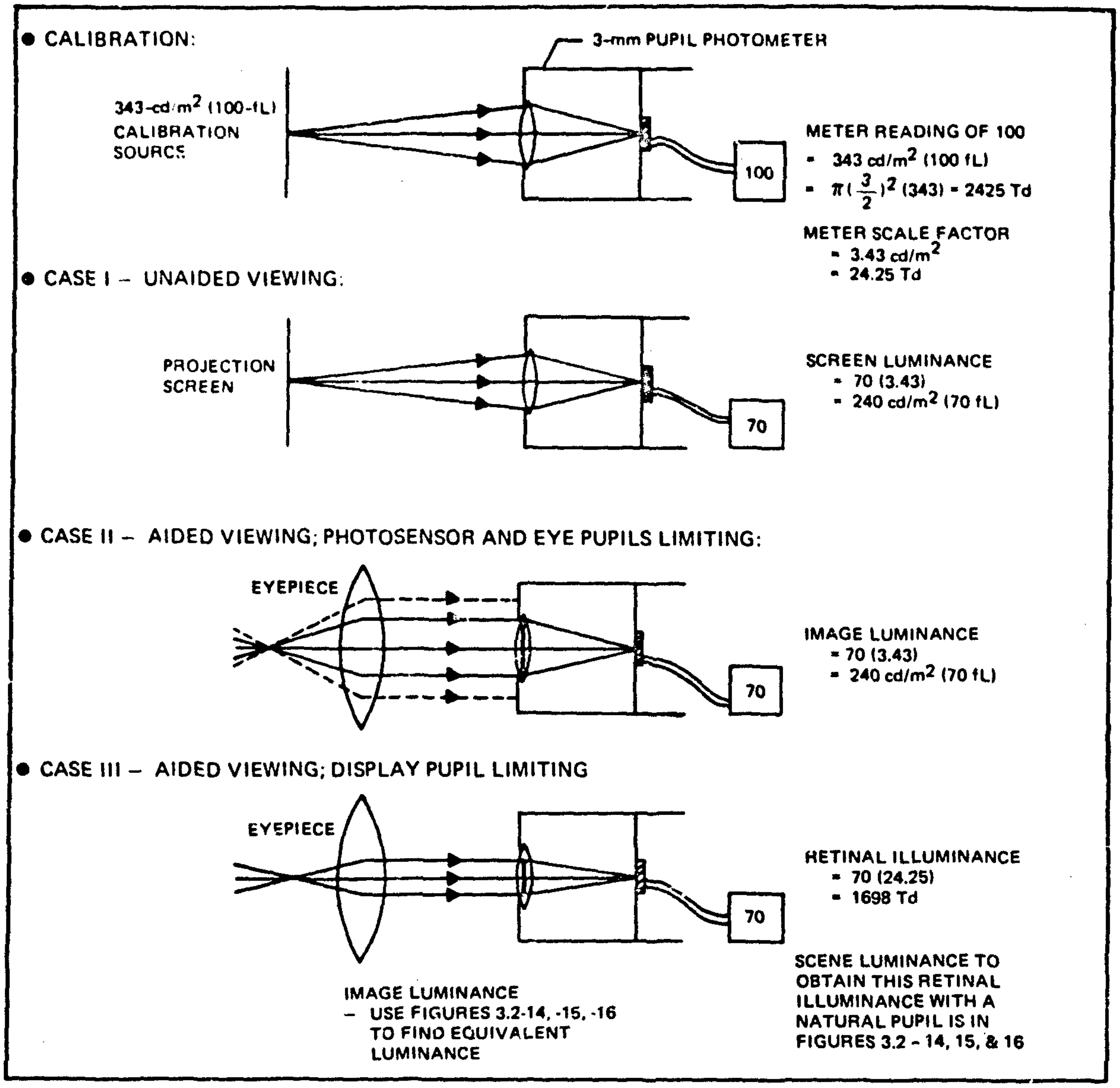


Figure 3.2-21. Display Image Luminance Measurement. Proper use of a photosensor such as the one in Figure 3.2-20 is best explained in terms of specific examples such as those illustrated here. Assume that the photometer is calibrated to obtain a meter reading of 100 with a typical standard luminance source of 343 cd/m² (100 fL). A meter reading of 1 then corresponds to a luminance of 3.43 cd/m² (1 fL) and a retinal illuminance of 24.25 Td.

Luminance measurements for a source such as a projection screen (Case I) can then be made as with any photometric telescope. For a virtual image display such as a microscope that has an exit pupil larger than 3 mm and larger than the natural eye pupil at the display image luminance in use (Case II), the image luminance is again simply read directly from the meter.

When the display exit pupil is smaller than the pupil of both the sensor and the user's eye (Case III), the meter reading must be converted to retinal illuminance in trolands (Td). To determine the image luminance, which is defined as the luminance of a surface viewed with a natural pupil that would yield the same retinal illuminance, conversion charts such as those in Figures 3.2-14, 15, and 16 must be used.

Noticeably absent here is a discussion of the case where one of the two pupils, either the eye or the photosensor, is larger than the display pupil while the other is smaller. Although the treatment of the data in this case follows the same principles as above, it is perhaps simpler to change the size of the photosensor pupil and recalibrate.

3.2.4 PHOTOMETRY OF IMAGERY DISPLAYS (CONTINUED)

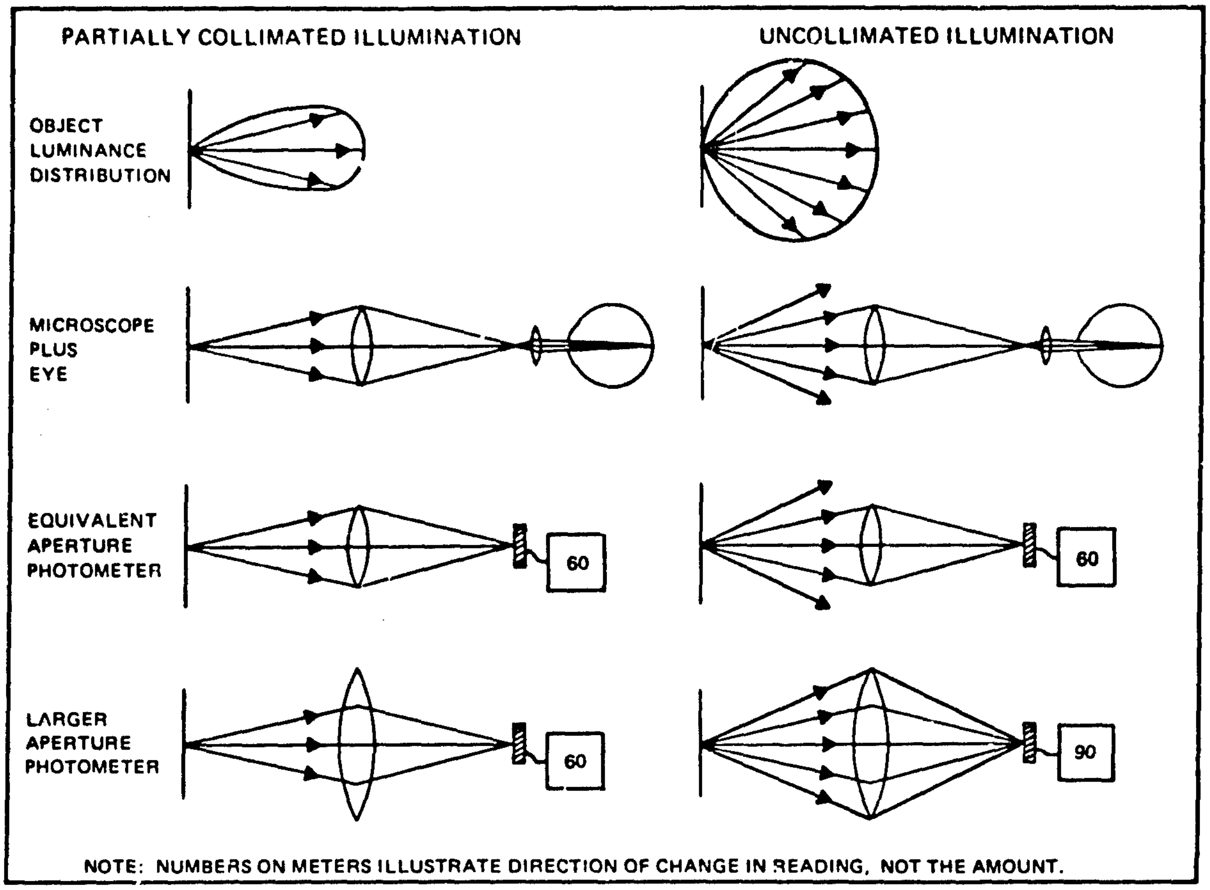


Figure 3.2-22. Potential Errors in the Photometry of a Luminous Surface. Knowledge of source luminance is necessary to determine display transmission and to be able to predict the image luminance that will result when a particular display is used with the source. These are primarily problems with microscope-type displays, where the illumination source is often interchangeable, rather than with projection displays that usually are built with the illumination source integral to the display.

One of the least recognized sources of error in measuring source luminance is failure to match the numerical aperture of the photosensor, defined as in Figure 3.2-18, to the numerical aperture of the display that will be used with the source. As a result, the angular size of the bundle of rays that contributes to the measurement is not the same as that which contributes to the luminance of the image.

As this figure illustrates, several factors determine whether a significant error will occur, particularly the collimation of the illumination source (see Section 3.2.11).

All the factors that should be controlled in any particular measurement situation cannot be covered here. However, so long as the collimation of the source, specified in terms of numerical aperture, is not significantly less than the numerical aperture of the display, then it is generally sufficient to simply use a photosensor with a numerical aperture smaller than that of the display.

It should be noted that the effective numerical aperture of a photosensor in this application varies with its distance from the source. This is controlled by specifying that it must be in focus for the source distance.

3.2.5 IMAGERY TRANSMISSION

RECOMMENDATIONS:

In the absence of more adequate data, base display image luminance calculations for achromatic imagery on a density value of 1.6.

As Figure 3.2-17 illustrates, the luminance of the displayed image is reduced by the absorption of light in the film being viewed. The proportion of the incident light that passes through the film is known as *transmittance*, T, and is usually expressed as log 1/T, or *density*. The relationship between the two units is illustrated in the next figure. Film densities are routinely measured, and limiting values for most kinds of film are published. However, these values provide little guidance for the display designer.

Imagery density values used to calculate display image luminance should meet several criteria:

- They should describe target areas as they appear on imagery processed exactly as it will go to the interpreter.
- They should be measured over a meaningful area on the imagery.
- They should include a reasonable proportion of such areas on the imagery.

It is not appropriate to simply measure the average density over an entire frame because at any one moment the display user will be looking at a small area that may have a density much different than the average. It is also possible to sample too small an area so that one is essentially measuring the density of individual objects. Other things being equal, sampling over a smaller area will yield a wider range of density values. Therefore, if in order to provide enough light for worst case situations, a value at the upper extreme of the measured densities is used, a smaller aperture will yield a higher density and a demand to provide more light.

One approach is to use the average density over the image area that yields best vision. Referring to Section 3.5, this is estimated rather arbitrarily as 2 degrees. For a display magnification range of 10 to 100 X, the corresponding distance on the imagery, and hence the most appropriate densitometer sampling aperture is about 0.1 to 1.0 mm (Figure 3.5-3).

The best available imagery density data for black and white imagery is illustrated in Figure 3.2-24.

The problem of density is considerably more complex with color than with black and white imagery. At least seven different types of densities for color transparencies are in use (Ref. 27). To be useful for specifying illumination requirements. the type of measurement used must reflect the spectral sensitivity of the eye, as opposed, for example, to the spectral sensitivity of duplicating film. A special weighting factor to take account of the spectral transmission of the illumination source may also be desirable. Although data on maximum density range is available for most color films, no data of the type shown in Figures 3.2-23 and -24 are known.

3.2.5 IMAGERY TRANSMISSION (CONTINUED)

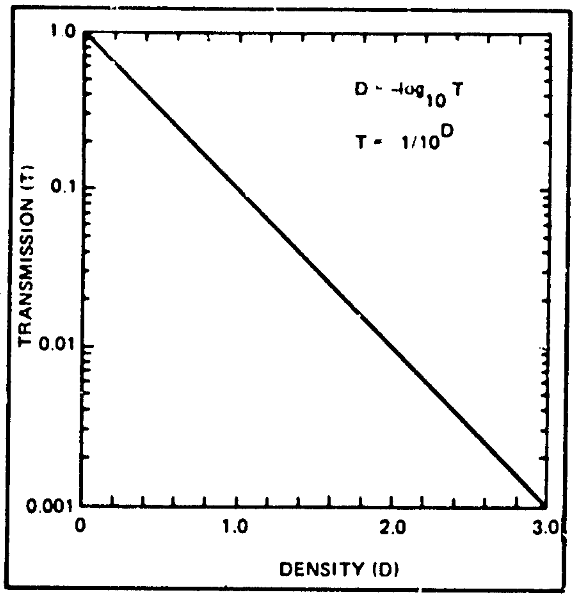


Figure 3.2-23. Transmission and Density. The expression for display image luminance in Figure 3.2-19 includes a term for the transmission of the imagery. Imagery is usually described in terms of density, which is related to transmission in the manner illustrated here.

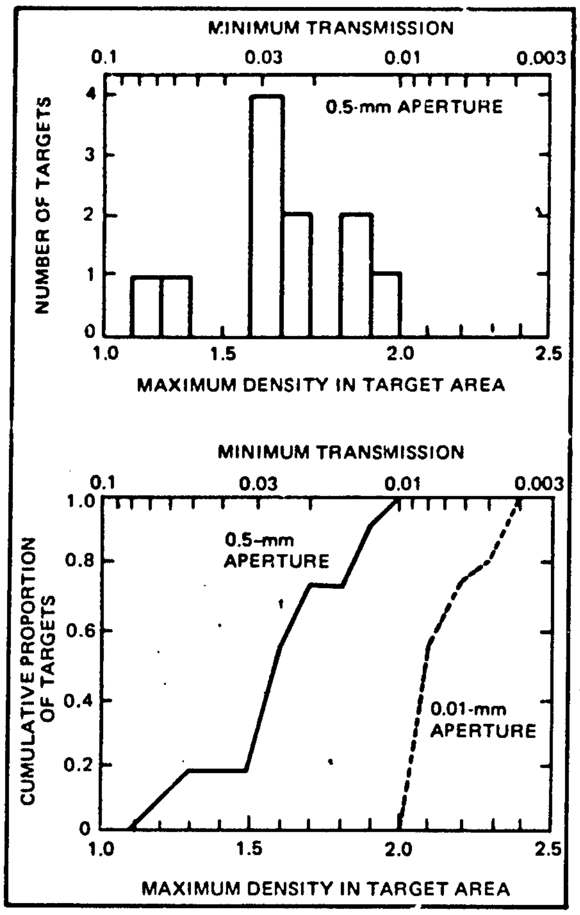


Figure 3.2-24. Imagery Density Distribution. The only known imagery density data collected with an aperture size useful for estimating display image luminance are illustrated here (Ref. 28,D).

These measurements were made within the immediate target area of 11 randomly selected operationally realistic targets imaged on high-quality 3414 aerial film. Normal exposure and processing were used.

For the 0.5-mm aperture, each target area was scanned manually and the maximum density obtainable was recorded. These values for the 11 targets are plotted in the upper graph as a histogram. For the 0.01-mm aperture, each target area was scanned automatically on a microdensitometer and the density at each of several thousand points was recorded. The points for a single target were plotted as a histogram and the point where a smooth visually fit curve would reach zero frequency was taken as the maximum density for that target. This procedure usually eliminated several extremely high-density values. Finally, these values were converted to macrodensities to correct for optical effects at the small aperture.

The upper graph shows the number of targets that had each maximum density when measured with the 0.5-mm aperture. These data and the equivalent data for the 0.01-mm aperture are plotted below in terms of cumulative proportions. As expected, the 0.01-mm aperture densities are much higher.

To the extent that the 0.5-mm aperture data are realistic, a value of 1.8 to 2.0 in the image luminance equations in Figure 3.2-19 will ensure adequate image luminance. Since the values plotted here represent maximum density for each target area, even designing for a density of 1.6 should ensure an adequate image luminance.

3.2.6 LUMINANCE AND VISUAL PERFORMANCE

RECOMMENDATIONS:

Provide the capability of increasing display image luminance (see Section 3.2.3) to the following levels:

- **For casual examination to locate general features, 35 cd/m^2 (10 fL, 400 Td).**
- **For performing normal interpretation functions, at least 85 cd/m^2 (25 fL, 800 Td) and preferably 340 cd/m^2 (100 fL, 2,300 Td).**
- **In displays for extensive, detailed examination of imagery, 1,750 cd/m^2 (500 fL, 3,500 Td).**

If the display is intended for achromatic film, assume a film density of 1.6 (Section 3.2.5).

Before incorporating the higher values specified above in hardware, conduct tests to ensure that such levels are actually usable in imagery display configurations. (See Section 3.2.6.2.)

Provide a luminance adjustment with a range of at least 100 to 1, with control setting equal approximately to the log of the luminance.

If a less than optimum luminance level must be provided, consider the need to increase luminance 50 to 100 percent for older users. (See Section 3.2.6.3.)

It is well established that, at least for a certain range, visual performance improves with an increase in image luminance. Section 3.2.6.1 summarizes data collected in laboratory situations on this relationship between vision and luminance level, and Section 3.2.6.2 treats the much less adequately studied situation of vision in ordinary imagery displays. The special problem of luminance requirements for older display users is covered in Section 3.2.6.3.

Because of the wide ranges involved, it is convenient to plot both visual performance and image luminance on logarithmic scales. The relatively small displacement on such a scale caused by a large increase in luminance tends to obscure the difficulty in achieving such an increase.

A method must be provided by which the display user can adjust the luminance level to compensate for variations in imagery transmission, the luminance in other portions of the work environment, and his personal preferences. In the absence of adequate quantitative data on any of these three variables, an adjustment range of 100 to 1 is suggested.

When even very small improvements in visual performance are important, as they often are in image interpretation, it is desirable to know the slope of the function relating visual performance to luminance as performance approaches its maximum. Unless one has an extremely large data sample, such as the hundreds of observations for each point plotted in Figure 3.2-30, random variation in performance makes it difficult to establish the slope of the curve in this region. Curves drawn using best-fit statistical procedures are a potentially misleading solution available to anyone with access to a computer. They obscure the very important fact that the slope of the resulting curve is heavily dependent on whether the mathematical function selected is logarithmic, hyperbolic, a polynomial, a power function, or some other choice. Admittedly there are also statistical techniques available for choosing among these possibilities, but if there is sufficient data available to make their use meaningful, the average performance probably follows a smooth path anyhow. Wherever possible in this document, the original average performance scores reported by the experimenter are shown, connected with straight lines.

It is possible that if a very high image luminance is provided, along with an allowance for very high-density imagery, there may be conditions under which sufficient light could reach the user's eye to cause damage. This topic is treated in Section 6.7.

Once a certain luminance has been achieved, the spatial distribution may become more important than the level of the luminance. See Sections 3.2.11, 3.2.12 and 7.3.3.

3.2.6.1 LABORATORY DATA

The laboratory test data relating visual performance to luminance level that are summarized in this section support several conclusions:

- Over a limited range of both variables, visual performance improves with an increase in image luminance.
- Each successive increase in visual performance requires a successively larger increase in luminance. As a result, providing enough light to achieve absolute maximum visual performance may not be economically feasible.
- The luminance level at which visual performance effectively reaches a maximum varies with the task. More difficult tasks benefit more from higher luminance. Difficulty generally increases with a reduction in target size, target contrast or time available to perform the task.

Because of their importance, three figures from Section 3.1.6 are reproduced here as Figures 3.2-31, -32 and -33. A fourth figure in that section, 3.1-22, is also relevant.

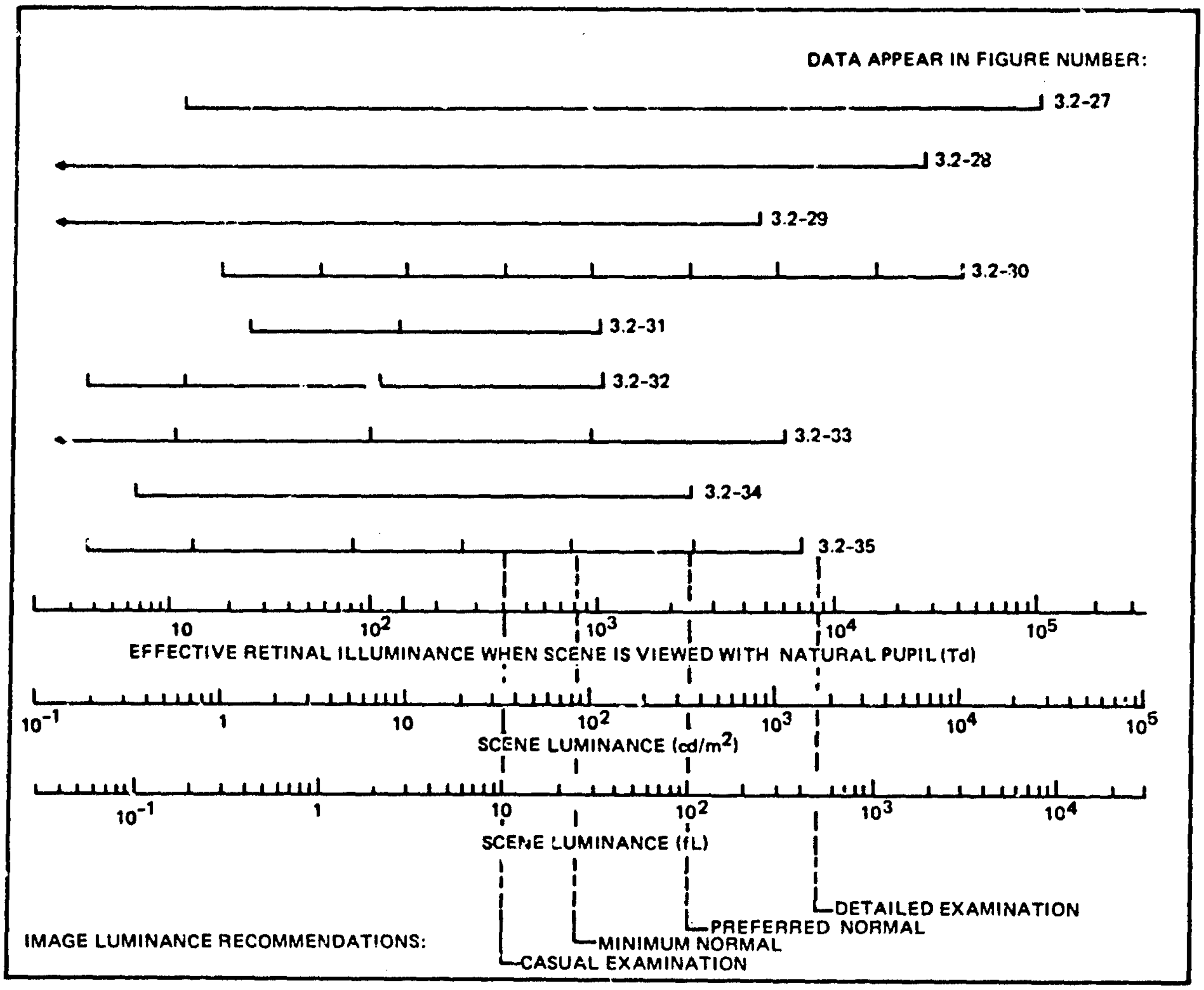


Figure 3.2-25. Laboratory Studies on the Effect of Image Luminance. To simplify making comparisons, the luminance levels used in the studies summarized in this section are illustrated here. Where a large number of different levels were used, only the range is shown. The four luminance levels cited in the recommendations above are indicated by broken lines.

3.2.6.1 LABORATORY DATA (CONTINUED)

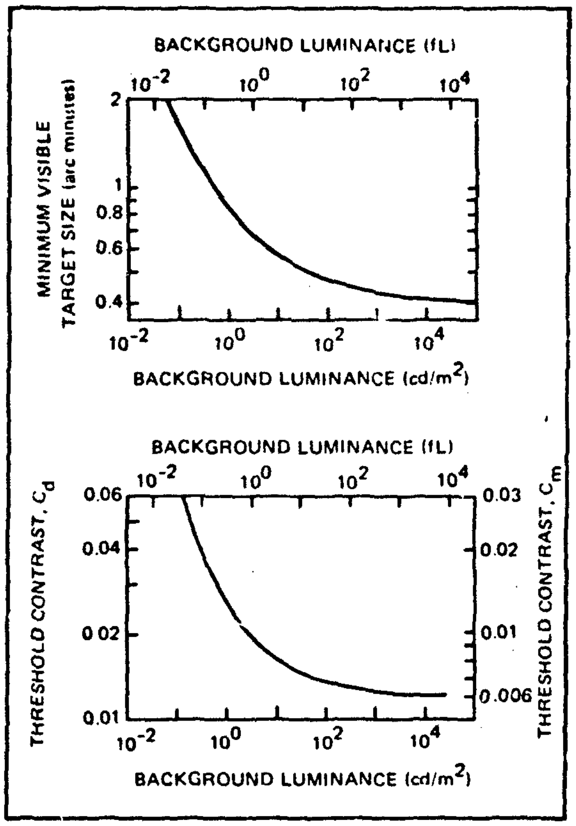


Figure 3.2-26. Luminance and Visual Performance. Curves fit to the results from several studies on the relationship between visual performance and illumination level published prior to 1944 are illustrated here (Ref. 29,X). The upper curve shows the minimum size high-contrast target that can be resolved. The lower curve shows the minimum *contrast* at which a relatively large target can be detected.

These curves are included here primarily to illustrate the fact that as the maximum visual performance level is approached, larger and larger increases in luminance are required to obtain additional improvement in performance. Because of the wide variability in the original data on which these curves were based, they are useful only as an indication of the general relationship between luminance and visual performance.

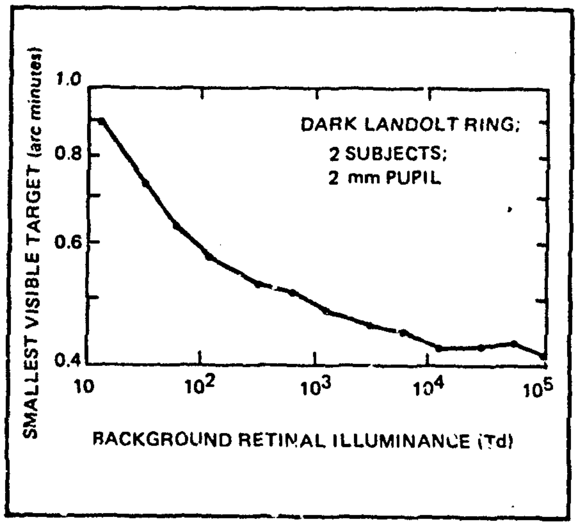


Figure 3.2-27. Effect of Luminance on Ability To Resolve a Landolt Ring. In this study, ability to report the orientation of the break in a dark *Landolt ring* continued to improve as retinal illuminance increased up to approximately 10,000 Td (Ref. 30,C). This corresponds to a scene luminance of about 2,000 cd/m^2 (600 fL) viewed with a natural pupil. The display field in this study subtended 30 degrees, and the 2-mm pupil was projected into the subject's eye.

3.2.6.1 LABORATORY DATA (CONTINUED)

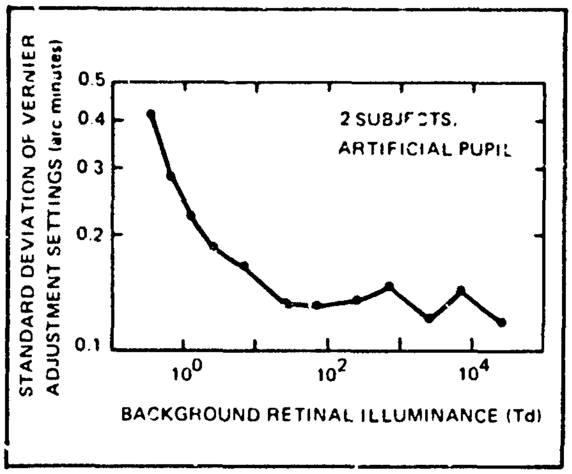


Figure 3.2-28. Effect of Luminance on Vernier Acuity. In this study two subjects aligned two narrow bars in a *vernier acuity* task (Ref. 31,B). The two bars combined were 4.5 degrees long and were seen against a 12-degree field. The artificial pupil was projected into the subject's eye. Performance showed little improvement as retinal illuminance increased beyond about 20 Td. This corresponds to a scene luminance of 1.3 cd/m^2 (0.4 fL) viewed with a natural pupil.

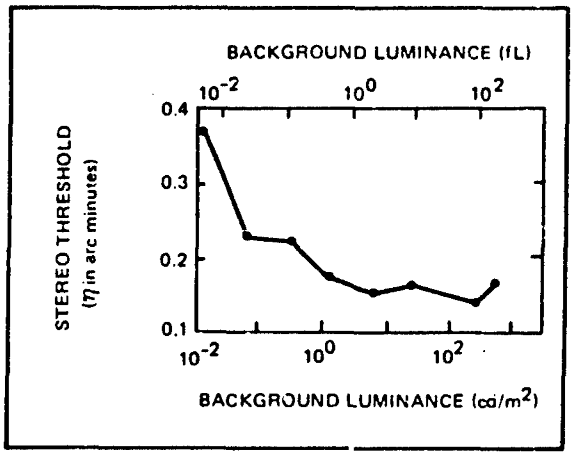


Figure 3.2-29. Effect of Luminance on Stereo Acuity. This curve shows performance of two subjects on a three-rod *stereo acuity* test (Ref. 32,C). Viewing was with natural pupils. Performance showed little improvement as luminance increased beyond approximately 7 cd/m^2 (2 fL).

3.2.6.1 LABORATORY DATA (CONTINUED)

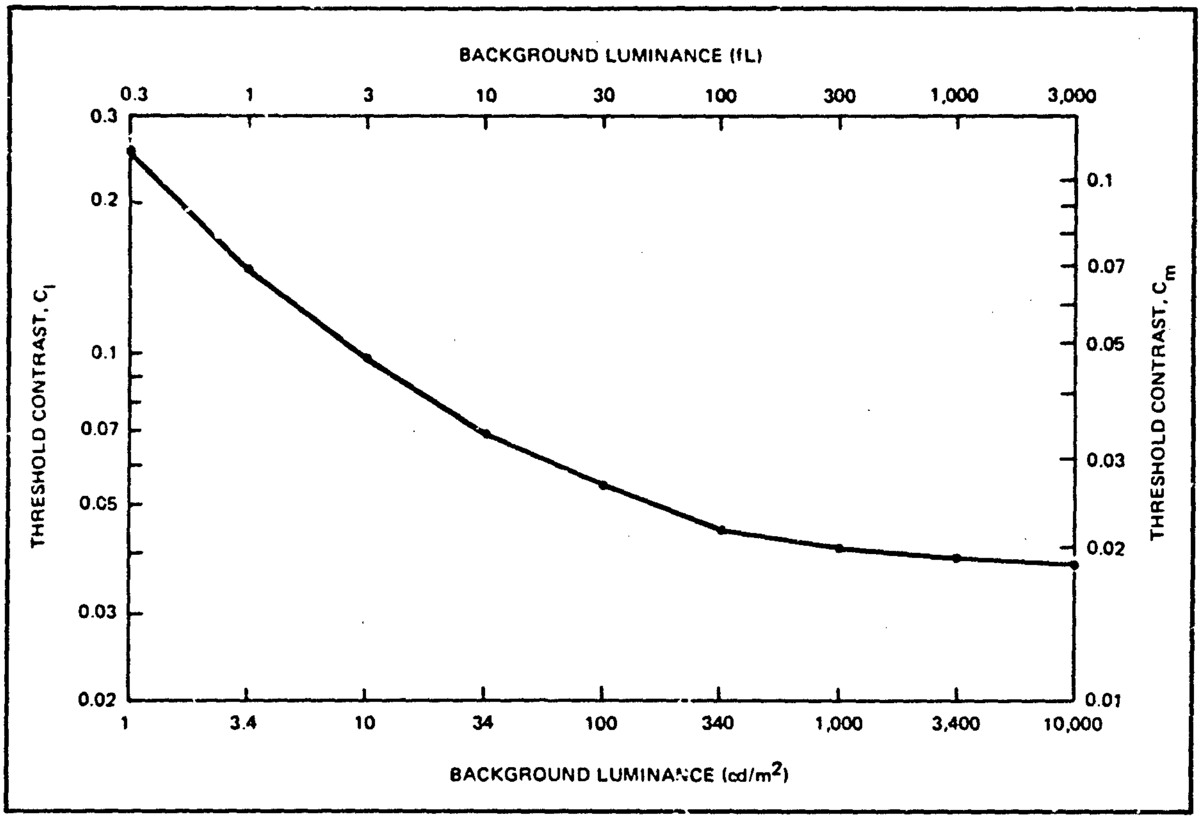


Figure 3.2-30. Effect of Luminance on Threshold Contrast. The most extensive data relating visual performance to luminance are those collected by Blackwell and his fellow workers (Ref. 33,B). In most of these studies, the highly experienced test subjects attempt to detect a light circular target that can appear during one of several time intervals. Viewing is binocular without optical aids. The background and equiluminous surround exceeds 120 degrees, thereby nearly filling the subject's visual field.

This curve shows threshold contrast, defined as detection success 50 percent better than chance, for 10 subjects. The target disc subtended 4 arc minutes and appeared for 1/5 second during one of four intervals. Changing the success criterion, for example to 90 percent detection, raises the threshold curve but does not change its shape. (See Figure 3.1-17.)

There was an improvement in vision for each increase in luminance, even when the background luminance went from 3.400 to 10.000 cd/m^2 (1,000 to 3,000 fL). However, this last threefold increase in luminance reduced the contrast threshold only 5 percent, from 0.038 to 0.036. It is not possible at present to estimate whether this improvement might have a significant impact on the work output of the display user.

Because of the large number of subjects and test trials, and the fairly reasonable test conditions, the curve shown here is one of the best available estimates of the relationship between background luminance and threshold contrast. However, it is well to keep in mind that contrast thresholds will vary by a factor of at least 2.5 across individuals (Figure 3.1-17), and as a function of many other variables, some of which are summarized in Section 3.1.10. Referring to the curve shown here, a contrast threshold change of 2.5 corresponds to a luminance change of several orders of magnitude.

Throughout this document, the average value for a set of test measurements is shown as a dark disc on a graph. This is probably what the discs in this figure represent, but the available literature leaves open the possibility that these are really just discrete points measured on curves fit to the original, unreported, test data.

3.2.6.1 LABORATORY DATA (CONTINUED)

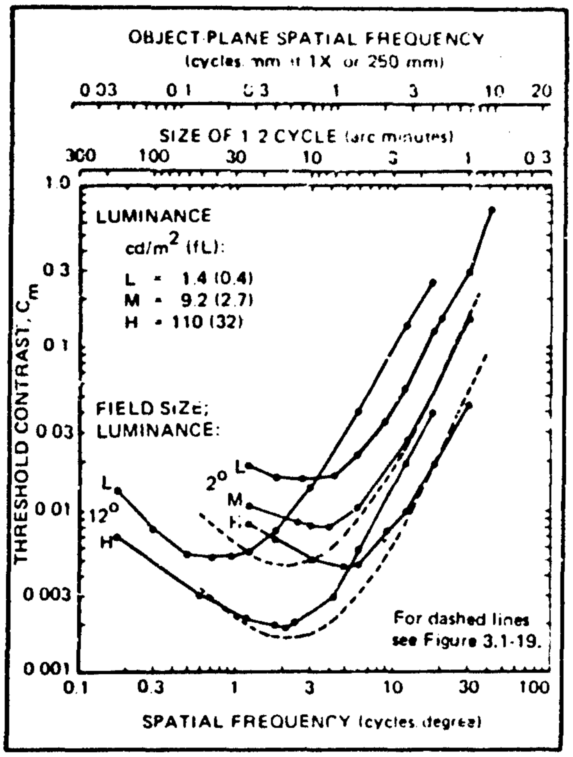


Figure 3.2-31. Effect of Luminance on Contrast Sensitivity. The test conditions for this study (Ref. 25,B) were as follows:

- *Square-wave grating*
- 2- by 2-degree field at 7m (23 ft) or 12- by 12-degree field at 1m (3 ft)
- Incandescent illumination
- 18- by 18-degree surround, [illegible]ly equiluminous
- Binocular viewing
- Criterion—subject reduced contrast to minimum where he still could see the lines
- 1 subject

Only three luminance levels were tested; the maximum, 110 cd/m² (32 fL), yielded better performance than did 9.2 cd/m² (2.7 fL).

(This illustration also appears as Figure 3.1-25.)

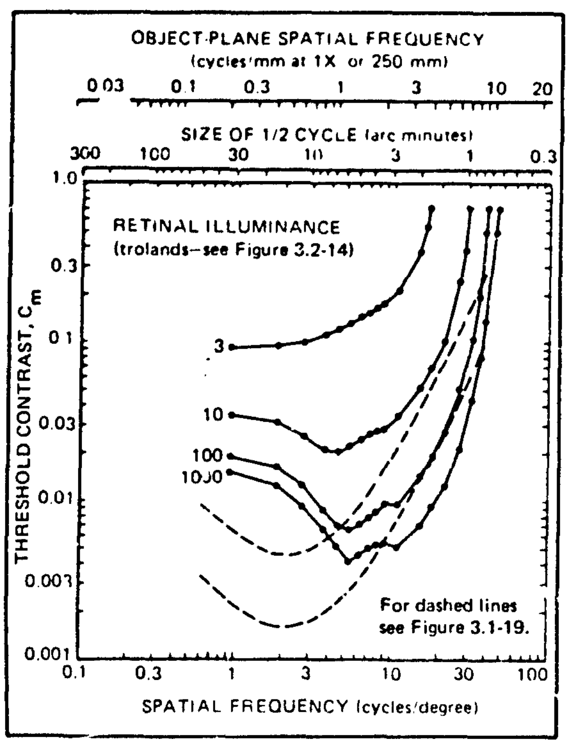


Figure 3.2-32. Effect of Luminance on Contrast Sensitivity. The test conditions for this study (Ref. 35,C) were:

- *Sinusoidal grating*
- 2-degree-diameter field
- Green CRT display, P31 phosphor
- 30-degree equiluminous surround
- Monocular viewing, 2-mm pupil
- Criterion—contrast increased until subject said he could see grating
- Data reported for 1 subject

Vision improved up to the maximum level of 1,000 Td. This corresponds to a scene luminance of 110 cd/m² (32 fL) viewed with a natural pupil.

(This illustration also appears as Figure 3.1-23.)

3.2.6.1 LABORATORY DATA (CONTINUED)

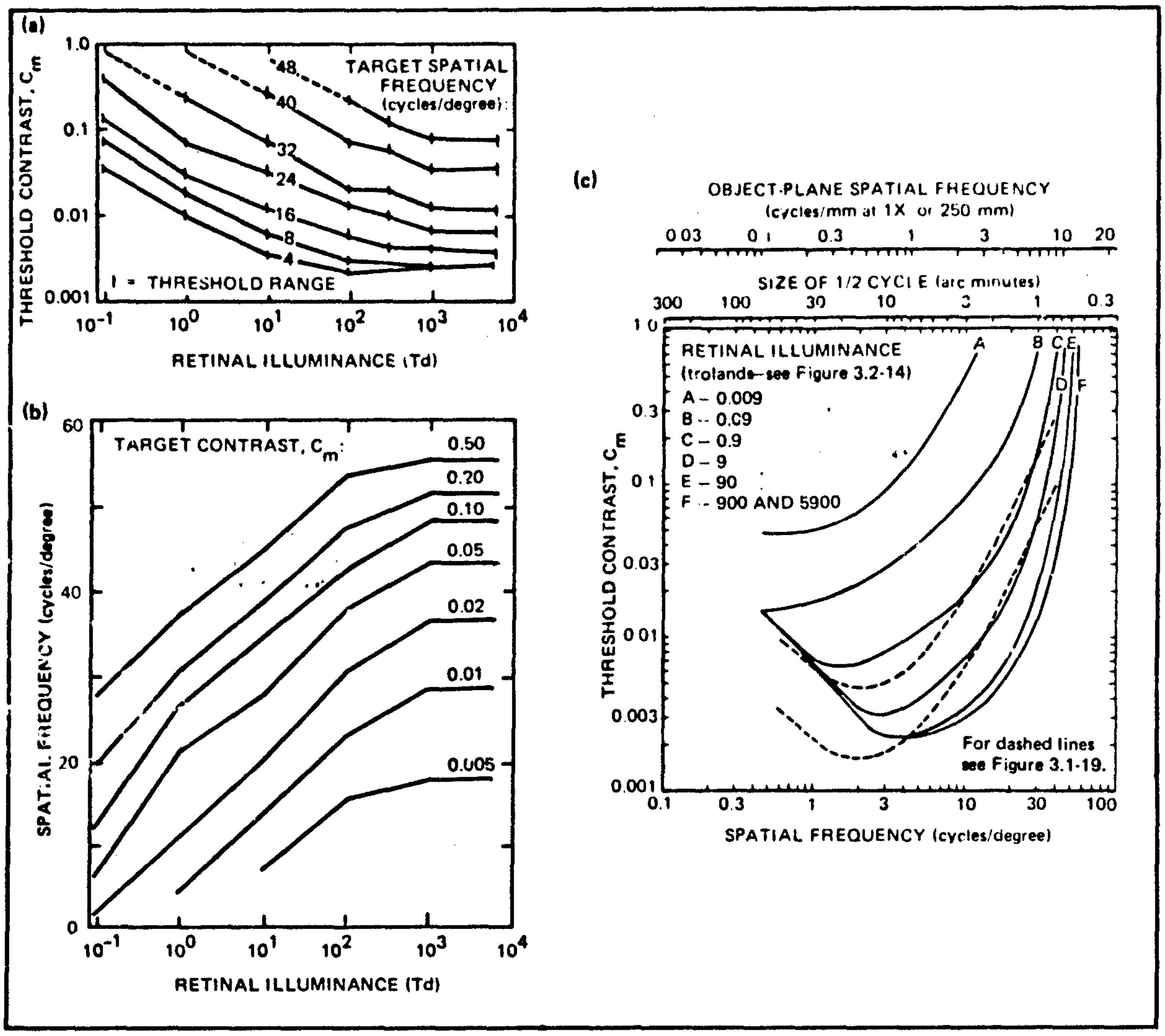


Figure 3.2-33. Effect of Luminance on Contrast Sensitivity. The test conditions for this study (Ref. 36,C) were:

- Sinusoidal grating
- 4.5-degree-wide by 8.2-degree-high field
- Monochromatic green illumination, 525 nm
- Dark surround
- Monocular viewing; 2-mm pupil, projected into eye
- Criterion—subject varied contrast to bracket level at which grating was just perceptible
- 1 subject

According to the author, performance was the same for the two highest luminances, 900 and 5,900 Td, and these are shown as a single curve in (c). These correspond to scene luminance of 100 and 1,200 cd/m^2 (30 and 350 fL) viewed with a natural pupil.

Parts (a) and (b) show the same data as (c), replotted to illustrate the impact of luminance at specific target frequencies and modulations.

(The right-hand illustration also appears as Figure 3.1-24.)

3.2.6.1 LABORATORY DATA (CONTINUED)

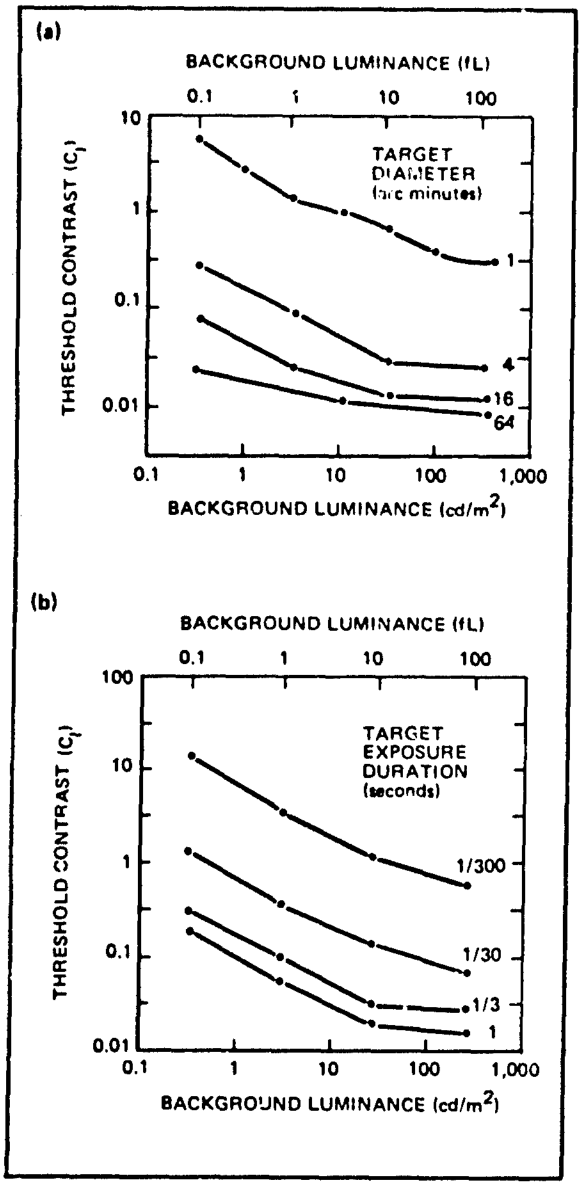


Figure 3.2-34. Interaction of Luminance and Visual Task Difficulty. These curves describe the ability of two subjects to detect light circular targets (Ref. 37,B). The test conditions are described in Figure 3.2-30.

These curves, which are plotted as C_l, not C_m, suggest that increasing luminance will yield greater benefits in difficult viewing situations than in easy ones. Referring to (a), which is based on a target exposure time of 1/3 second, an increase in luminance had a much greater impact on small targets than on large ones. In (b), which is based on a single target size of 4 arc minutes, the last order of magnitude increase in luminance had a much greater effect on threshold contrast with short target exposures than with long exposures.

3.2.6.1 LABORATORY DATA (CONTINUED)

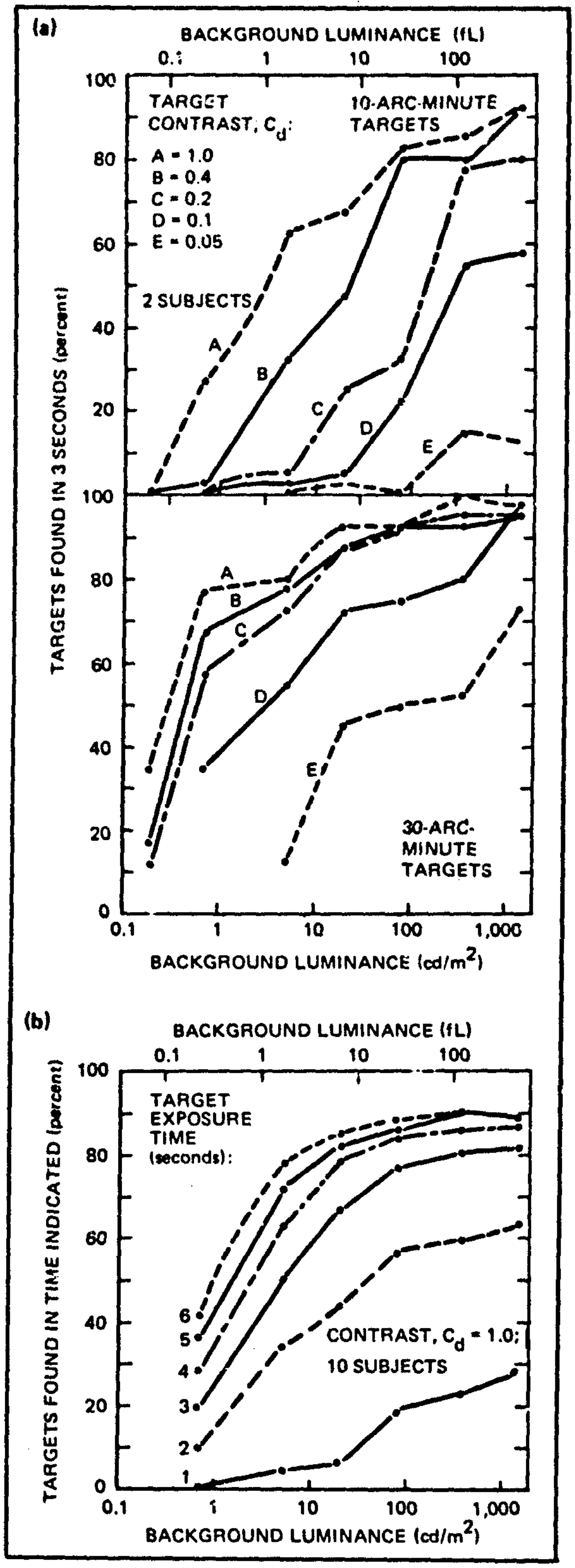


Figure 3.2-35. Effect of Luminance on Search Performance. The benefit of higher luminance values in the study illustrated here varied with the test conditions (Ref. 38,B). In this study, subjects searched for a square target in an array of 15 dark circles of equivalent area. The entire array was seen at a single contrast. The display field was 20 by 20 degrees; the surrounding area was not described. Binocular unaided viewing was used. Two target sizes, 10 and 30 arc minutes across, were used.

The stimulus array disappeared when the subject pressed a button to indicate that he had found the target or that he was satisfied that no target was present. This allowed the data to be treated in terms of target detection success as a function of time.

Part (a) shows the percentage of targets found within the first 3 seconds. With the exception of size/contrast/luminance conditions that were completely impossible, the tendency was for the more difficult viewing conditions to benefit most from higher luminance. That is, performance on the large, high-contrast targets reached maximum with a luminance at which performance on the other targets was still improving.

A similar effect can be seen in (b), which shows target detection success at six different intervals after the array appeared. In this situation, which was limited to small high contrast targets, the highest luminances did not contribute to the number of targets finally found but did help the subjects find targets faster.

These results are relevant to imagery displays whenever the display user's performance is limited by any of the three variables included in the study—target size, target contrast, and time available to complete the task.

3.2.6.2 IMAGERY DISPLAY DATA

This section summarizes the two studies available on the effects of image luminance collected using test subjects, imagery, and displays typical of an imagery interpretation work situation. Because of the way these data were collected and reported, it is difficult to establish exactly how they impact display design. They are included here because they contribute to the discussion in the introductory part of Section 3.2.6, not because they lead directly to decisions about what image luminance to provide.

In one of the studies summarized in this section, display users indicated the minimum luminance they required and in another they indicated what they preferred. Notably lacking is information on what luminance, if any, they would consider excessive. In the absence of a redesign of the work environment or special training to show the display user the value of high image luminance levels, this would seem to set an upper limit on the maximum luminance it is useful to provide, regardless of what laboratory data may imply about visual performance. It is important to collect such data with a reasonable range of display configurations and ambient illumination conditions. Such data should be less variable than data on preferred luminance because it is usually easier to judge when an image is poor than to judge when it is good.

In addition to the work summarized here, there is some indication, primarily based on comments by interpreters using microscopes to view imagery, that there is an upper limit on the acceptable image luminance for this kind of display. The typical comment is to the effect that as the image luminance is increased beyond a certain point the image contrast is noticeably reduced and the image becomes more difficult, or at least less pleasant, to see. Physically, there is no way the image contrast can change simply from an increase in the source luminance. Therefore, if this phenomenon is real, it must be due in some way to a nonlinearity in the response of the eye to the luminance distribution in this kind of display. In this regard the work described in Section 3.2.11 on the impact of glare is probably more relevant than the work in Section 3.2.6.1 describing visual performance when the luminance of a display that fills the entire visual field uniformly is changed.

In one study, several individuals experienced at viewing imagery for purposes of determining its physical characteristics, such as density, granularity or resolution, served as subjects (Ref. 39,X). They estimated the luminance required to detect or to recognize simple geometric shapes on color test imagery. Estimates were made by increasing the luminance from zero until it was deemed acceptable. The minimum image luminance judged satisfactory by 95 percent of the test subjects ranged from 0.07 to 7.0 cd/m^2 (0.02 to 2.0 fL), depending on the particular visual task and target/background combination involved. No correction was made for photometer pupil size as described in Figure 3.2-21.

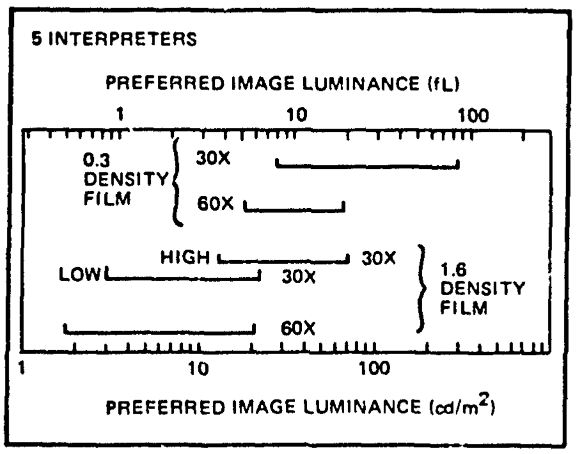


Figure 3.2-36. Preferred Microscope Image Luminance. Five image interpreters viewed two samples of low-contrast imagery in a Bausch and Lomb Twin Dynazoom microscope (Ref. 41, D). For each viewing condition, image luminance was first set to maximum and then was reduced by the interpreter to his preferred level. The 0.3 density imagery was viewed in stereo, while the 1.6 density sample was viewed with a single eye. The bars in the figure illustrate the range of preferred values for the five interpreters.

Image luminance was measured with the film in place. Film density was measured with the same photometer used to measure image luminance. It measured over a field of about 10 degrees. It had a 3-mm entrance pupil. No correction was made for photometer pupil size as described in Section 3.2.4. For the 1.6 density, 30X viewing condition, the interpreters each reported two luminances, one high and one low.

3.2.6.3 EFFECT OF USER AGE AND VISUAL ABILITY

A number of changes occur in the eye with age (Ref. 41). These include a reduction in transmission and in pupil size, both of which reduce the proportion of illumination that reaches the retina. It has been suggested that older individuals should therefore be provided with more light than younger ones. For example, one handbook states that to obtain the same contrast detection performance as a 20-year-old observer, a 40-year-old observer will require 40 percent more light and a 60-year-old observer will require 100 percent more (Ref. 42). Somewhat smaller increases are suggested as adequate to maintain the same visual acuity.

The best available test data, summarized below, suggest that older individuals and individuals with subnormal vision achieve their best visual performance at approximately the same illumination levels as normal individuals. To the extent that this is true, increasing the illumination level especially for older individuals will help only for task situations where the normally sighted individual can see adequately at an illumination level much lower than required for best vision. Figure 3.2-39 expands on this idea.

The implication for display design is that if enough illumination is provided for younger users to reach maximum visual performance, this illumination will also be adequate for older users. The former group, however, will have slightly better performance.

To place this topic in proper perspective, it should be noted that the reference just cited (Ref. 42) speaks of luminance increases of only 40 to 100 percent. Most of the curves in this section show luminance changes in terms of increments five or ten times as large.

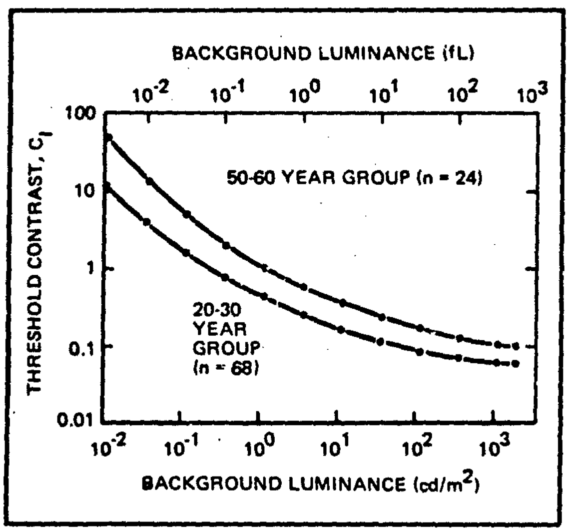


Figure 3.2-37. Effect of Luminance on Contrast Thresholds for Different Age Groups. Contrast thresholds for two groups of subjects differing in age are shown (Ref. 43 C). The subjects were selected to have 20/30 or better visual acuity on a standard clinical test. The target was a light disc adjusted by the subject to be barely visible. Otherwise, viewing conditions were as described in Figures 3.1-16 and -17.

The two groups differed in their ability to see low-contrast targets. However, there is no suggestion in these two curves that there is any difference in the luminance level at which the two groups were able to reach maximum performance.

3.2.6.3 EFFECT OF USER AGE AND VISUAL ABILITY (CONTINUED)

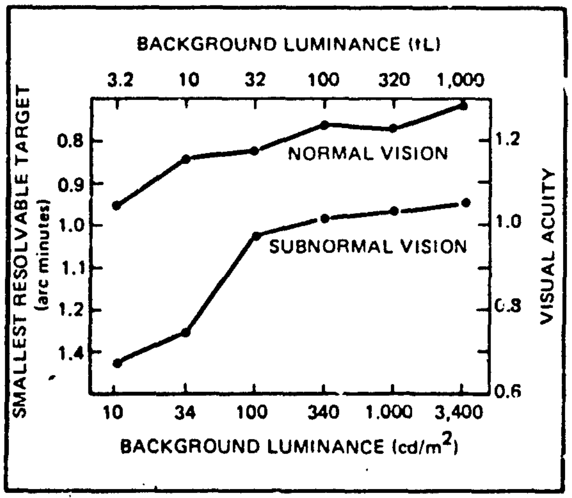


Figure 3.2-38. Effect of Luminance on Visual Ability of Individuals with Normal or Poor Vision. In this study, individuals were separated into groups by visual ability rather than age. Visual performance for the two groups of 12 subjects each, described as having normal and subnormal vision, are shown (Ref. 44 C). The normal vision subjects could resolve the checkerboard test targets when its critical detail subtended 1.0 arc minute while the subnormal vision subjects could not. The luminous surround covered at least 90 degrees. Viewing was monocular with a natural pupil.

As in the previous figure, the two groups clearly differed in ability, but there was no evidence to indicate that they reached maximum visual capability at different luminance levels.

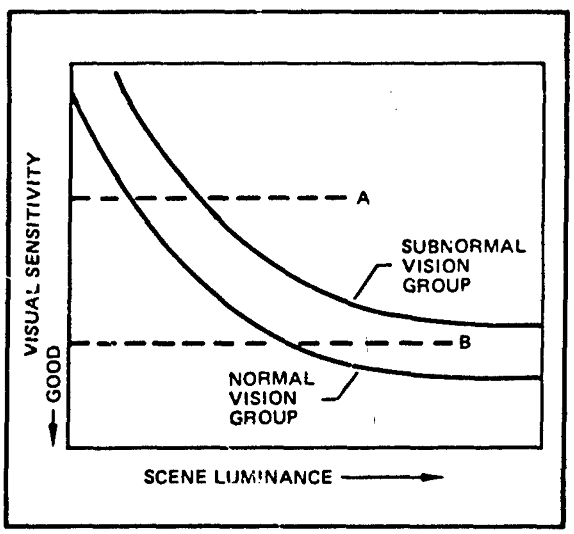


Figure 3.2-39. Increasing Illumination to Compensate for Subnormal Vision. This figure illustrates the hypothetical variation in visual performance with scene luminance for two groups of subjects that differ in visual ability. The two curves are similar to those in Figure 3.2-37, but have been distorted slightly to clarify the difficulty in simply increasing luminance to overcome the problems of individuals with subnormal vision.

Suppose a particular activity requires an individual to function at the visual discrimination level indicated as A in the illustration. Then increasing the luminance by a moderate amount from the minimum at which the normal vision group can perform the activity will also allow the subnormal vision group to perform it. However, as the visual requirements for the activity move closer to the maximum possible, larger increases in luminance are required. Eventually a point such as B is reached at which no amount of increase in luminance will allow the subnormal vision group to succeed.

3.2.7 ILLUMINANT SPECTRAL DISTRIBUTION AND VISUAL PERFORMANCE

The spectral distribution of radiant energy from different light sources varies widely and can be further modified with filters. There are several possible benefits from imposing limits on the spectral distribution of the radiant energy used to illuminate achromatic imagery. Section 3.2.7.1 below considers limitations on energy at wavelengths within the visible region of the spectrum, and Section 3.2.7.2 considers wavelengths outside this region, primarily ultraviolet. (The safety aspects of ultraviolet are covered in Section 6.8.1).

The limitations imposed with displays intended for viewing color imagery are considerably more stringent than those considered here for achromatic imagery. They appear in Section 3.2.9.

3.2.7.1 LIMITATIONS WITHIN THE VISIBLE SPECTRUM

RECOMMENDATIONS:

Illuminate achromatic imagery with radiant energy that includes at least a major portion of the visual spectrum and has a nominal appearance of white.

Do not attempt to improve vision by use of an illumination source with an extremely narrow wavelength range. This is an acceptable, though not a desirable approach, on special-purpose displays when it is necessary to reduce problems with chromatic aberration in the display itself; however, some users will probably have difficulty with such illumination. Avoid wavelengths near either end of the visible spectrum because they make such a small contribution to luminance (Figure 3.2-2). Avoid short wavelengths because the increased refractive power of the eye may make focusing difficult (Section 3.4.6) (also, see the discussion of the potential hazard from short wavelength light in Section 6.8.1.3).

Possible limitations on the spectral distribution of display luminance fall into two categories:

- Distributions of specified shape that include most or all of the visible spectrum
- Narrow band or monochromatic distributions

For sources that cover most or all of the visible spectrum, such as incandescent, fluorescent, and xenon arc lamps, there is no known data to support the use of any one source over the others. Possibly a source with most of the radiant energy at one or both extremes of the visible spectrum would have a deleterious effect on visual performance, but the low efficiency of such a source in converting electrical energy into luminous energy would make it an undesirable choice anyway.

One study that fits into this category compared success in locating targets on aerial photographs illuminated by an incandescent source with a *color temperature* of either 2360° or 5500° K (Ref. 45,A). There was no indication that the two color temperatures had any effect on performance.

In other studies, slight visual performance differences have been reported for relatively small differences in spectral distribution of the illumination source (Ref. 46,C). However, the experimental conditions have generally not been adequately controlled, and, in the absence of confirmatory studies by other investigators, these results remain controversial.

Considering the second type of limitation that might be imposed, the best available data indicate that little if any improvement in vision is obtained by reducing the spectral range of the illumination to a narrow band of wavelengths.

If any such improvement did occur, it would have to be weighed against two disadvantages:

- In a large proportion of individuals, the color fringes produced on the retina by chromatic aberration serve as a clue to the direction of accommodative error (Ref. 47,B). With monochromatic light these individuals, at least initially, are unable to focus their eyes

3.2.7.1 LIMITATIONS WITHIN THE VISIBLE SPECTRUM (CONTINUED)

properly. With practice, most eventually overcome this difficulty, apparently by learning to use some other kind of cue.

- Many individuals will simply find the color of such luminance unpleasant.

There are three major difficulties in attempting to determine experimentally whether vision is better with a particular narrow spectral band or with ordinary full spectrum white light. The first difficulty is in eliminating differences due to the relative sensitivity of the eye to radiant energy of different wavelengths. As Figure 3.2-2 illustrates, the sensitivity of a particular test subject can differ widely from the standard luminosity function. The best approach is generally to increase the radiant energy at each spectral condition tested to achieve maximum visual performance.

The second difficulty involves the differential effect of the limiting aperture at different wavelengths. As Figure 3.2-40 illustrates, the reduction in the diffraction limit for a fixed aperture as wavelength increases can significantly reduce visual performance at the longer wavelengths.

The third difficulty occurs because the amount of chromatic aberration present in the eye is sufficient to make a normally sighted person, who can just focus clearly at infinity with white light, nearly 0.75 diopter myopic when viewing with short-wavelength (blue) light (Section 3.4.6). It is possible to correct this focus error with a minus lens, but the best approach is to avoid blue light in applications where focus is critical.

In the study described in Figure 3.2-33, the modulation sensitivity of the eye was measured with near-monochromatic red, green, and blue light (Ref. 36). The authors concluded that when the test data were properly corrected for the different optical transfer values due to diffraction, there was no difference in modulation sensitivity of the eye for the three colors.

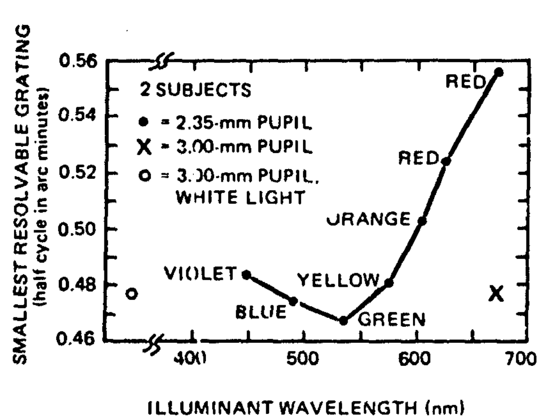


Figure 3.2-40. Visual Acuity and Illuminant Wavelength. In this study visual acuity was measured with a high-contrast square-wave grating (Ref. 48 B). The background luminance was increased at each wavelength condition tested to obtain maximum performance. Narrow-band filters were used to limit the spectral ranges tested.

For the smaller artificial pupil, performance generally dropped with increasing wavelength. Increasing the pupil size at the longest wavelength essentially eliminated this reduction in performance, indicating that the decrease was due primarily to diffraction effects at the pupil.

The fact that white light produced nearly as good visual performance as any other spectral distribution in this study generally supports the conclusion that there is no benefit to providing a narrow spectral band illuminant as a means of improving vision.

(The limitation imposed by diffraction on resolution is discussed in Section 3.3.2).

3.2.7.2 ULTRAVIOLET

RECOMMENDATION:

To ensure best vision, eliminate radiant energy with wavelengths shorter than 400 nm from the image.

The need to keep ultraviolet radiant energy shorter than 315 nm below certain limits in order to prevent any chance of injury to the user is discussed in Section 6.8. Ultraviolet radiant energy can also contribute directly to a reduction in vision because it causes the lens, and to a lesser extent, the cornea of the eye to *fluoresce*. This appears to the viewer as a haze that fills his visual field and reduces the contrast of the image he is viewing. Radiant energy with a wavelength of 300 to 400 nm has been reported to cause fluorescence in the eye (Ref. 49). For most sources the amount of energy at wavelengths shorter than 400 nm will be much less than the amount near the center of the visible spectrum, and the reduction in contrast will be correspondingly small. However, since there is no need for this loss, it should be eliminated by filtering to remove the radiant energy shorter than 400 nm.

Many types of glass have low transmission in the wavelength region below 320 nm, the spectral region that causes eye damage (Section 6.9.1.2), and relatively high *transmission* in the region just below 400 nm, that causes fluorescence in the eye (Ref. 50).

The limitation of ultraviolet radiant energy for safety purposes is treated in Sections 6.8.1.1 and 6.8.1.2.

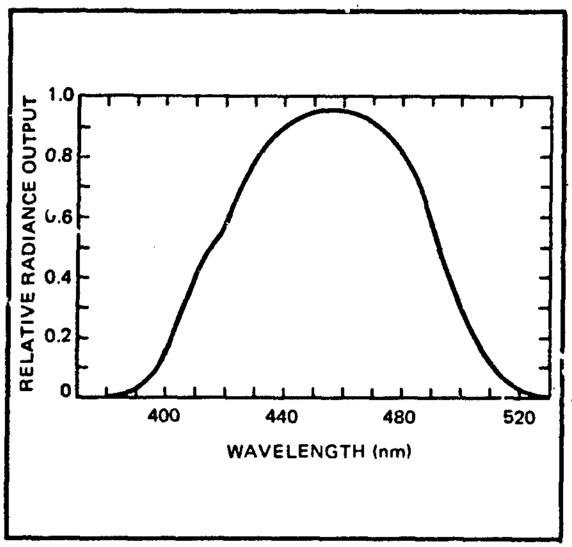


Figure 3.2-41. Ultraviolet Output of an Incandescent Lamp. Both fluorescent and incandescent lamps produce sufficient ultraviolet energy to be sold commercially as ultraviolet sources. The spectral energy distribution for an incandescent lamp sold with a filter to eliminate radiant energy longer than about 520 nm is illustrated here (Ref. 51). Only a very small portion of the energy is shorter than 400 nm. When this light is directed obliquely into the eye while viewing a normally illuminated scene, a very distracting purple haze is produced.

This figure illustrates that even incandescent lamps have the capability of providing sufficient ultraviolet radiant energy to reduce visual performance. In most applications, the reduction would probably not be very significant.

3.2.8 LUMINANCE AND COLOR PERCEPTION

RECOMMENDATION:

Use the same image luminance levels for color imagery displays as are recommended in Section 3.2.6 for achromatic imagery.

As in the case of achromatic imagery treated in Section 3.2.6, color vision improves with image luminance over the luminance ranges tested. The limited test data available are not adequate to specify a particular image luminance that will yield maximum ability to perceive color, so at this point the luminance recommendations in that section are also the best that can be made for viewing color imagery.

The figures in this section illustrate that increasing the luminance of a small target increases sensitivity to a difference in *hue*. Also, color imagery with a content typical of ordinary snapshots appears best when viewed on a surface with a luminance of 2,400 to 4,800 cd/m^2 (700 to 1400 fL). Figure 3.2-44 suggests that part of this improvement may have been due to the increase in saturation of the colors in the imagery as image luminance increased. Failure of the authors to specify imagery density makes it impossible to determine image luminance, although one can perhaps assume the density did not differ from the density of color aerial imagery.

Additional discussion of luminance and color perception appears in Section 5.2.4.

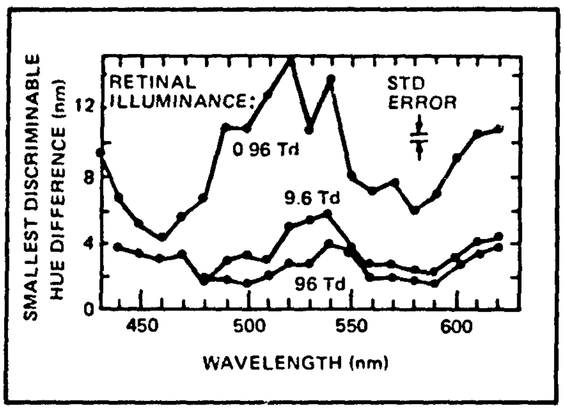


Figure 3.4-4?. Impact of Luminance on Hue Discrimination. In this study a single subject matched the hues of the halves of a 50-arc-minute circular area viewed against a 6-degree equiluminous background (Ref. 52, C). A 2-mm artificial pupil was used. There is some uncertainty about the luminance units used by the experimenter, but the values used here for retinal illuminance are probably correct.

The smallest discriminable difference in hue decreased markedly with each increase in the retinal illuminance of the target area. The maximum retinal illuminance used, 96 Td, corresponds approximately to a scene luminance of 7 cd/m^2 (2 fL) viewed with a natural pupil.

3.2.8 LUMINANCE AND COLOR PERCEPTION (CONTINUED)

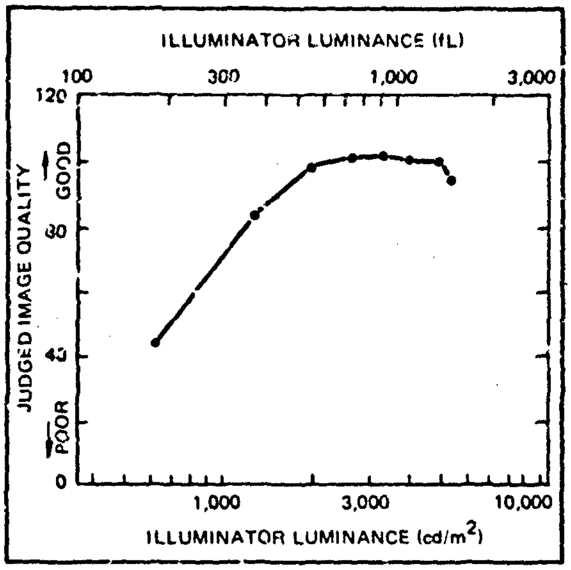


Figure 3.2-43. Optimum Luminance for Displaying Color Transparencies. In the study illustrated here, five subjects judged the quality of ten 200- by 250-mm (8- by 10-in) color transparencies mounted on an illuminator with the range of luminances illustrated (Ref. 53, C). Image content was presumably typical of snapshots, not aerial photographs, and the quality criteria were presumably esthetic. The transparencies probably included three different unspecified kinds of film, and most were judged to have been exposed to within 1/3 stop of optimum. Density was not specified. A xenon arc lamp was used. Luminance color temperature was 5,000°K.

The 0.9 by 1.2m (3- by 4-ft) neutral surround had a luminance of 320 cd/m^2 (93 fL) and a color temperature of 3,000°K. Surround luminance had little impact on the results. Testing with two subjects indicated that an increase in surround luminance of 40 times only doubled the optimum illuminator luminance.

The best illuminator luminance was found to be between 2,400 and 4,800 cd/m^2 (700 and 1,400 fL).

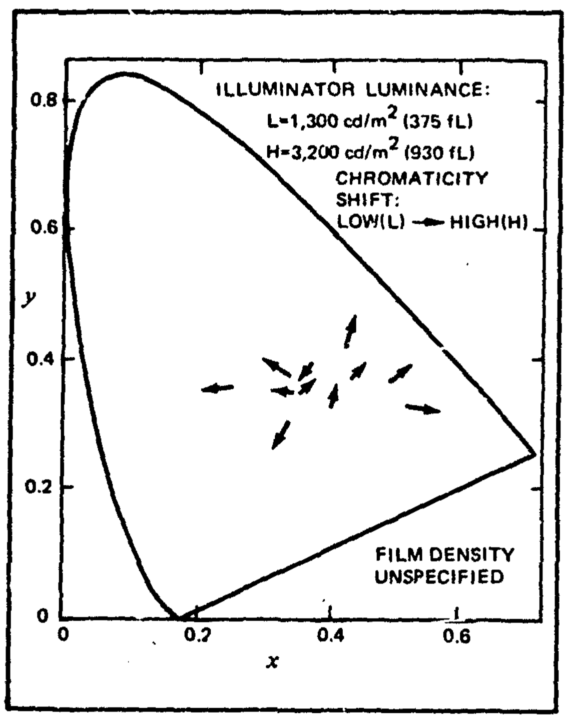


Figure 3.2-44. Impact of Luminance on Apparent Chromaticity. In the study summarized in the previous paragraph, the effect of increasing illuminator luminance on the apparent *chromaticity* of 11 areas in several different transparencies was also measured (Ref. 53,B). The arrows illustrate the chromaticity shifts that occurred with an increase in luminance. Movement toward the edge of the chromaticity triangle indicates increased *saturation* and, presumably, increased color contrast.

The failure to report imagery density makes it impossible to determine image luminance in this study.

(These data are plotted on the CIE chromaticity diagram, which is discussed in Section 5.2.1.3).

3.2.9 ILLUMINANT SPECTRAL DISTRIBUTION AND COLOR PERCEPTION

RECOMMENDATIONS:

Use an illuminant with a color temperature of at least 5000°K in order to enhance discrimination of colors in the yellow region of the spectrum.

If feasible, use an illuminant with the energy concentrated in three spectral bands centered on the absorption peaks of the film dye layers in order to display colored areas with maximum contrast.

When color is intended to contribute to the detection of targets, compare different illuminant spectral distributions on the basis of their contribution to increasing the contrast between typical target/background combinations.

If the second and third recommendations above are not feasible, provide an illuminant with a color rendering index of at least 90 as a last alternative to placing no other restrictions on the illuminant spectral distribution.

Provide an illuminant that does not change spectral distribution as the intensity is varied.

The discussion in this section makes frequent use of color terms and concepts explained in Section 5.2, and particularly in Sections 5.2.1 and 5.2.4. In most cases, those explanations are not repeated here.

Proper limits on the illuminant spectral distribution in a color imagery display depend heavily on the contribution color is expected to make to the interpretation process. Although the following two categories are highly oversimplified, and are combined in many interpretation situations, they at least provide a convenient basis for discussing the problem.

- Use of color as a means of increasing the distinctiveness, or contrast, of target objects relative to their background, thereby making them easier to detect.
- Use of color as an aid in identifying an object or area on the ground; this application implies that the color will be quantified by visual matching or physical measurement, or perhaps simply by comparing it with remembered colors.

Although this section considers both categories, the emphasis is on increasing color contrast as an aid in detecting a target. This topic is also summarized in Section 5.2.3. The effect of illuminant spectral distribution on color matching is treated in detail in Section 5.2.4.7.

The importance of considering the intended purpose of color in the imagery is illustrated by the fact that there are already at least three indices of the quality of an illuminant spectral distribution (Ref. 54):

- The *color rendering index* (CRI) indicates how similar a set of standard colors appear under the test illuminant and under a reference illuminant; this index is discussed below.
- The *color discrimination index* (CDI) indicates the average perceived difference between the colors in a standard set when viewed under the test illuminant; this concept is discussed below.
- The *color preference index* (CPI) indicates how closely the colors in a standard set viewed under the test illuminant are to their preferred appearance.

There is at present no official recommendation on the spectral distribution of an illuminant for viewing color imagery when the goal is to detect a target or to determine the color of an area on the imagery by visual matching. The closest thing to a standard that exists is the ANSI standard for viewing color transparencies, which specifies an illuminant with a *color rendering index* (CRI) of 90 and a correlated *color temperature* of 5000°K (Ref. 55). Although the specific basis for these values is not given in the standard, they are apparently

3.2.9 ILLUMINANT SPECTRAL DISTRIBUTION AND COLOR PERCEPTION (CONTINUED)

from studies such as the one summarized in Figure 3.2-44, which provided a small amount of evidence that an illuminant with a color temperature of 5000°K is more efficient than one with a color temperature of 4000°K or 6000°K (Ref. 53 D). That is, the luminance at which judged image quality reached a maximum was about 5 percent lower for an illuminant color temperature of 5000°K than for the other two values. The color temperature of the surround was either 2800°K or 6000°K. The quality judgements were based on esthetic criteria rather than ability to detect targets. In other words these data, and this standard are primarily concerned with whether amateur and commercial snapshots will have a pleasant appearance. Another ANSI standard intended for appraising color quality and uniformity in graphic arts materials may be more relevant (Ref. 56). It requires a 5000°K illuminant for comparing original artwork against first proof prints, but requires a much bluer light, with a color temperature of 7500°K, in order to enhance discrimination of the yellow ink when final production prints are being compared with approved samples.

Three aspects of the illuminant spectral distribution are considered below:

- The need for using a high *color temperature* in order to discriminate among yellow colors.
- The potential benefit of using a combination of three narrow band sources as a means of increasing *saturation* and color *gamut*.
- The need to compare illuminant spectral distributions on the basis of their contribution to enhancing the contrast of target objects.

The importance of using a high color temperature illuminant can be seen most easily in the lower left-hand part of Figure 5.2-13. This figure shows illuminant color temperature plotted on the best available *uniform chromaticity scale* (UCS). On this scale, the relative number of discriminable *saturation* steps for any *hue* is indicated approximately by the length of the line connecting the *chromaticity* of the illuminant to the *spectrum locus*. As can be seen in Figure 5.2-13, a low color temperature illuminant, such as a typical 3000°K incandescent lamp, is very close to the yellow portion of the spectrum locus, making it difficult to discriminate among various shades of yellow. Changing to a higher color temperature illuminant moves the neutral point away from the spectrum locus, increasing the number of discriminable steps in the yellow region. Some microscopes that use an incandescent lamp for illumination include a blue filter for this purpose (see the two bottom entries in Figure 3.2-45). There is no way to set an exact lower limit on illuminant color temperature, but it should probably be at least 5000°K, and perhaps even higher.

Color should make the greater contribution to distinguishing a target of one color from a background of another if the color area, or *gamut*, of the display, measured in terms of discriminable color steps (as in Figure 5.2-13), is as large as possible. For material such as color film, this condition will occur when the illuminant consists of three narrow spectral bands, one centered at the peak of the spectral density curve of each of the three dye layers (Ref. 5.2-17 covers the math involved in this concept). Whether the increase in color gamut will result in a significant improvement in discriminability of colors has not been tested. One problem will be the reduction in the luminous efficiency of the illuminant if the narrow spectral bands must be obtained by filtering. It may be possible to obtain a sufficiently good approximation to the three bands by proper choice of the phosphors in a fluorescent lamp. For example, there has been some success in designing fluorescent lamps to increase the color gamut for specific sets of paint chips (Ref. 54).

One potential problem with this type of illuminant is that relatively small changes in the balance between the amount of energy in the three spectral bands will make large changes in the color of the displayed image. These changes will interfere with visual color matching (Section 5.2.4) unless both the target and reference colors consist of the same kind of film and are viewed under the same illuminant.

Before considering the third aspect of illuminant spectral distribution, which follows directly from the discussion of the second in the previous paragraph, it may be helpful to review the purpose and development of the color rendering index (CRI). Color shifts caused by differences in the spectral distribution of illuminants of equivalent *chromaticity* led to the establishment by the International Committee on Illumination (CIE) of the CRI (Ref. 57). The CRI indicates the amount of color shift in a sample of test objects illuminated with a test

3.2.9 ILLUMINANT SPECTRAL DISTRIBUTION AND COLOR PERCEPTION (CONTINUED)

illuminant, relative to their colors under a standard illuminant of the same chromaticity. The standard illuminant is chosen to provide a continuous, relatively smooth spectral energy distribution. Color rendering indices are given on a scale of 0 to 100, with 100 indicating exact duplication of colors and 50 representing the appearance of the test objects under a warm-white fluorescent lamp.

The test objects used for the CRI are eight Macbeth color chips. The results are therefore dependent on the spectral reflectances of these eight chips. The CIE recommends that special CRI's be derived for specific applications where the Macbeth chips could yield misleading results. The viewing of color transparencies is probably such a situation.

Derivation of a special CRI for viewing color imagery would involve several steps, as shown below. Computational details are available (Ref. 58).

- Select a representative sample of at least eight imagery colors; these should be representative of targets typically of concern to interpreters.
- Determine the spectral transmission of these targets, as they appear in operational imagery.
- Determine the chromaticity of each target image, when illuminated by standard and test illuminants. (The CIE method requires that these illuminants have approximately the same chromaticity.)
- Determine the average color shift between the two illuminants, in 1960 Uniform Chromaticity Scale units (Figure 5.2-11).

In addition to simply av[illegible]ng the chromaticity shifts, as is done with the general [illegible], attention should be paid to the direction of the shifts. Lamps with equal chromaticities and CRI's exist which, because they shift the chromaticities of the Macbeth color chips in opposite directions, produce significant differences in the color of many surfaces (Ref. 59).

The third aspect of the illuminant spectral distribution to be considered is its contribution to providing the maximum contrast between each target and its background. Unlike the CRI, which is concerned with how closely the color of some surface seen under a particular illuminant matches its so-called true color, the interpreter is concerned with how noticeable the target is against its background. This suggests the need for what might be termed a color contrast discrimination index (CCDI).

Because, as Figure 5.2-1 illustrates, color includes both chromaticity (hue and saturation) and a dimension equivalent to luminance, both chromaticity and luminance should be included in the computation of color contrast. Because there is presently no good way of combining them, it will be necessary to calculate them separately and hope they don't disagree on which illuminant spectral distribution is best.

The CCDI would be derived much like a special CRI, with two major differences. First, the sample of colors would consist of typical target/background pairings, such as a ship on water, or a military vehicle on sand, dirt, grass or concrete, as they would appear in operational imagery. Second, the values used to compute the index would represent the contrast between each target and its background, rather than their color shifts. Target/background separations on the uniform chromaticity scale (UCS) would serve for computing chromaticity contrast, at least until some better scale becomes available, and luminance contrast would be computed in the normal fashion (Figure 3.1-10). To compute a single quality index for a particular illuminant, nonlinear weighting of individual pair contrasts might be needed to take account of the greater importance of increasing low contrasts as opposed to maintaining large ones.

Whether one uses the general CRI currently available or develops a special CRI based on imagery or a CCDI based on contrast in the imagery, the question of the impact a particular index value can have on display user performance remains unanswered. Raising the required value for any of these indices will generally increase both the display purchase price and power needed to obtain a particular image luminance. Performance data collected in realistic work situations will be necessary to determine if the cost is justified.

3.2.9 ILLUMINANT SPECTRAL DISTRIBUTION AND COLOR PERCEPTION (CONTINUED)

LAMP	REFERENCE SOURCE TYPE	REFERENCE SOURCE COLOR TEMPERATURE (degrees Kelvin)	COLOR RENDERING INDEX (CRI)
40-WATT FLUORESCENT:			
WARM WHITE	PLANCKIAN	3000	53
WARM WHITE DELUXE	PLANCKIAN	3000	77
COOL WHITE	PLANCKIAN	4400	70
COOL WHITE DELUXE	PLANCKIAN	4200	84
XENON ARC	DAYLIGHT	6500	94
METAL ARC	PLANCKIAN	5000	71
SUN GUN (INCANDESCENT)	PLANCKIAN	3400	98
SUN GUN + BLUE FILTER	DAYLIGHT	6500	87

**Planckian Source* is defined in Section 8.0, Glossary.

Figure 3.2-46. Color Rendering Index (CRI) for Typical Lamps. This figure lists the color rendering index (CRI) of several typical lamps, along with the color temperature of the reference source with which each lamp is compared when computing or measuring the CRI (Ref. 57). These color temperatures can be taken as applying to the lamps themselves, but much more complete listings are available for exact work (Ref. 50). As can be seen here, incandescent and xenon arc lamps have higher CRI values than do fluorescent ones, and the increase in color temperature achieved by the addition of a blue filter to an incandescent lamp may be at the expense of a reduction in CRI.

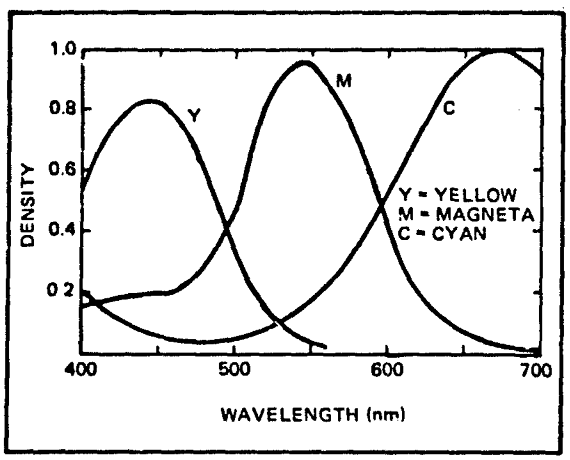


Figure 3.2-47. Dye Characteristics of Typical Color Film. The peaks of the density curves for the three dyes in this typical aerial color film are at approximately 440, 550 and 670 nm. These are also the wavelengths of illuminant radiant energy that will yield maximally saturated image colors.

3.2.10 TEMPORAL VARIATION

RECOMMENDATION:

Eliminate perceptible flicker from the visual field of the display user. In most, but not all situations, a frequency of 80 Hz will be adequate. In many situations, a much lower frequency will be adequate. (Cathode ray tube requirements are covered in Section 4.2.)

Few displays provide the user with an image in which the luminance remains absolutely constant. Fluorescent lamps have a large variation at 120 Hz, which is twice the powerline frequency, and incandescent lamps have a similar but lower amplitude variation. Some fluorescent lamps do not conduct equally in both directions, introducing an additional 60-Hz variation known as a subharmonic (Ref. 60). The output from special controllable intensity sources and combinations of lamps can vary at other frequencies.

If the frequency at which the luminance of a surface varies is sufficiently high, it appears constant, while if the frequency is too low, it appears to flicker. The point of transition between these two conditions is known as the critical flicker frequency (CFF), the critical frequency, or the flicker frequency.

Flicker is extremely annoying to many individuals and should be avoided in an imagery display. This applies both in the image area and in peripheral areas such as at the extreme edge of a light table, where the flicker may distract the user from concentrating on the image.

There are too many variables that affect CFF to allow setting a single value that can serve as a design limit in all situations. A few of these variables are reviewed below. More thorough treatment is available in other sources (Ref. 61), including a literature survey that exceeds 1,000 articles (Ref. 62).

Simple square-wave or sinusoidal variation in luminance is the most common in CFF research. However, many other waveforms have been tested, and some of these can have a significant effect on the results (Ref. 63).

The following very general principles hold in most situations, though not in all:

- CFF increases as the luminance increases (Figure 3.2-47).
- CFF increases as the size of the area being viewed increases (Figure 3.2-47, -48, -50).
- Depending on the viewing conditions, CFF may be higher or lower in the periphery of the visual field than at the fixation point (Figure 3.2-47, -48, -50). In some situations, particularly when large areas are involved, flicker is more noticeable in the peripheral than in the central visual field.
- CFF increases as the *temporal modulation* increases (Figure 3.2-47, Part (d)).
- CFF varies with the relative duration of the light and dark intervals (Ref. 64).
- There is considerable variation among individuals in their sensitivity to flicker (see range data is Figure 3.2-51).
- For test areas larger than 1 degree, the relative luminance of the surround has little effect (Ref. 65).
- Very brief, very high luminance flashes raise the CFF more than would be predicted by the luminance averaged over time (Ref. 64).
- The apparent frequency of a flickering surface is not a good cue to the frequency of luminance variation; the flicker that occurs at a frequency just below the CFF is usually perceived to be at about 20 Hz, regardless of the value of the CFF (Ref. 66).
- For most viewing situations a frequency of 60 Hz does not appear to flicker: for surfaces larger than 20 degrees with a luminance greater than 340 cd/m^2 (100 fL), 80 Hz is usually adequate (Ref. 67).

3.2.10 TEMPORAL VARIATION (CONTINUED)

The chance of flicker occurring with fluorescent lamps can be reduced in several ways:

- Use a higher frequency power source.
- Shift the phase of the power to adjacent tubes (Ref. 66).
- Select lamps that have little or no subharmonic (60-Hz) variation in output.
- Cover the ends of the tubes, where the subharmonic is usually higher than near the center (Ref. 69).
- Use lamps that incorporate longer persistence phosphors; these generally produce longer wavelengths, and because of the resulting increase in red light these lamps are usually known as "warm."

The experiment described in Figure 3.2-51 below provides a useful demonstration that the frequency at which flicker is just perceptible (which provides the definition of CFF in most studies) is not necessarily the same as the frequency at which it is obvious or a problem. As measured by having 20 subjects adjust the frequency for a 17-cd/m^2 (5-fL) surface that filled the visual field, the average values for the four criteria were as follows (Ref. 70,C):

- Just perceptible (CFF) = 70 Hz
- Just uncomfortable = 61 Hz
- Just intolerable = 56 Hz

The acceptability of a certain amount of flicker must be expected to vary widely with particular circumstances. In the absence of test data proving that an adequate proportion of the display user population does not find a particular amount of flicker objectionable, the best display design approach is still to ensure that it is not perceptible; this makes the CFF as normally defined the best currently available criterion.

3.2.10 TEMPORAL VARIATION (CONTINUED)

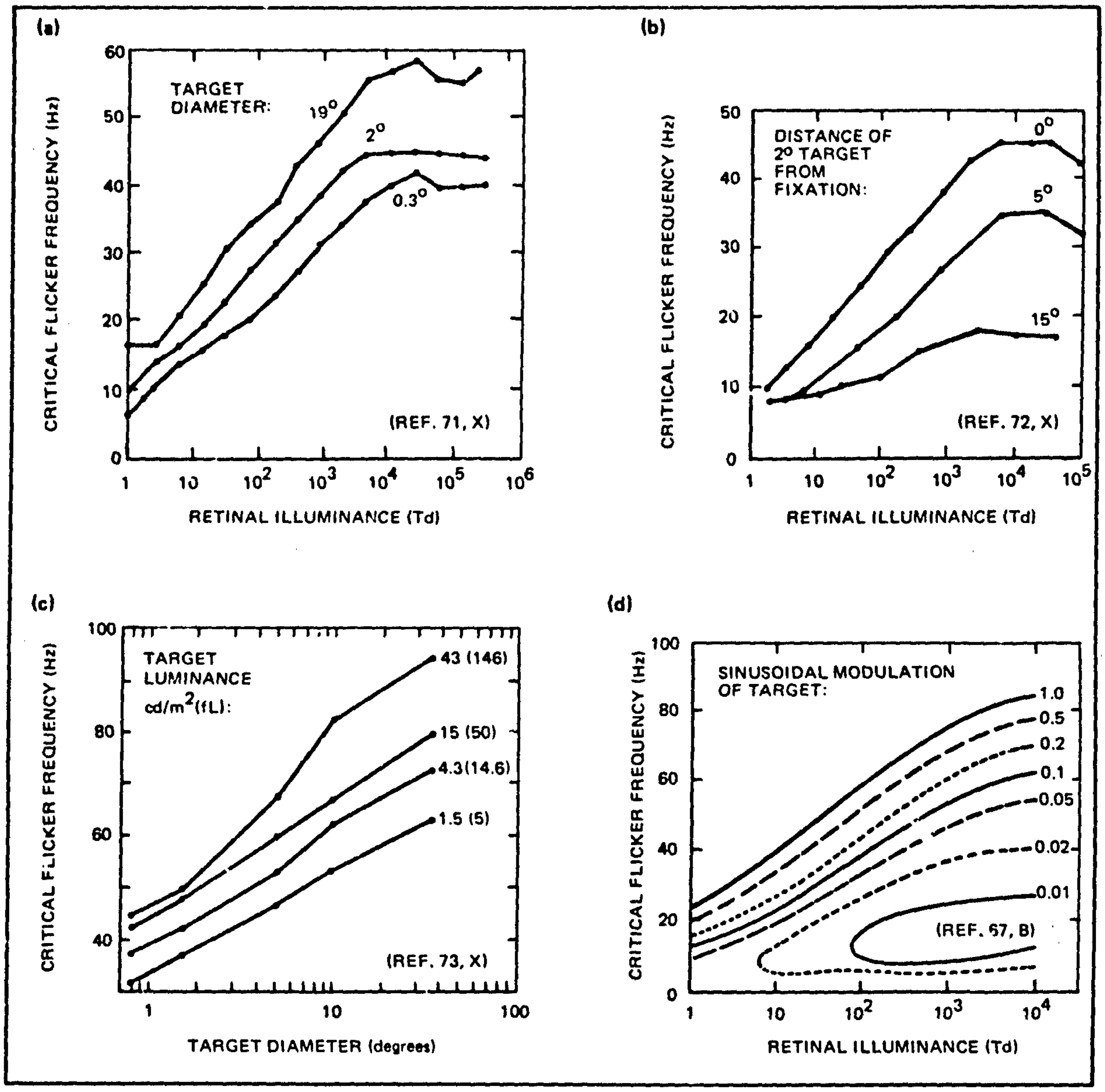


Figure 3.2-47. Typical CFF Data. These four figures illustrate how CFF increases with luminance (a,b,c,d), target size (a,c), and luminance modulation (d). Modulation in this situation is defined as:

$$M = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

Part (b) also suggests that CFF decreases with distance from the fixation point. This has been found in some studies, but the reverse has been found in many others, particularly when a natural pupil is used rather than an artificial one as in this study (Ref. 74). The results in Figure 3.2-50 are more appropriate to most flicker problems in displays.

3.2.10 TEMPORAL VARIATION (CONTINUED)

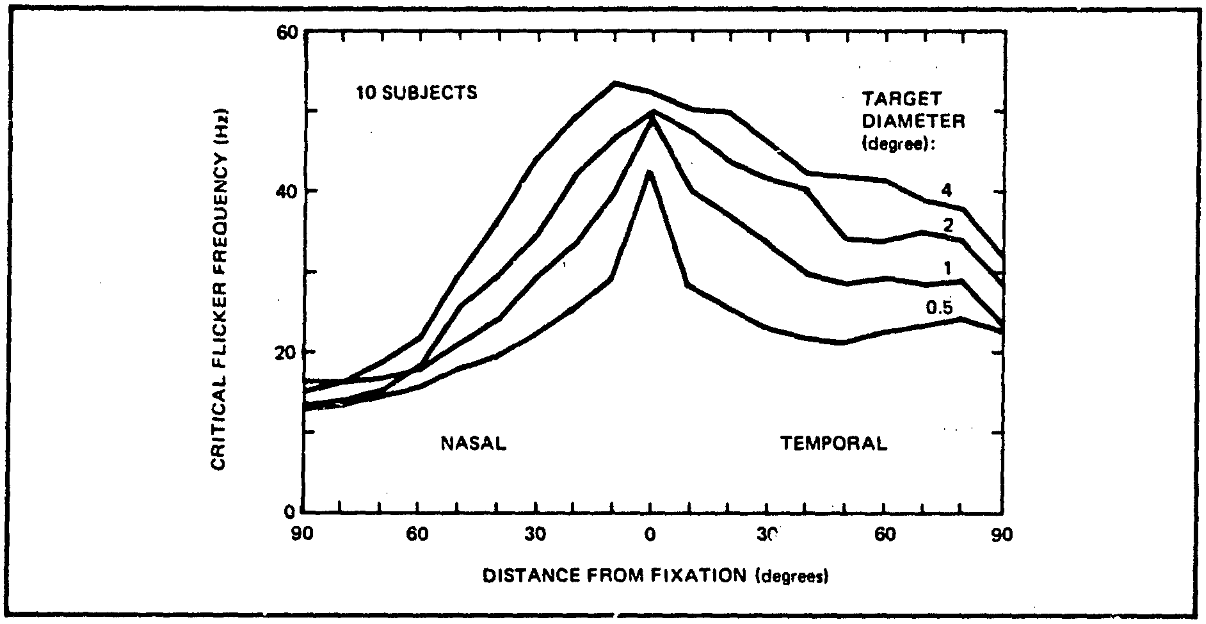


Figure 3.2-48. Effect of Target Size and Retinal Location on CFF. This figure illustrates the change in CFF that results from variations in the size of the test target and in the location of the test target in the visual field (Ref. 75,B). The luminance of the test target was 110 cd/m^2 (32 fL), and the light and dark durations were equal.

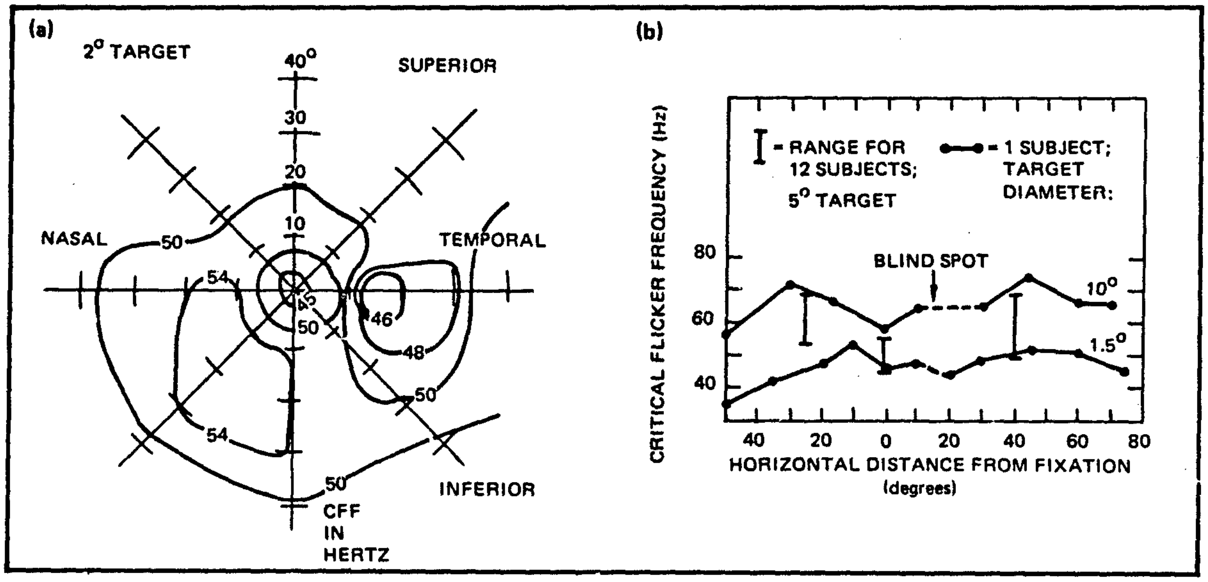


Figure 3.2-49. CFF and Retinal Location. In the study illustrated here, CFF was higher in some parts of the periphery than at the fixation point (Ref. 76,C). Viewing was with a natural pupil. Luminance was not reported.

Part (a) shows regions of equal CFF, plotted against the visual field for one subject. A reduction in CFF occurred at the fovea and near the blindspot. The two curves in (b) are based on the same subject and two other target sizes. They can be compared with the CFF ranges for 12 young test subjects measured at three retinal positions and a fourth target size, 5 degrees.

3.2.10 TEMPORAL VARIATION (CONTINUED)

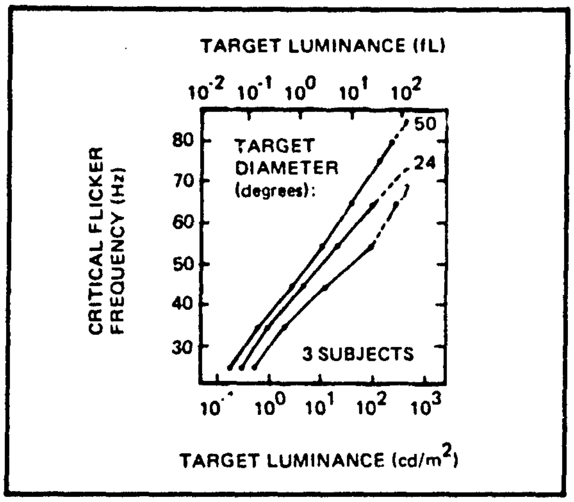


Figure 3.2-50. Effect of Target Size and Luminance on CFF. This figure illustrates the change in CFF that results from variations in the size and luminance of the target field (Ref. 76a,B). The upper data points are based on only two, rather than three subjects, and are therefore connected with broken lines.

In another study, this author demonstrated that the CFF did not change as the central portion of the target field was removed, indicating that CFF was being determined by the periphery of the field (Ref. 76b,C). The amount of test field that could be removed without changing CFF varied from 20 percent for a 7-degree field, to 66 percent for a 50-degree field.

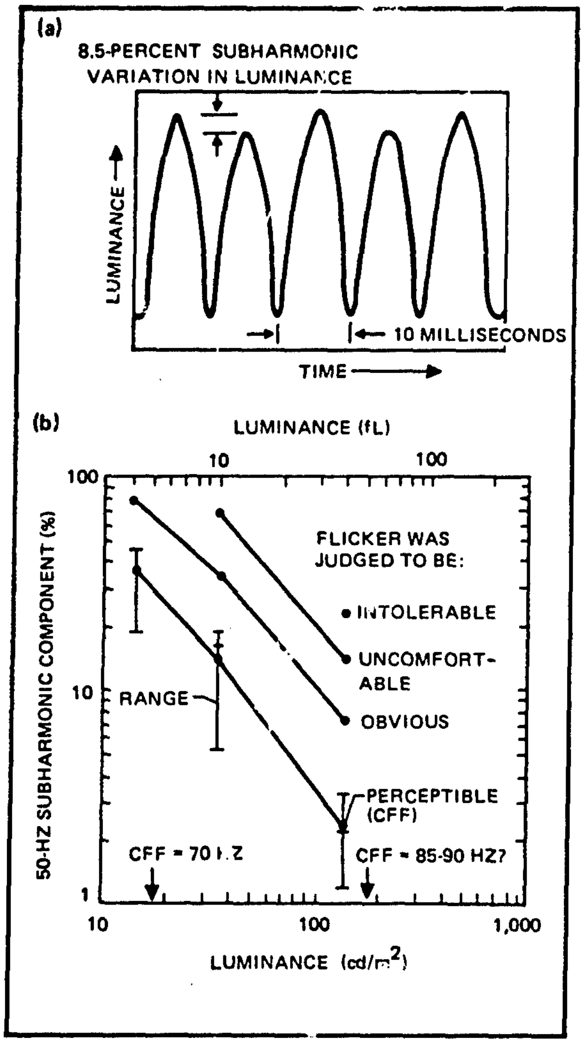


Figure 3.2-51. Contribution of the Subharmonic. A fluorescent lamp that is operating properly may appear to flicker because of a subharmonic variation in luminance at the powerline frequency imposed on the basic luminance variation at twice the powerline frequency. This occurs along the whole length of some fluorescent lamps, perhaps because the lamp is acting like a rectifier, and at the ends of most (Ref. 69).

In (a), luminance variation over time is shown for a lamp with an 8.5-percent subharmonic (Ref. 77). Part (b), which is based on a 50-Hz powerline frequency such as is used in Great Britain, shows the impact of a 50-Hz subharmonic at three luminance levels (Ref. 70,C). The test field in this experiment essentially filled the subject's visual field. The subharmonic component that was just perceptible dropped sharply with luminance, reaching a value of 2.2 percent at 135 cd/m^2 (40 fL). Data for three subjects are shown here.

Evaluation of the contribution of the subharmonic variation in luminance to the perception of flicker in this experiment is seriously hindered by the absence of good comparison data on CFF under similar viewing conditions but with no subharmonic present. The best available data are measurements made by these authors (Ref. 70) on different subjects with a luminance of 17 cd/m^2 (5 fL), which yielded a CFF of 70 Hz. They also extrapolated from other data to obtain an estimated CFF at 170 cd/m^2 (50 fL) of 85 to 90 Hz.

3.2.11 SPATIAL VARIATION

The several kinds of spatial variation that the designer should consider in choosing the luminous energy required to illuminate imagery are summarized below.

3.2.11.1 SIZE OF THE AREA ILLUMINATED

RECOMMENDATION:

When a small exit pupil display device is used with a large luminous surface intended for direct viewing of the imagery, as with a typical microscope/light table combination, provide a separate high-intensity light source for the small exit pupil display.

Imagery displays that utilize a microscope for viewing at high magnification, in combination with a light table for viewing the imagery unaided or with a tube magnifier, impose two very different luminance requirements. When viewing the imagery without the microscope, image luminance is simply the light table luminance times the imagery transmission. If a tube magnifier is used, its transmission must also be included, but it is usually sufficiently close to unity that it can be ignored.

When the imagery is viewed with the microscope, the image luminance is reduced by two factors. The first is conveniently expressed as the ratio of the eye pupil area for unaided viewing to the microscope exit pupil area (Figure 3.2-19). The second is the transmission of the microscope, which may be quite low if the design is complex. In a typical situation the microscope might have an exit pupil diameter of 1 mm while the eye pupil diameter under the particular illumination conditions might be 3 mm, yielding a reduction in image luminance by a factor of 9. Assuming a fairly complicated microscope containing an optical switch or two, transmission might be only 50 percent, making the image luminance in the microscope only 1/18 the image luminance for direct viewing.

In addition to causing an undesirably large difference in luminance as the user moves from microscope to light table (Section 3.2.12), this means that the entire light table surface must provide 18 times the amount of light required for direct viewing. A much better approach is to provide an intense small-area source that is kept positioned in the microscope object field.

One way to reduce display cost and power consumption is to illuminate only a portion of the standard 1-meter length (40 in) commonly provided on present light tables. This may be reasonable, since observation suggests that most interpreters seldom use more than a third to a half of the presently available length for viewing imagery. An alternative approach that does not reduce the options available to the display user is to provide a separate high-intensity source for the microscope display, as is suggested above. This will reduce the luminance required across the light table surface, making it less expensive to procure and maintain. Addition of a means of turning on separate portions of the surface independently will also reduce power consumption and glare problems.

In most displays the imagery is illuminated by a source that extends well beyond the edge of the display field. At least part of the light from outside the field that reaches the display objective lens is scattered across the image, reducing its contrast. Unless it can be demonstrated that this effect is not significant for a particular display, then it should incorporate some means by which the user can limit the illuminated area to the display field, or shield the objective lens.

In some situations it is also possible to obtain a large improvement in the transfer of contrast from imagery to image by reducing the area on the imagery that is illuminated to a small portion of the display field (Ref. 78). This improvement was probably due to the reduction in scattered light, although coherence effects may also have occurred. While this reduction in field size is not appropriate for most viewing situations, it may be useful when studying especially important details.

3.2.11.2 UNIFORMITY

RECOMMENDATIONS:

Limit variation in luminance across the effective display image field and across the normally used portions of a light table to 50 percent. (The luminance recommendations of Section 3.2.6 also apply to all frequently used display areas.)

Limit variation in luminance across small portions of the display surface, such as the width of a single lamp in a grid of lamps, to 10 percent.

Variation in luminance across the display can be distracting to the user and, if extreme, will reduce the usefulness of part of the display. Limitations on the luminance fall off from the center to the edge of a display of 50 to 67 percent have been proposed (Ref. 79).

There is no known test data to establish the validity of these or any other specific limit. Even the amount of variation that can be detected is not known, one study obtained a value of 2 percent over a 4-degree test field (Ref. 80) and another obtained a value of 10 percent independent of field size over the 1- to 5-degree-field size range tested (Ref. 81). The application of these values to a display image field subtending 40 to 60 degrees or to a 1m (40-in) long light table is not obvious. They may have more relevance to the problem of setting limits on luminance variations over a small portion of a display surface. For example, they imply that a grid of fluorescent lamps used to illuminate the surface of a light table should be spaced and diffused so that the luminance variation does not exceed about 10 percent.

In the absence of any test data, a maximum variation in luminance across a display field of 50 percent is suggested. This applies only to the portion of the field over which image quality is useful, which does not always include the entire display field.

3.2.11.3 DIVERGENCE AND COHERENCE

The divergence of the light rays from a single point on the imagery can be specified in terms of *numerical aperture* (NA), defined just as for the case of an entrance aperture (Figure 3.2-18). The divergence of two typical illumination sources is illustrated below. The theoretical impact of the ratio of illumination source to display numerical apertures on microscope resultion has been developed (Ref. 82). Measurements on two standard imagery displays, the Bausch and Lomb Zoom 70 and the Wild M5 microscopes, yielded some but not all of the predicted effects, and it is not clear whether all the observed effects were due to the ratio of the numerical apertures or perhaps to reduction in scattered light through the reduction in the portion of the display field being illuminated (Ref. 81).

Coherent illumination used in a properly designed display should increase the contrast transfer at low spatial frequencies at the expense of the higher frequencies (Ref. 84). However, the diffraction pattern visible around sharp edges and the grain in the imagery, sometimes called "ringing," seriously reduces the acceptance of such displays by the users. Viewers have been designed to eliminate this problem (Ref. 85), but it is not known if they were successful.

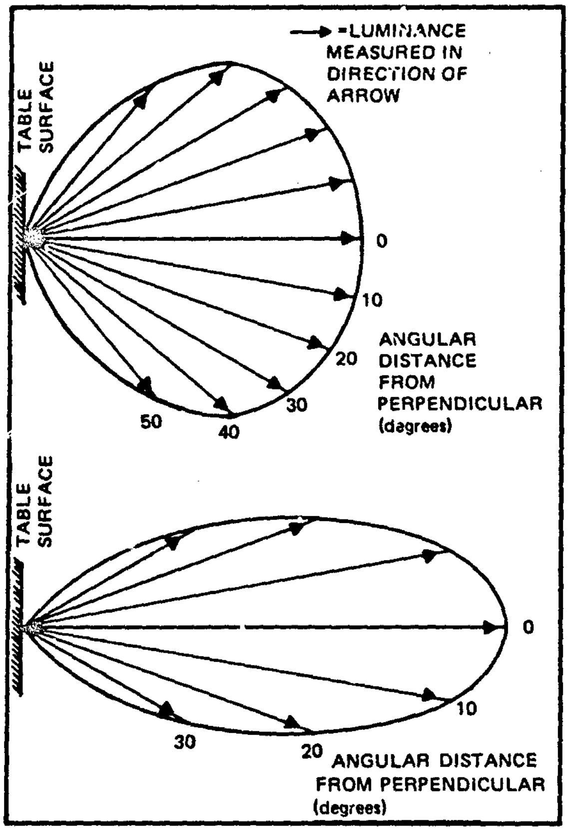


Figure 3.2-52. Divergence for Typical Sources. The upper portion of this figure illustrates the relative intensity of the light leaving a single point on the surface of a typical modern light table (Ref. 86). The light was from a close-packed grid of tubular gaseous discharge lamps, diffused by a sheet of translucent plastic.

The lower portion illustrates similar data for a high-intensity source mounted on the same light table. The light was produced by an incandescent lamp and partially collimated with a lens, after which it passed through the same translucent diffuser as in the upper example.

The scales are distorted in this illustration, the peak intensity of the lower source being approximately 25 times that of the upper.

3.2.12 GLARE

RECOMMENDATIONS:

Eliminate surfaces with a luminance greater than twice the image luminance or less than about one-tenth the image luminance from the display user's visual field.

Eliminate small intense sources that might cause glare.

Prevent images of room lights from appearing on imagery and screen surfaces.

Evaluate the use of small, semitransparent apertures as an aid in viewing dark areas surrounded by light areas such as clouds or snow.

Be particularly careful to eliminate glare sources in displays used by older individuals.

The ability of the display user to see details in imagery will be reduced by *glare* and by *veiling luminance.* As used here, veiling luminance is light scattered across the image that causes a reduction in image contrast, while glare is any light or absence of light that reduces the ability of the display user to resolve details present in the displayed image. Glare, while it may reduce the contrast of the retinal image, has no effect on the contrast of the image in the display (Ref. 87). Glare is covered in this section, and veiling luminance in the next (3.2.13).

There are several common sources of glare in an imagery display:

- Uncovered portions of the light table surface within the user's visual field as the imagery is viewed directly or with a tube magnifier or microscope

- The higher luminance of imagery on the light table surface, which is seen peripherally as a much lower luminance image, is viewed centrally in a display such as a microscope that has low transmission or small exit pupils. (See Sections 3.2.3 and 3.2.4 for a discussion of how display image luminance is reduced in proportion to display exit pupil size; this might occur, for example, when a microscope is used without eyecups on a large light table.)

- Images of room lights or other highly luminous surfaces reflected from the surface of the imagery

- Low density areas such as clouds or snow surrounding a dark target area on the imagery, or a dark area containing small low density areas

The first three sources of glare can be eliminated by properly locating and shielding potential glare sources. Light tables should be designed so that any luminous area not covered by a particular imagery format can be shielded. In the absence of this feature, cardboard and masking tape will continue to make a significant contribution to the display user's work environment. Potential trouble from room lighting can be evaluated by treating the imagery on the light table or the surface of a projection screen as if it is a mirror and considering whether it will provide the user with an image of any room lights or other high-luminance surfaces. Methods of shielding room lights are given in Section 7.3.

A shield close to the eyepiece of a microscope-type display is usually essential to eliminating glare, particularly if any of the luminous surface supporting the imagery is visible from this area. Many styles of eyecups and eyeshields have been built, and none seems to satisfy everyone, particularly spectacle users. The best solution, in addition to minimizing the luminous surface area visible from the user's eye position, is to provide as many different designs as possible and let each user choose the one that works best for him.

The fourth source of glare, being inherent in the imagery, can only be corrected by manipulating the imagery area displayed to the user. One approach, if the imagery is accessible, is a thin plastic or metal sheet containing a series of different sized apertures. By placing this on the imagery with an appropriate sized aperture centered on the area of interest, light from the surrounding area can be reduced or eliminated. An opaque material would probably be easiest to fabricate, but a semitransparent material would eliminate the reduction in vision apparent with very dark surrounds in Figures 3.2-53 and -55 below. A second approach is to place an adjustable aperture in the illumination system that can be used to limit the area on the imagery that is illuminated.

3.2.12 GLARE (CONTINUED)

Two kinds of display formats are commonly used in glare research. One involves a target seen against a very small background with a relatively large surround that has a luminance much different than the background. This research, some of which is illustrated below, indicates that for backgrounds subtending only a degree or so, raising the luminance of the surround above that of the background by a factor of 2 or 3, or redu ing it by a factor of 2 in one experiment and considerably more in others makes the target more difficult to resolve. These effects are smaller for larger backgrounds and for smaller surrounds.

This research suggests that the luminance of the area surrounding a small important detail should be approximately the same as the immediate background area and, in particular, should not be more than twice nor less than one-tenth the background value.

The reduction in vision when the surround luminance is greater than the background luminance can be explained, not necessarily correctly, in terms of light scattered across the retinal image of the target. Since this explanation does not apply to the vision loss for dark surrounds, some other factor, possibly neural, must also be operating.

The second common kind of glare research involves measuring the reduction in vision that results from one or more small, intense sources in the visual field. The impact on vision in this case depends on the illuminance caused by the glare source at the eye, relative to the luminance of the target, and on the angular separation of the glare source and the target. In general, glare sources of this type reduce the visiblity of a target more as (Ref. 88):

- Glare source luminance increases,
- Area of the glare source increases,
- The distance between the glare source and the target decreases, and
- The target becomes more difficult to see because of a reduction in its size or contrast.

Much of the recent work in this area has been in support of the Illuminating Engineering Society (IES) effort to develop better lighting recommendations. Reviews of this and earlier work are available (Ref. 89).

Direct quantitative application of the results of this kind of glare research is very difficult. However, to the extent possible, all such glare sources should be eliminated from the display user's visual field.

A phenomenon related to glare is the reduction in visual ability that occurs for a brief interval following a sudden change in image luminance. This loss is obvious in everyday situations such as driving into a dark tunnel on a sunny day or exiting from a dark theater into the afternoon sun. It occurs because the eyes require a finite amount of time to adapt to the new luminance. Unfortunately no data are available on the duration of this loss, but in one series of studies in which measurements were made 0.3 second after the luminance change, contrast threshold after the luminance was doubled was 7 percent worse, and after it was cut in half it was 17 percent worse (Ref. 90,B). For luminances up to 1,370 cd/m^2 (400 fL), the loss was relatively independent of the initial luminance value.

Without additional data it is impossible to know whether this effect lasts long enough to be of any significance to the display user. If it does persist more than a second or so, it should be considered when deciding what limits to place on potential glare sources.

Glare becomes more troublesome for individuals past the age of 40 (Ref. 91). This is apparently the result of changes in the ocular media of the eye.

3.2.12 GLARE (CONTINUED)

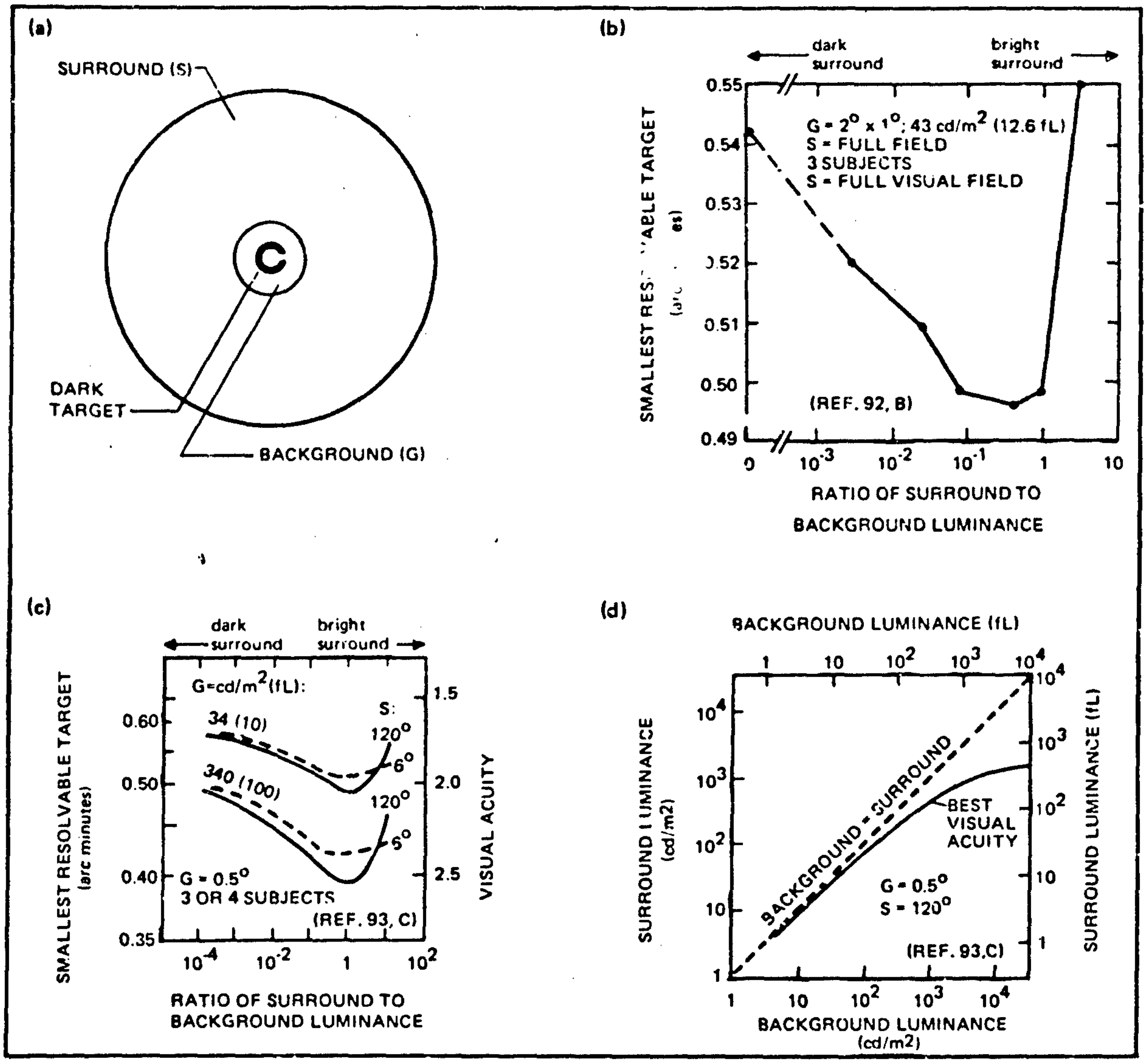


Figure 3.2-53. Visibility of Landolt Rings. One type of glare experiment, illustrated here, involves a target seen against a small background (G) contained in a relatively large surround (S). For small backgrounds, such as those used in the two studies summarized in (b), (c), and (d), vision was best when the surround luminance was equal to or slightly less than the background. Performance dropped sharply when the surround luminance exceeded the background by a factor of only 2 or 3, and when it became very dark.

The curves in (c) show two effects. First, the impact of changing the ratio of surround to background luminance was greater for a 120-degree than for a 6-degree surround. Second, so long as the surround luminance does not differ from the background by a factor of more than about 10, there is considerable benefit from increasing the size of the surround. Another way of describing this second effect is to note that whatever the experimenter chooses to call the surround, the visual system apparently responds to an area larger than 6 degrees. (The area outside the surround was probably dark, but it is not possible to be certain from the available reports.)

3.2.12 GLARE (CONTINUED)

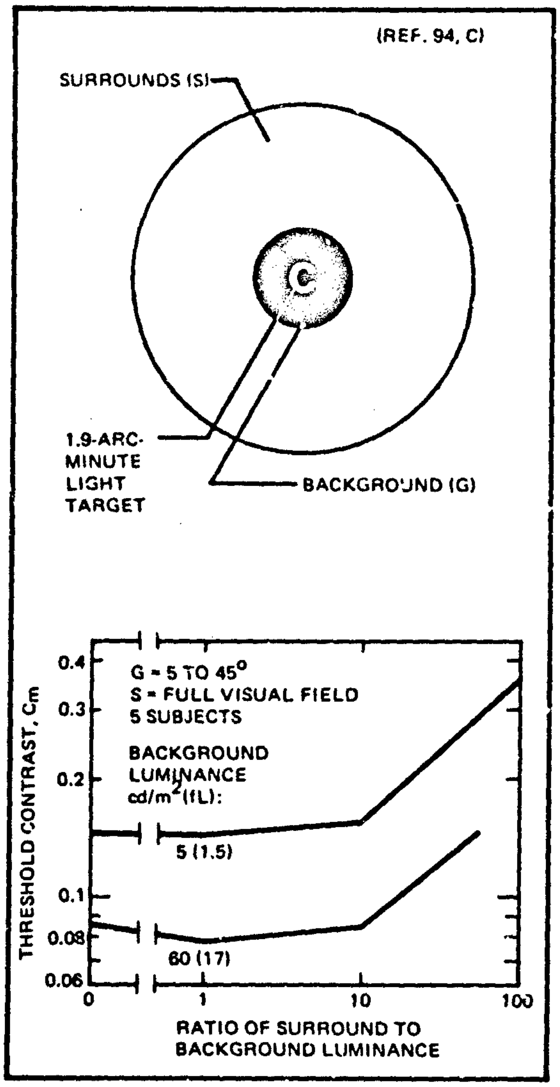


Figure 3.2-54. Visibility of Landolt Rings. The effect of surround to background luminance ratio was smaller in this experiment than in those described in Figures 3.2-53 and -55. This may have resulted from the larger background used here.

The effect of the surround was essentially the same throughout the full range of background sizes, 5 to 45 degrees; the authors suggest that this could have resulted from an artifact in the experimental design. Because of the many differences, it is difficult to make a direct comparison with the other experiments.

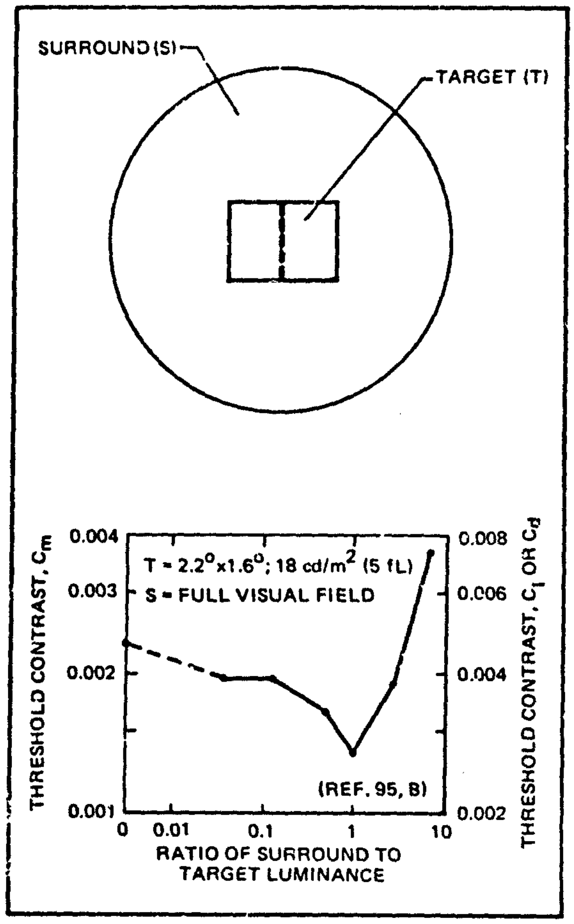


Figure 3.2-55. Contrast Threshold. The experiment illustrated here was very similar to those described in the previous figure, except that the target and background were replaced by two adjacent rectangular areas, and the smallest detectable luminance difference between them was measured. The results were similar to those in the previous figure, but the impact of a small reduction in background luminance was considerably larger.

3.2.13 VEILING LUMINANCE

RECOMMENDATIONS:

Reduce veiling luminance to a minimum with antireflection coatings and screens.

Locate optical surfaces so that there is a minimum chance of fingerprints and dirt that would cause veiling luminance.

Eliminate potential sources of veiling luminance; in the case of a microscope used to view film on a light table, this may mean restricting the region of intense illumination to the area viewed by the objective lens.

As is discussed in Section 3.2, the term *veiling luminance* applies to any light that is spread across a significant portion of the displayed image and thereby contributes to a reduction in image contrast. Common sources of veiling luminance include the following:

- Reflections from optical surfaces and support structures inside the display. A significant portion of this light may originate outside the object field of the display, particularly if the illumination source is only slightly collimated (Section 3.2.3).
- Defects on the optical surfaces, such as fingerprints, that scatter light
- Reflections from the several surfaces of a screen display. (Specular reflections that fall to one side of the area the user is studying, rather than directly on it, are glare, not veiling luminance, and are treated in Section 3.2.12.)
- Light that illuminates the surface of the display user's eye and surrounding facial area and travels from there to the surface of the eyepiece, where it is reflected back into his eye. The most common source for this light is inadequately shielded light table surfaces.

Veiling luminance is not necessarily uniform, and may in fact appear as a ghost image of an intense source. A simple example not involving a display is the image of a ceiling luminance reflected from the surface of directly viewed film, as in Figure 7.2-5. If such an image appears to one side of the area being viewed, it does not reduce image contrast and its primary impact is as a source of glare. The topic of glare is covered in Section 3.2.12.

The importance of keeping optical surfaces clean in order to obtain maximum image contrast is illustrated in Figure 3.2-55 below.

Many specular reflections from display screens can be reduced or eliminated by properly orienting the screen relative to the user and the offending light sources. Placement of the screen perpendicular to the user's line of sight should be avoided because it can reflect an image of his face. Specular reflections can also be significantly reduced by the use of antireflection coatings and polarizing screens (Ref. 96).

The illuminance incident on a rear projection or cathode ray tube (CRT) screen is reflected diffusely at the back surface, where it strikes the material that spreads the image-forming light if it is a rear projection screen or the phosphor if it is a CRT. The amount of diffusely reflected light that reaches the eye can be reduced by use of a low transmission layer in the screen. This reduces the ratio of veiling luminance to image luminance because the former must pass through twice while the latter goes through only once.

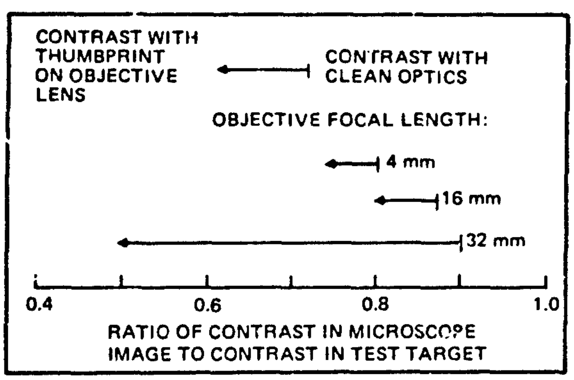


Figure 3.2-55. Reduction of Image Contrast by a Thumbprint. Foreign material such as a fingerprint can seriously reduce image contrast. The test object in this study consisted of an opaque disc one-tenth the diameter of the display field, surrounded by an evenly luminous area that extended well beyond the display field (Ref. 97,D). The condenser was set to full aperture. Contrast was measured photometrically.

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C - Crawford, 1936
F - Flamant, 1948
L - Lythgoe, 1933
R - Reeves, 1920 (Ref. 16)
S - Spring and Stiles, 1948

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15. The weighted average of the six curves in Figure 3.2-5 was made visually at each integral value of log luminance, with the resulting data points indicated as dark circles in Figure 3.2-11. For convenience in plotting a polynomial was fit to these points:

$$d = \sum_{n=0}^{8} C_n L^n, \text{ where}$$

d = pupil diameter in mm,
L = log luminance in cd/m^2,
C_0 = 5.638800
C_1 = −0.567400
C_2 = −0.268300
C_3 = −0.031880
C_4 = 0.028300
C_5 = 0.002563
C_6 = −0.001223
C_7 = −0.000051
C_8 = 0.000019

It is important to keep in mind that this curve has absolutely no theoretical significance.

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$$L_d = TL_s G\,NA^2, \text{ where}$$

L_d	=	screen image luminance
T	=	transmission of the display
L_s	=	source luminance (the lamp)
G	=	screen gain
NA	=	numerical aperture

Since this expression includes the luminance of the lamp itself, it is generally not useful for the kinds of applications described in Section 3.2.3.

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3.3 ANALYSIS OF DISPLAY PARAMETERS

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SECTION 3.3 ANALYSIS OF DISPLAY PARAMETERS

This section is addressed to two basic questions facing the display designer.

- What display *image quality* is required?
- What magnification is required?

Some of the many analytical approaches that have been used in attempting to determine display image quality and magnification requirements are summarized below. So long as one starts with reasonably good information about the imagery being viewed, then these techniques provide considerable insight into the relative importance of different display parameters. However, the validity of the answers obtained is severely limited by the absence of established techniques for including the reduction in vision caused by the *grain* in the imagery. The available information on this topic is discussed in Section 3.3.5.

The display quality should not significantly reduce the information the user can extract from the imagery. The meaning of "significant" depends both on the importance of the information and the ease with which better quality, larger scale coverage of the same target area can be obtained.

Display image quality requirements interact with display magnification. Increasing the display magnification makes smaller details visible, at least up to the limits set by factors such as diffraction (Section 3.3.2) and by modulation transfer losses in the display (Section 3.3.3). At the same time, increasing magnification interferes with use of the display by reducing both the depth of focus and the imagery area visible within the display field.

The minimum magnification that must be provided is affected by many of the same factors that influence minimum display field size (introduction to Section 3.6). That is, the display user needs to view some minimum imagery area within a single field of view. This area is usually much smaller if unaided viewing of the imagery is possible, as on a typical microscope/light table combination, than if it is not, as on a rear screen projector. This is discussed further in Section 3.3.1.

At the other extreme, the maximum magnification should be high enough to not impose any limit on the smallest or lowest contrast details the user can see in the imagery. Approaches to establishing maximum useful magnification are discussed in Sections 3.3.2 and 3.3.3.

It is assumed in this section that the quantity of light reaching the retina is adequate to achieve maximum visual performance. If not, then evaluation of parameters that can change retinal illuminance, such as display exit pupil size, must include possible reduction in visual ability from low light level (Section 3.2.7).

It is likely that many users of modern high-quality *binocular* imagery displays suffer less from inadequate image quality than from poor registration between the images presented to the two eyes. (Registration requirements are discussed in Sections 3.7.4 and 3.7.5) Designing to achieve adequate registration between the two images when the display exit pupils allow significant head movement is often made more difficult because the registration varies with eye position. Techniques such as the computer program developed by Freeman at Pilkington Perkin-Elmer Ltd. to calculate and display the distribution of aberrations and misregistration across the image field should make it easier to meet design goals in this area (Ref. 1).

The ideas in Sections 3.3.2 and 3.2.3 are developed much more thoroughly in a number of other sources (Ref. 2).

3.3.1 MAGNIFICATION UNITS AND REQUIREMENTS

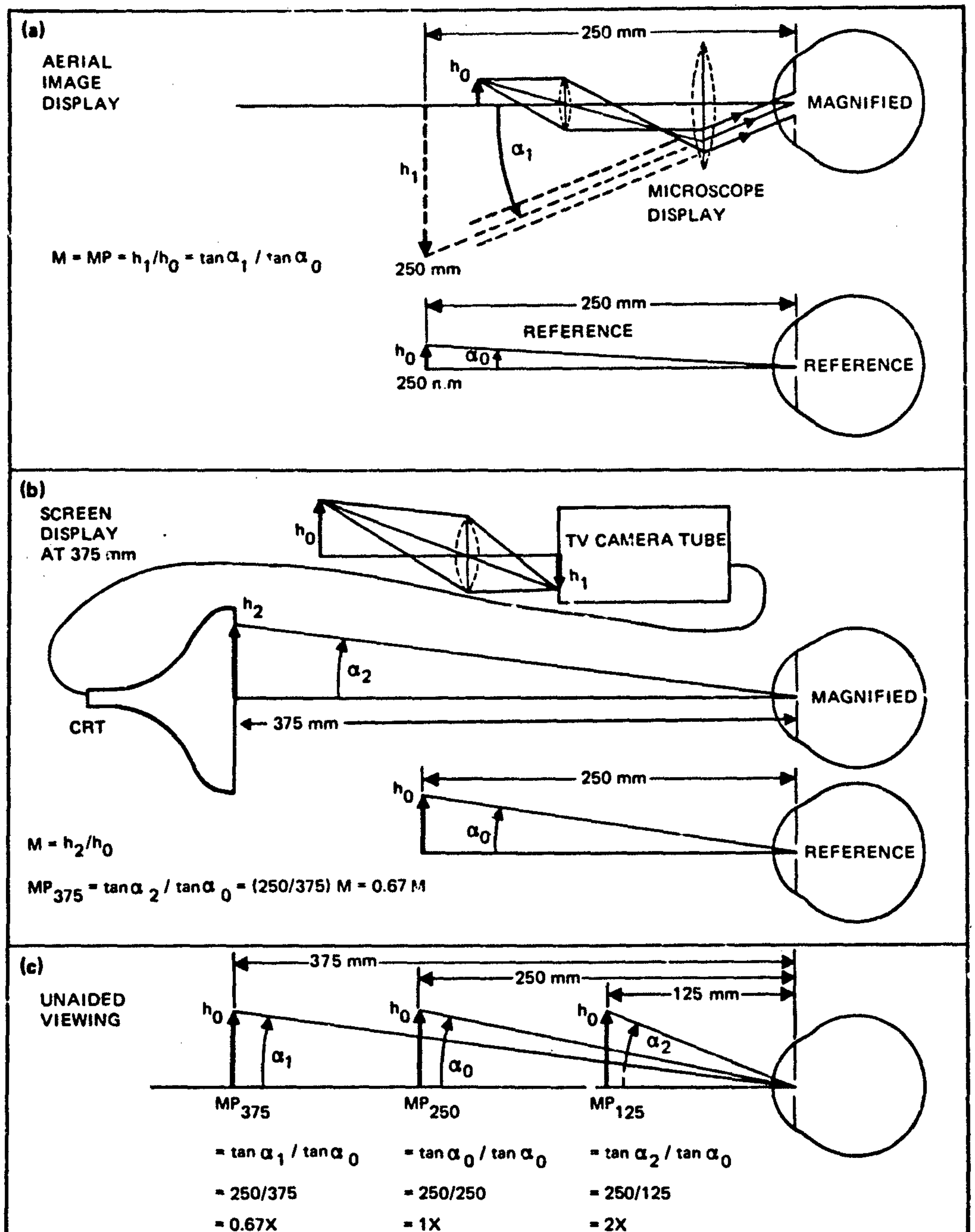
This section defines magnification (Figure 3.3-1) and considers the minimum range and methods of adjusting magnification. Analytical approaches used to determine the maximum useful magnification are given in Sections 3.3.2 and 3.3.3. These techniques are helpful in that they provide some insight into how magnification interacts with other display parameters. However, because they have not yet been applied to the viewing of objects containing grain, they do not at present provide an adequate basis for selecting a specific value when grain is a significant factor in limiting the quality of the imagery.

One common approach to estimating the display magnification required is based on knowledge of the resolution capability of the display in terms of resolvable cycles per millimeter per magnifying power. For example, if the resolution of the imagery is 50 cycles per millimeter and the display is capable of resolving 5 cycles per millimeter per magnifying power, then a display magnifying power, or magnification, of 50/5 = 10X is required. Although useful for some purposes, this approach does not treat as many of the variables involved as do techniques such as those described in Section 3.3.3.

Most imagery displays incorporate a range of magnification. There are basically two options for the mechanism that changes magnification. A *zoom* system provides infinitely adjustable control, while discrete lenses, usually mounted in a rotary turret, allow stepwise changes. The zoom system is generally preferred by users, probably for its convenience and because it allows magnification to be changed without blocking sight of the image. For stereo viewing (Section 5.1), zoom permits magnifying the two members of the stereo pair differently to compensate for scale differences. For monocular viewing, there are no experimental data to support either approach over the other. The only known test required interpreters to use either a zoom or a discrete magnification display to search two kinds of imagery for targets (Ref. 3,C). Under some of the test conditions, magnification was adjusted slightly more frequently with the zoom system, and it resulted in a very slightly better accuracy score. These differences, however, were not significantly different than would be expected from chance variations in performance, which led the authors to conclude that under their work conditions there was nothing to be gained from either system relative to the other.

Minimum display magnification is determined largely by the size of the largest area that must be visible to the user at one time and by the display field size. Because the need to view an imagery area of a particular size is so task dependent, there is no general analytical solution. A few of the variables involved are treated in Section 3.5. In most cases, however, the designer must depend heavily on statements by potential users regarding what they want and what is currently satisfactory. In most cases, the minimum display magnification required will be lower if the interpreter can only view the imagery in the display than if he can view it unaided in order to read edge labeling and to obtain a general impression of content and quality.

3.3.1 MAGNIFICATION (CONTINUED)



M = Magnification

MP = Magnifying power at the viewing distance indicated by the subscript

h_0 = Height of an object

h_1, h_2 = Height of images of h_0

α = Angular subtense of object or image

Figure 3.3.1:. Magnification and Magnifying Power (continued on following page)

3.3.1 MAGNIFICATION (CONTINUED)

Figure 3.3-1: Magnification and Magnifying Power. In order to analyze an imagery display, it is sometimes necessary to distinguish between magnification and magnifying power. These are defined as follows;

- *Magnification* is the ratio of image to object size, with size expressed either as linear extent or as the tangent of angular subtense.
- *Magnifying power* is the ratio of the retinal image size of an object in a particular viewing situation to its retinal image size when it is located at a standard, or "reference" distance from the eye. Although the reference distance is arbitrary, a value that corresponds to a nominal near point for visual work, 250 mm (10 in), is nearly always used (Ref. 4).

Part (a) shows a typical *aerial image display*. So long as the manufacturer used the standard reference distance of 250 mm (10 in), the magnifying power for this type of display is the same as the magnification engraved on the display and the two terms can be used interchangeably. As the equations illustrate, magnification is the ratio of image to object size, $\tan \alpha_1/\tan \alpha_0$. It is also the ratio of the length of an imaginary image, h_1, located 250 mm (10 in) from the eye and defined by the central ray entering the eye, to the length of the object, h_0.

Part (b) shows a typical *screen display*. For a screen display, the magnification is usually given as the ratio of object to screen image length, h_2/h_0. Retinal image size, and therefore magnifying power also, vary with distance from the screen. The magnifying power due just to viewing distance in this example is 250/375, or 0.67. The magnifying power for the display, as viewed from 375 mm, is $\tan \alpha_2/\tan \alpha_0$ or $(250/375)(h_2/h_0)$, or 0.67 M.

Part (c) shows how magnifying power varies with viewing distance for unaided viewing. If the object being viewed is closer than 250 mm (10 in), the magnifying power is greater than unity, while if the distance is further than 250 mm, it is less. A young individual who can accommodate an object at a distance of 125 mm (5 in) is therefore effectively using a magnifying power of 2X. A magnifier will therefore provide him with only half as much increase in retinal image size as it will for an individual who must view the object unaided at a distance of 250 mm (10 in).

Note that in this figure the ratio of the tangents of two angles is approximately the ratio of the two angles, so long as the angles are small.

3.3.2 DIFFRACTION LIMIT TO USEFUL MAGNIFICATION

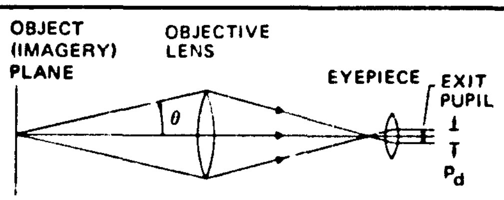
A useful starting point for an analysis of an optical display is to assume that everything will go the way it should and the display will perform as well as the laws of physics allow. If this happens, the performance limitations are set by *diffraction* and the display is said to be *diffraction limited*. In a diffraction-limited display, knowledge of the size of the limiting aperture allows one to calculate the distribution in the image plane of the light from a single point in the object plane.

The next four figures develop the concept of a diffraction-limited display system and the following two relate this concept to what the user can see in the display. In general, the discussion assumes that the basic limit on the display is the maximum numerical aperture that can be obtained. As with most imagery displays, the illumination is assumed to be incoherent and relatively diffuse. (See Section 3.2.11.3.)

One of the applications of the concepts developed in this section is to estimate the upper limit of useful magnification for a display. As the figures in Section 3.1 illustrate, larger image features can be seen at lower contrast, at least up to the point where a half cycle subtends a visual angle of perhaps 20 arc minutes. Further increase in size beyond this value appears to decrease visibility. Increasing display magnification increases the size of details in the image, but so long as the *numerical aperture* (NA) is fixed, because of diffraction it also increases the blur in the image. When the blur becomes too large, the usefulness of further increases in magnification is negated by the parallel increase in blur. This magnification is referred to as *empty magnification*. Typically any value in excess of 1,000 NA is called empty magnification (Ref. 5). In a more general sense, any increase in display magnification that does not result in an increase in what the user can see in the imagery can be said to be empty magnification.

In some ways the prevalence of the empty magnification concept is unfortunate. Because it is generally based on vision test data obtained with simple high-contrast targets, it does not necessarily describe performance for complex scenes. Also, it does not provide a means for handling the effect of optical defects in the display, such as aberrations and scattered light. Finally, it does not include the impact of film grain.

In order to understand the limit imposed by diffraction on optical display performance, it is essential to know the relationships among three display parameters, numerical aperture, magnification, and exit pupil size. These are summarized in Figure 3.3-2.



$$NA = n \sin\theta = \frac{0.5 p_d M}{250} = \frac{p_d M}{500}$$

$$\text{EFFECTIVE } f \text{ NUMBER} = \frac{1}{2\,NA} \quad \text{(Ref. 6)}$$

$$M = \frac{500\,NA}{P_d}$$

$$P_d = \frac{500\,NA}{M}$$

$$\frac{NA}{P_d} = \frac{M}{500}$$

NA = numerical aperture
θ = half the acceptance aperture angle
P_d = display exit pupil diameter (mm)
M = display magnification
n = index of refraction = 1 if object is in air

Figure 3.3-2: Numerical Aperture. The angular size of the bundle of light rays that is accepted by the display objective lens is generally expressed as either the numerical aperture (NA), or the effective f number, defined as illustrated here. Numerical aperture, exit pupil size, and display magnification are related by the equations shown (Ref. 2). These relationships are basic to an understanding of how diffraction limits display performance.

NOTE: The effective f number is equal to the f number only for the special case where the object is in the focal plane of the objective lens (Ref. 7).

3.3.2 DIFFRACTION LIMIT TO USEFUL MAGNIFICATION (CONTINUED)

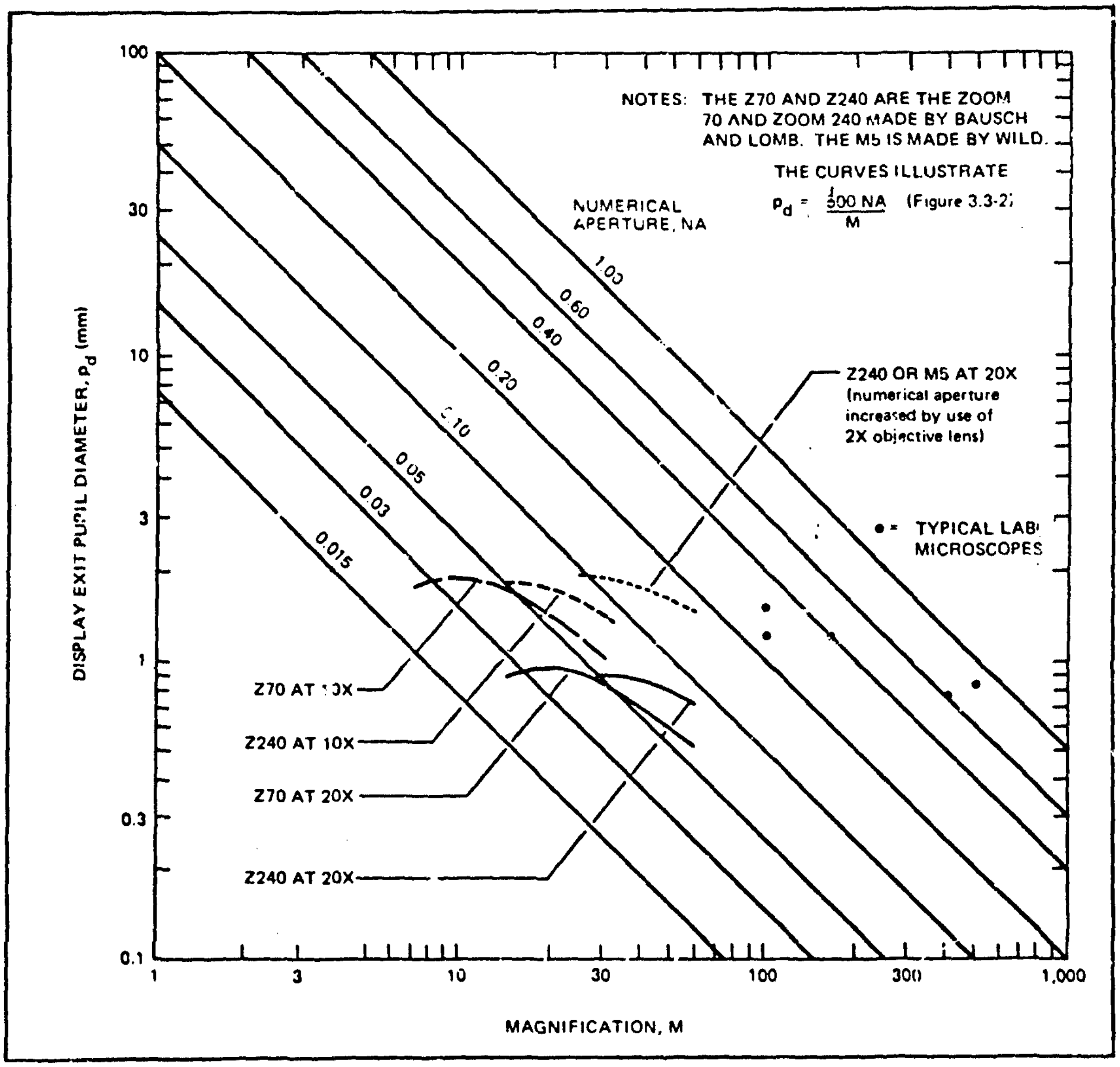


Figure 3.3-3: Relationship of Display Parameters. The relationship of display numerical aperture, magnification, and exit pupil size is illustrated here. Values for several microscopes typically used to view imagery which have continuously variable magnification (zoom) systems, and for microscopes typically used for laboratory work are included for comparison (Ref. 8). Note that both types of microscopes tend to maintain exit pupil size by increasing numerical aperture as magnification is increased.

3.3.2 DIFFRACTION LIMIT TO USEFUL MAGNIFICATION (CONTINUED)

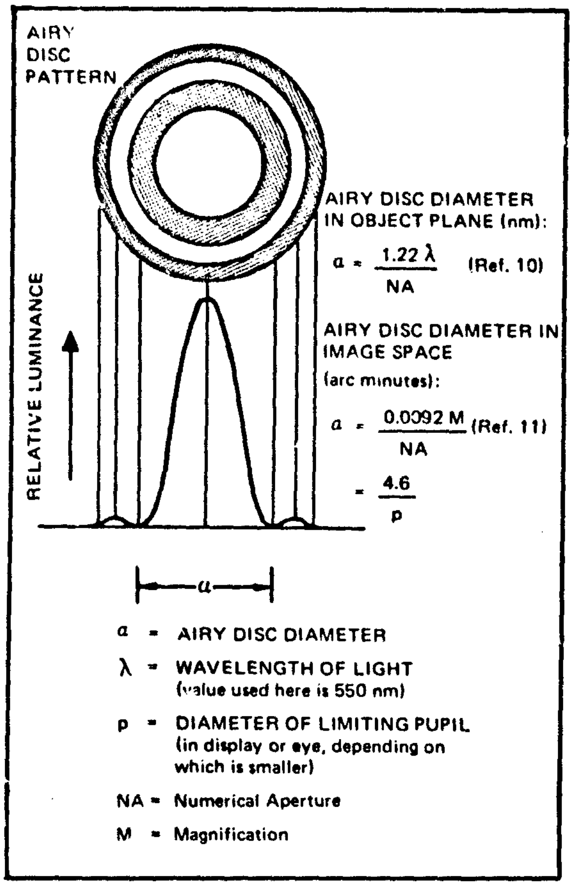


Figure 3.3-4: Diffraction and the Airy Disc. Ideally, the light from a single point in the object plane would fall on a single point in the image. However, even if the display is optically perfect, diffraction will cause the light to be spread over a finite area in the image. This area is known as the *Airy disc*.

The luminance distribution in the Airy disc for a bright point is illustrated here (Ref. 9). Most of the light falls in the central area, which is surrounded by a series of concentric dark and light rings. Only the first light ring is shown. Regardless of how well the display is made, the size of the Airy disc sets a limit to how precisely the imagery is reproduced on the retina of the display user's eye.

The size of the Airy disc is conventionally defined as either the diameter or the radius measured to the center of the first dark ring. The diameter is used in this document.

The equations that relate the diameter of the Airy disc in image and object space to the magnification, numerical aperture, and exit pupil diameter of a microscope-type display using incoherent illumination are included in the figure. If the display pupil happens to be larger than the eye pupil at the particular image luminance condition in use, then the eye pupil is the limiting aperture and determines the size of the Airy disc.

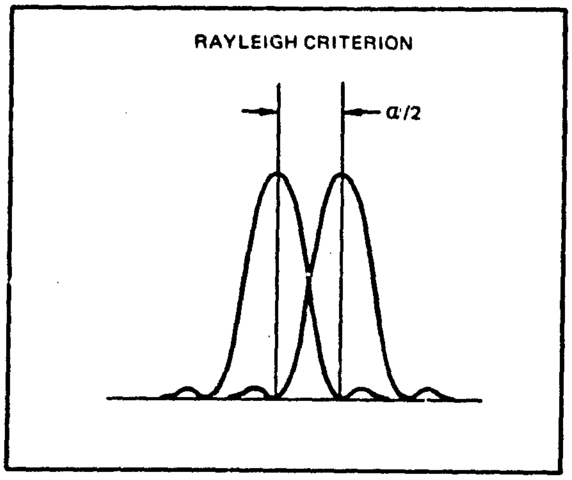


Figure 3.3-5: The Rayleigh Criterion. The luminance distribution in the image produced by a diffraction-limited display depends on the luminance distribution in the Airy disc corresponding to each point in the object plane of the display. The luminance distributions for two adjacent luminous points separated by the radius of the Airy disc, $a/2$, are illustrated here. This particular separation is known as the *Rayleigh criterion*.

Two points or lines can be resolved as two rather than as one if the image luminance somewhere between them drops sufficiently below the maximum image luminance of each. For many viewing situations, though not for all, they will be resolvable as two at a spacing slightly smaller than the Rayleigh criterion (Ref. 12).

3.3.2 DIFFRACTION LIMIT TO USEFUL MAGNIFICATION (CONTINUED)

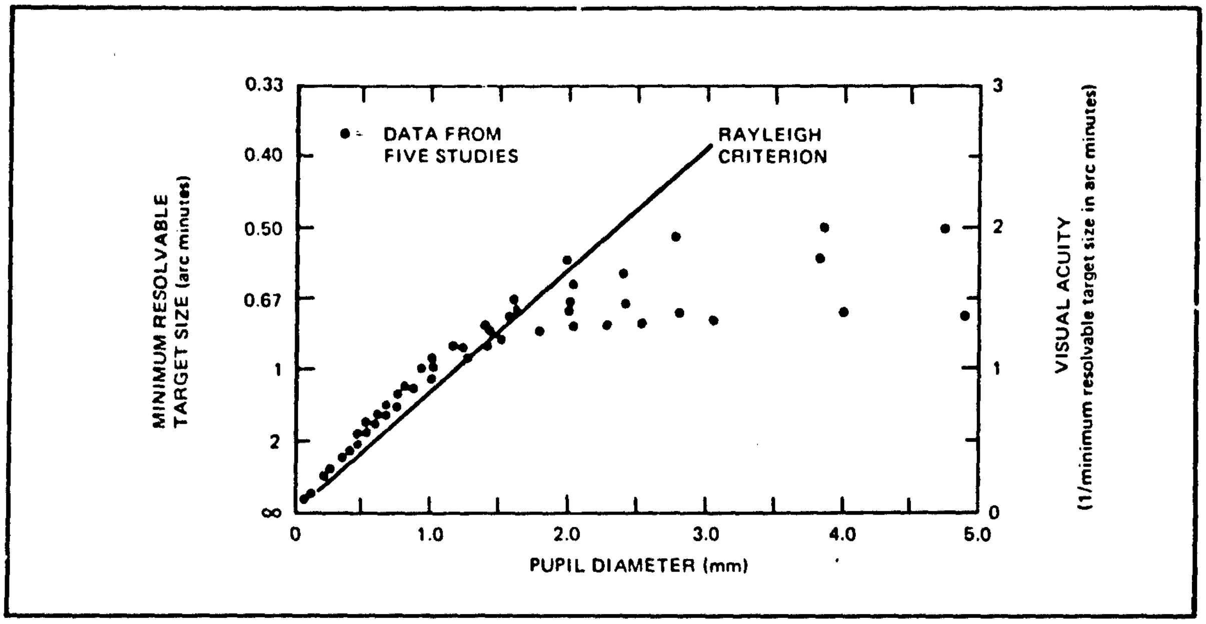


Figure 3.3-6: Relation of Visual Performance to the Rayleigh Criterion. Ability to resolve details at different display pupil sizes as measured in five different experiments is compared here with the Rayleigh limit (Ref. 13,X). The vertical axis is linear for *visual acuity*, which is the reciprocal of the smallest resolvable visual angle in arc minutes. As a result, the Rayleigh limit plots as a straight line in this figure.

Although it was somewhat conservative, the Rayleigh limit generally described the visual performance data adequately up to a pupil diameter of about 2 mm. Beyond 2 mm, visual performance remained relatively constant. Because of this relationship, it is common to treat the eye as if it is diffraction limited for pupil diameters of 2 mm or less. Although theories are abundant, it is not yet certain whether the eye deviates from the diffraction limit beyond 2 mm because of aberrations or simply because of limitations in retinal sensitivity (Ref. 10).

3.3.2 DIFFRACTION LIMIT TO USEFUL MAGNIFICATION (CONTINUED)

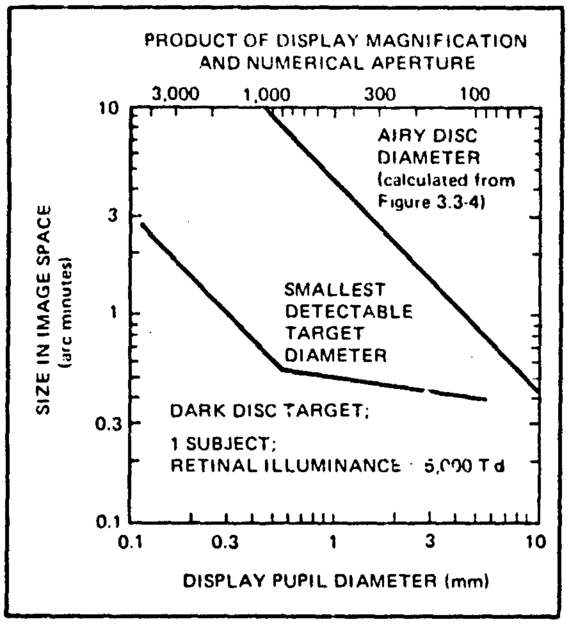


Figure 3.3-7: Variation in Visual Performance with Display Pupil Size. Visual performance as a function of display pupil size is illustrated here (Ref. 5,C). These data are not significantly different from those reported in Section 3.1.9 except that they describe detection of a single point, rather than resolution of parallel bars. However, they extend down to a smaller pupil size, and the fact that they can be fit with two straight lines on a log/log plot makes them convenient for the present application. The two straight lines, though a good visual fit for the reported data, are most likely an artifact of the small amount of data involved; more data would probably yield a smooth curve.

The display was a good quality telescope. Numerical aperture was varied by different sized apertures placed over the objective lens. Different power eyepieces were used to magnify the target disc and the Airy disc associated with it. The pupil size range was from less than 0.1 mm to over 8 mm. The subject's task was to locate an opaque disc in one of four locations. Except for the reversal in target polarity, the task is quite similar to that used by Blackwell (Figures 3.1-16 and 3.2-30).

The size of the smallest detectable target in image space decreased rapidly with increasing pupil size until the pupil diameter reached about 0.55 mm. As the upper scale shows, this corresponds to a magnification of 900 NA.

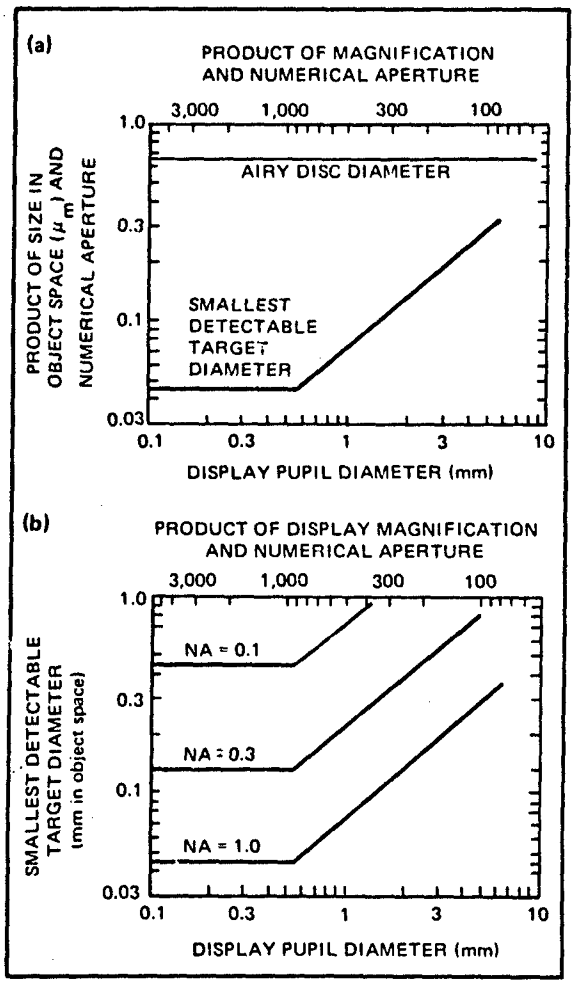


Figure 3.3-8: Determination of Useful Magnification. The data in the previous figure are plotted here with size expressed in terms of the linear distance on the imagery (Ref. 14), rather than as a visual angle in the image. Numerical aperture is assumed to be fixed, which means that magnification varies inversely with pupil size and the size of the Airy disc on the imagery is constant (Figure 3.3-4). Part (a) shows the general case for any numerical aperture, while (b) shows only the performance data for several specific values of numerical aperture.

As the test data show, ability to detect the target increased as magnification increased up to 900 NA and as the pupil diameter decreased to 0.55 mm. At this point the diameter of the Airy disc was approximately 15 times the diameter of the target disc. In other words, the target disc was very blurred. Increases in magnification beyond this value did not improve performance. Whether a magnification of 900 NA would actually be worth using in a specific situation would depend on a number of factors, including whether the reduction in resolvable target size justified the reduction in area covered on the imagery.

It is possible to interpret the visual performance data shown here in terms of the contrast of the image seen by the test subject. As the Airy disc increases in size relative to the target disc, the light from the target disc is spread over a larger area, reducing the luminance difference between the center of the target image and its background. For example, image contrast, C_m, for a dark target when the Airy disc is 15 times the size of the target has been estimated as 0.02 (Ref. 15).

3.3.3 MODULATION TRANSFER

The *modulation transfer factor* for a display is the ratio of image to object modulation at a particular *spatial frequency*. The modulation transfer factor measured over the useful spatial frequency range for the display is the *modulation transfer function* (*MTF*) for the display.

The term *modulation* applies to only one of several ways of quantifying *contrast*, or the difference in luminance between two points on a surface. Precise usage limits the term *modulation* to objects having a sinusoidal luminance distribution in one dimension (Ref. 16). In order to avoid imprecise usage and to make the terminology more consistent within this handbook, the term "contrast" is generally used. Contrast units that have been calculated with the equation for modulation (shown in Figure 3.1-10) are identified as "contrast, C_m."

A complete modulation sensitivity curve for the eye is shown in Figure 3.1-19. It is possible to estimate the modulation sensitivity of the eye/display combination by multiplying the modulation sensitivity for the unaided eye at each spatial frequency by the modulation transfer factor for the display at that frequency. There is an unresolved controversy about the validity of cascading modulation transfer functions in this manner. In theory, differences in the coherence of the image-forming light at various points in its passage through the display/eye system can introduce major errors (Ref. 17). In the only known study that included measurement of visual performance while using the display, the predictions obtained by using this computational procedure, plus an adjustment for stray light within the display, proved to be very good (Ref. 18).

The goal of increasing display magnification is to shift the modulation sensitivity curve of the eye in the spatial frequency domain of the object space by the amount of the magnification. That is, increasing magnification by 50X should enable the user to see an object with a particular contrast that is 50 times smaller in size.

However, as magnification is increased, the modulation transfer factor for a given spatial frequency (in image space) drops. This limits the useful magnification in a manner analogous to what occurred in the analysis given in Section 3.3.2. The figures that follow illustrate this effect for microscopes typical of the kind normally used for viewing imagery.

The modulation transfer of an imagery display is typically measured using illumination conditions that differ from those that will occur when the display is used to view imagery. As a result, the reduction of image contrast by veiling luminance caused by stray light may be underestimated by the modulation transfer measurement (Section 3.2.12).

Whether there is a best magnification for viewing specific objects, rather than just an upper limit on useful magnification, depends on why the minimum in the visual contrast sensitivity curve (Figure 3.1-19) occurs. The most likely interpretation is that more contrast is required for an object to be visible when the *luminance gradient* across the edges that define the object becomes less than the gradient equivalent to a spatial frequency of 1 to 3 cycles per degree. If this is true, then magnifying an object beyond this point should make it less visible. It is easy to demonstrate that excessive magnification can make a very-low-contrast object in imagery less visible. It is not clear, however, whether this occurs because the eye is less sensitive to the larger image, because the increase in display magnification has actually reduced the contrast of the object, or because the increase in the visibility of the grain has obscured the edge.

The alternative interpretation for the minimum in Figure 3.1-19 is simply that the reduction in the number of test target cycles at lower spatial frequencies reduced the visibility of the target. If this interpretation is the correct one, then excessive magnification of a low-contrast edge should not reduce its visibility. The data in Sections 3.1.7 and 3.1.8 show that although the number of cycles present in a test target is important, other factors are also involved.

3.3.3 MODULATION TRANSFER (CONTINUED)

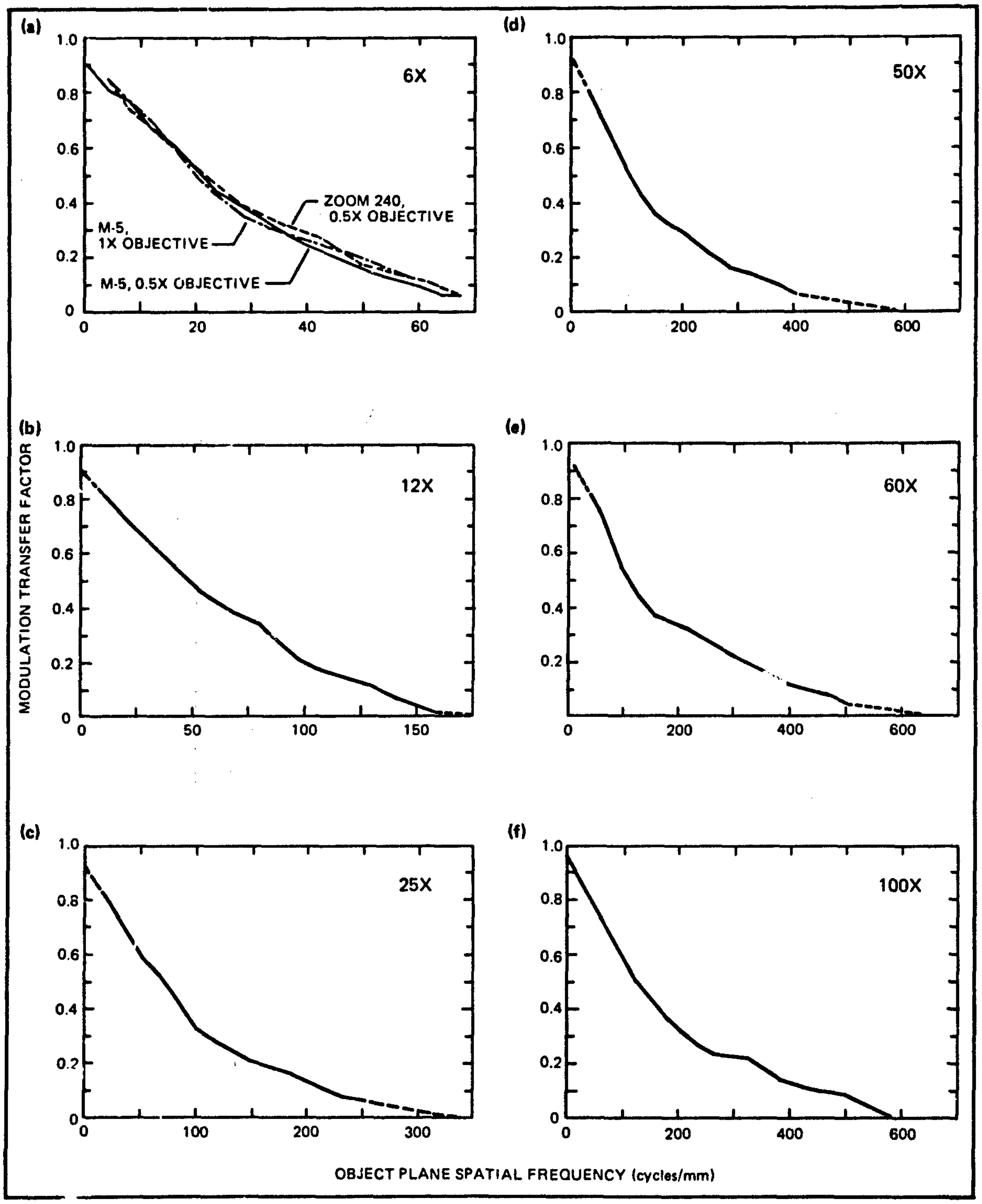


Figure 3.3-9: Sine-Wave Modulation Transfer Functions of Typical Imagery Displays (continued on following page)

3.3.3 MODULATION TRANSFER (CONTINUED)

Figure 3.3-9: Sine-Wave Modulation Transfer Functions of Typical Imagery Displays. This figure illustrates modulation transfer functions for two microscopes frequently used for viewing imagery, the Bausch and Lomb Zoom 240 and the Wild M-5 (Ref. 19,B). These data were originally reported as square-wave response and have been converted to sine-wave values.

The portion of the figure for a magnification of 6X shows three separate curves for different microscope and lens combinations. The other portions of the figure show averages based on a similar number of microscope/lens combinations, but at other magnifications.

Note the changes in horizontal scale in the graphs.

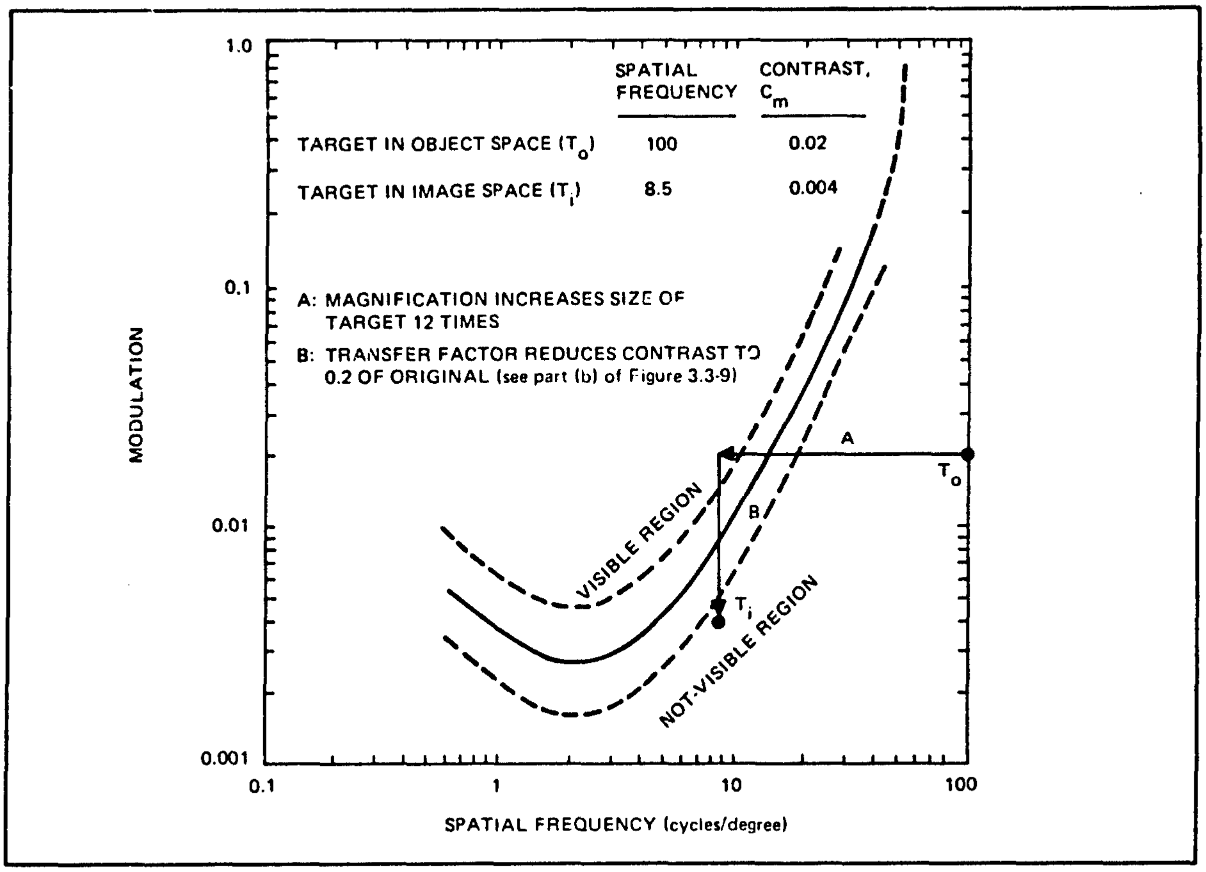


Figure 3.3-10. Effect of Display Parameters on Target Visibility. This figure shows how both display magnification and modulation transfer determine whether a particular target object recorded in the imagery will be visible in a display.

The solid curve shows the average modulation threshold and the dashed curves show the 90-percent population range for unaided viewing (Figure 3.1-19). A target, T_o is assumed to have a spatial frequency of 100 cycles per degree, making it too small to see, and a modulation of 0.02. When it is viewed in a display with a modulation transfer function (MTF) like the one in part (b) of Figure 3.3-9, the image of the target, T_i, has a spatial frequency of 8.5 cycles per degree, but a modulation of only 0.004. As a result, it is still not resolvable.

3.3.3 MODULATION TRANSFER (CONTINUED)

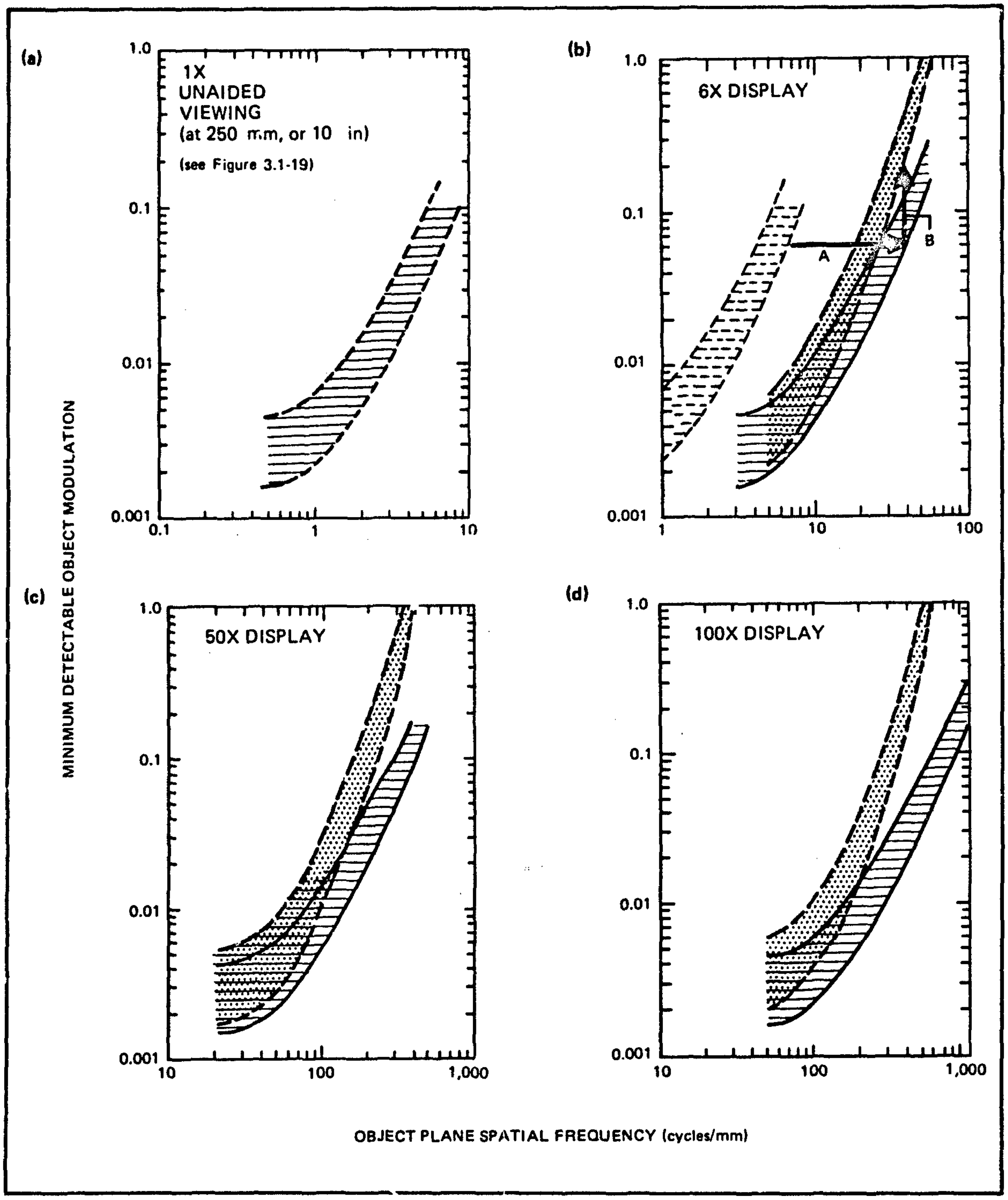


Figure 3.3-11. Effect of Display Parameters on Modulation Sensitivity of the Eye (continued)

3.3.3 MODULATION TRANSFER (CONTINUED)

Figure 3.3-11. Effect of Display Parameters on Modulation Sensitivity of the Eye. This figure illustrates the same concepts as Figure 3.3-10. However, instead of showing how the display shifts the target in image space, this figure shows how it shifts the visibility threshold curve of the eye in object (imagery) space. Part (a) is the modulation threshold range for 90 percent of the population from Figure 3.1-19, shown here in cycles per millimeter at the reference distance for a magnifying power of 1X, 250 mm (10 in).

In part (b), the arrow at A illustrates how display magnification shifts the eye threshold curve from (a) to a 6X higher spatial frequency. Arrow B shows how the modulation loss in the display at this spatial frequency decreases the modulation sensitivity of the eye, resulting in a requirement for a higher target modulation in the imagery. The modulation transfer values used here are from the same set of data illustrated in Figure 3.3-9.

Parts (c) and (d) show how the increase in imagery modulation required becomes greater with greater display magnification.

3.3.3 MODULATION TRANSFER (CONTINUED)

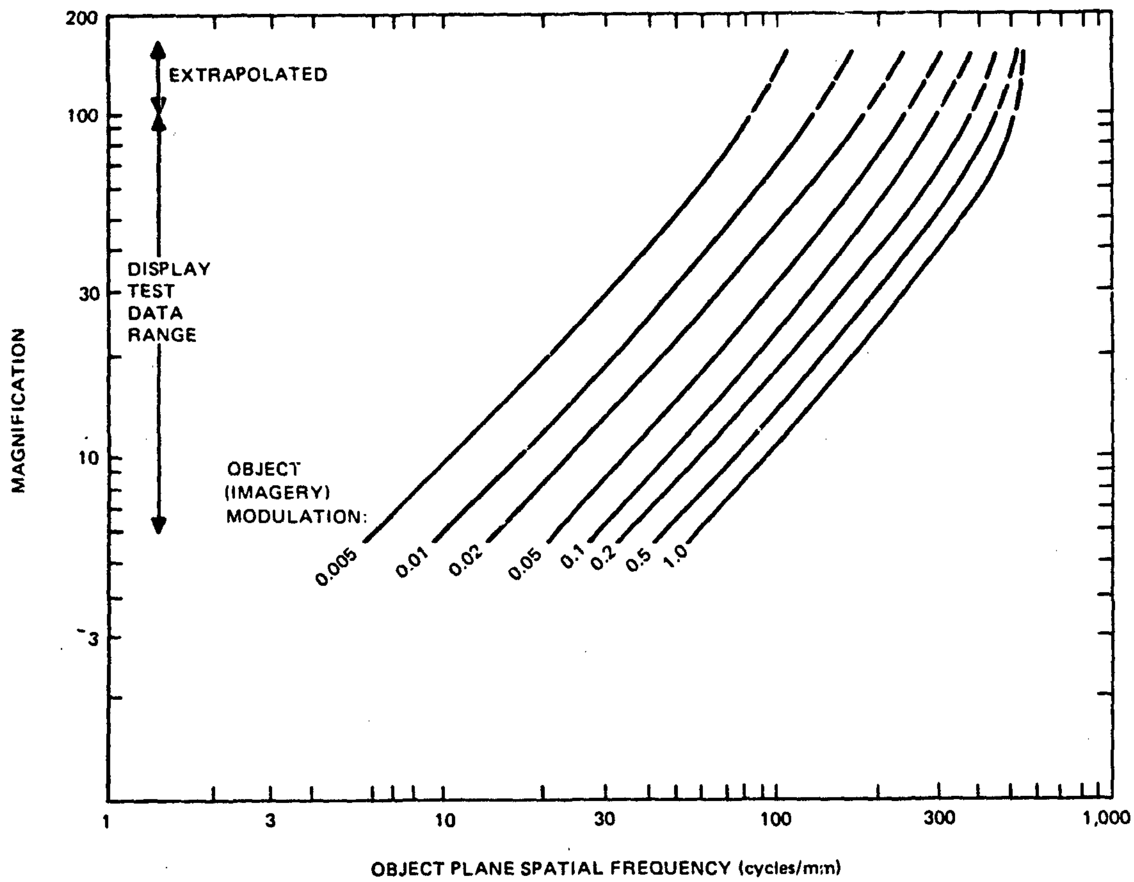


Figure 3.2-12. Display Magnification Required for Specific Object Contrast and Spatial Frequency (Ref. 19). By repeating the computations illustrated in the previous figure at a sufficient number of magnifications, it is possible to determine the minimum detectable modulation for any combination of spatial frequency and magnification within the range of the available display test data.

This information can in turn be used to determine the magnification required to see an object of any particular modulation and spatial frequency. Curves illustrating this function for an average observer are shown here; curves for observers at the extremes of the population sensitivity range are similar but are shifted horizontally.

As the magnification of a given display continues to increase, the modulation loss at the higher spatial frequencies will make the slopes of these curves shift to vertical, indicating that the increased magnification is not providing any increase in visibility.

3.3.4 WAVEFRONT ABERRATIONS

Like the Airy disc approach to analyzing the relationship between display and user discussed in Section 3.3.2, the MTF approach just described ignores several factors. For example, field curvature (Section 3.4.4) can severely degrade the off-axis MTF of a display, but its impact on what the user of a virtual image display can see depends at least in part on whether he has time to change accommodation as he looks around the field. It has been suggested that spherical aberration can also have less effect on the user than on the MTF of the display, because if it is in the proper direction, it will compensate for the spherical aberration of the eye (Ref. 20).

There is at present no experimental evidence to indicate that this compensation will actually happen, and the large variation in spherical aberration between different eyes represented in the average curves in Section 3.4.1 suggests that if it does occur it will be highly specific to particular individuals.

Conversely, the different image distances for differently oriented edges when astigmatism is present may be more troublesome to the user than MTF measurements would predict due to the fact that the user's accommodation control mechanism is faced with a conflict situation (Section 3.4.3). Also, as the data in Sections 3.1.5 through 3.1.10 show, visual performance depends not just on the traditional units of test target size and contrast, but also on the target shape, the number of cycles present, and similar factors.

A more adequate prediction of the performance of the eye/display combination should be possible by considering the distribution on the retina of the light that originated from a single point on the imagery. This distribution, known as the point-spread function, can be obtained from design data or by use of available ray trace equipment (Ref. 21).

A number of analytical approaches, ranging from vague hypotheses to detailed computational models, have been suggested to deal with these aspects of the eye/display combination. One of the more complete models, developed by Overington, includes terms intended to represent the display, the optics of the eye, and the retina (Ref. 20). Neither it nor any of the other models intended for a similar purpose are known to have demonstrated the capability for making useful predictions about the effect of changing specific display parameters.

3.3.5 IMAGERY EFFECTS

As is painfully obvious when silver halide imagery is enlarged excessively, it is made up of many small grains. At lesser enlargements these are not individually visible.

The grain structure of silver halide film is important to the display designer because it may set a much different limit on maximum useful magnification than would be predicted from visual performance measured with grainless targets. In addition, there are display designs, such as the use of coherent illumination, that enhance the visibility of grain at the expense of the details the viewer wishes to see, and it is reasonable to hope that there are designs for which just the reverse will occur. (See Section 3.2.11.3.)

Although grain has been extensively studied (Ref. 22), there is as yet no way to adequately characterize its impact on the visibility of details in the imagery. It is certain, however, that at least in the region where both the grain and the details in the imagery are marginally visible, it plays an important role.

None of the analytical models described in other parts of Section 3.3 treat the effects of grain on visual performance that become obvious whenever a piece of imagery is enlarged excessively. By necessity this factor is included, usually implicitly rather than explicitly, in techniques intended for assessing or predicting imagery quality.

For example, it is common to estimate the resolving power of a particular lens/film combination by combining the lens MTF with a modulation demand curve for the film (Ref. 23). The demand modulation curve is determined by using the particular film and processing being studied with a lens of known MTF to photograph resolution targets that include a range of modulations and spatial frequencies. Resolution readings are made on the imagery by several individuals using whatever display yields the highest value. In order to determine the modulation required in the light distribution arriving at the film surface for a particular spatial frequency target to be visible, the MTF of the photographic lens is removed mathematically. The resulting demand modulation curve can then be combined with the MTF of a different lens in order to obtain an estimate of the resolution that will be obtained with this second lens.

The modulation demand curve obtained in this way depends on the characteristics of two elements in addition to the film. These are the observer and the display he used to make the resolution readings. In theory it should also be possible to mathematically remove the effect of the display and thereby obtain a demand modulation curve for only the film and the observer. This could then be used to estimate the effect of a different quality display. The results, of course, would still suffer from all the shortcomings of using MTF to characterize the display and tri-bar resolution target readings to characterize visual performance. The demand modulation concept has been incorporated into other analytical techniques such as the threshold quality factor (TQF) (Ref. 24) and the modulation transfer factor area (MTFA) (Ref. 25), but no applications directly intended to evaluate the display in this fashion are known.

In the absence of good test data, magnification values used to read resolution targets on imagery provide some very limited guidance on the upper limit of magnification that will be useful. One source reports that the highest resolution values are obtained when the display magnification is approximately equal to the imagery resolution expressed in cycles/mm (Ref. 26,X). Another suggests that the best magnification falls between one-third and 1 times this value (Ref. 27).

3.3.6 RELATIVE RESOLVING POWER

One approach to the analysis of display quality that doesn't fit into the sequence in the previous portions of Section 3.3 is to compare the relative quality of the various system elements in terms of resolving power. This technique attempts to predict the resolving power of the total system from the known resolving power of each element. It suggests that by making the quality of one component sufficiently better than the others, it will have no impact on the total system quality and it can be ignored.

This technique is based on data from photographic systems and high-contrast test targets and as a result is not directly applicable to display design. However, it does illustrate that unless the resolving power of the display is better than the resolution of the imagery, then the display user will be unable to see all the detail present in the imagery.

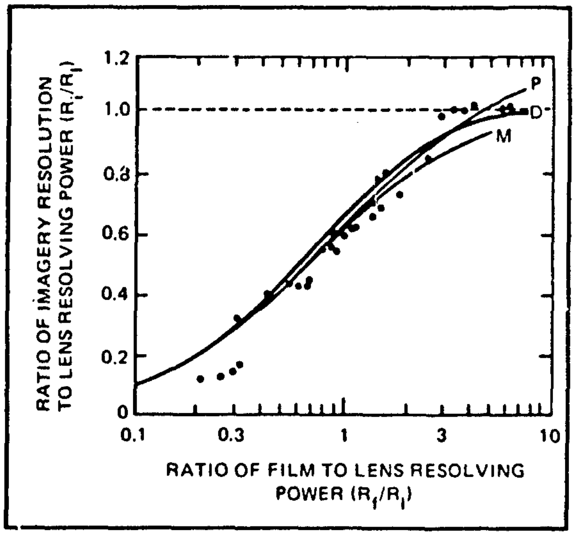


Figure 3.3 13. Relative Lens, Film, and Imagery Resolution. It would be useful to be able to predict the imagery resolution that will occur when a film and a lens of known resolving power are combined. Three equations developed to predict this relationship are illustrated here along with test data for various film/lens combinations (Ref. 28,B). Curve D, which is mathematically simpler than the other two and provides as good a fit is:

$$\frac{1}{R_i^{1.7}} = \frac{1}{R_f^{1.7}} + \frac{1}{R_l^{1.7}}, \text{ where}$$

R_i = imagery resolution,

R_f = film resolving power, and

R_l = lens resolving power.

The data in this figure indicate that if the resolving power of one element of the photographic system, in this case the film, is much greater than the resolution of the second element, the lens, then the imagery resolution obtained depends almost entirely on the resolving power of the poorer element, the lens.

SECTION 3.3 REFERENCES

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   Boutry, G. A. *Instrumental Optics* (translated by Auerbach, R.). Interscience, New York, 1962.

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4. About the only exception to the use of a value of 250 mm (10 in) as a reference distance for magnifying power is in the analysis of optical aids for the partially sighted. In this case, a different reference distance can sometimes provide a better indication of the benefit to be gained from a particular optical aid.

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   Kingslake, R. Illumination in optical images. Chapter 5 in Kingslake, R. (Ed.) *Applied Optics and Optical Engineering*, Vol. II. Academic Press, New York, 1965. See p. 207.

7. The f number is defined as the ratio of the focal length of a lens to the diameter of the largest parallel beam of light that can pass through the lens. As a result, the f number has no meaning unless either the image or the object is located in a focal plane of the lens. See, for example, Ref. 6.

8. See the Kenyon article in Ref. 2.

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10. Fincham, W. H. A. and Freeman, M. H. *Optics* (8th ed.) Butterworths, London, 1974. See Chapter XV.

11. The angular length in image space of an object x millimeters long in object space is xM/250 in radians, or 13.75 xM in arc minutes. Substituting the expression $a = 1.22\lambda/NA$ for x yields $a = 0.0092M/NA$. Substitution of 500/p for M/NA is based on Figure 3.3-1.

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    Also see Ref. 9.

13. See p. 333 of Ref. 9.

14. The relationship plotted here is d = 0.145 pa/NA, where
    d = distance on object in μm
    p = pupil diameter in mm
    a = distance in image in arc minutes
    NA = numerical aperture

15. See Figures 2 and 3 of Ref. 5.

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27. See p. 388 of Ref. 24.

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3.4 ABERRATIONS

3.4.1 Spherical Aberration

3.4.2 Coma

3.4.3 Astigmatism

3.4.4 Field Curvature

3.4.5 Distortion and Image Curvature

3.4.6 Chromatic Aberration

3.4 ABERRATIONS

The failure of the light rays from a single point in the object plane of a display to form a single image point is *aberration*. The aberrations of concern to the designer are the following:

- Spherical aberration
- Coma
- Astigmatism
- Field curvature
- Distortion
- Chromatic aberration

Except for those occasions when it is essential to the development of a particular argument, extensive description of each of these aberrations is omitted here. Most optics texts treat this subject (Ref. 1).

Beyond their obvious direct impact on display image quality as measured in terms of *resolution* or the *modulation transfer function* (MTF), little quantitative data on the impact of these aberrations has been published. What information is available on each aberration is summarized in the six sections below.

Three of the aberrations in this list--spherical aberration, astigmatism, and chromatic aberration--have been measured on the eye. The available data are included in the appropriate sections below. Preliminary results with a recently developed technique for measuring all the aberrations of the eye indicate that coma is also present in most eyes and that spherical aberration is significant for extremely large eye pupils (Ref. 2).

3.4.1 SPHERICAL ABERRATION

Spherical aberration is the difference in refracting power, and hence difference in focus distance, for light passing through peripheral as opposed to axial portions of a lens. Spherical aberration in a display contributes directly to a reduction in image quality as expressed in units such as resolution and MTF. From the point of view of the user, if the image quality expressed in these kinds of units is adequate, there is no need for a separate limit on spherical aberration.

There is some spherical aberration in the eye. As Figure 3.4-1 illustrates, the amount has been overestimated by the authors of some studies, apparently because the tendency of the eye to accommodate to a distance that is a compromise between the target distance and the eye's resting position of accommodation (Section 3.6.2) was not yet recognized.

The summary curves in Figure 3.4-1 and 3.4-2 obscure the very large variation among individuals reported in both studies. To the extent that these variations are not just measurement error, they indicate that spherical aberration has a much greater impact on vision for some individuals than is indicated here.

More accurate techniques have recently been used to measure spherical aberration of a single eye, but the data have not been reported in a form that can be easily compared with the results in Figures 3.4-1 and -2 (Ref. 3).

Attempts have been made to improve vision by the addition of a lens that compensates for the spherical aberration of the eye (Ref. 4, D). The test subjects required an unspecified amount of time to adapt to the compensating lens, after which visual ability was assessed informally as being unchanged. Attempts to eliminate spherical aberration by the use of annular or ringlike pupils have been similarly unsuccessful (Ref. 5).

The variation in *power* across the eye pupil is too irregular to be characterized completely as spherical aberration. In the study summarized in Figure 3.4-2 below, for example, there was considerable variation in the spherical aberration measured in the horizontal as opposed to the vertical meridian. In another study, these variations were mapped over the entire pupil (Ref. 6).

3.4 ABERRATIONS

3.4.1 SPHERICAL ABERRATION (CONTINUED)

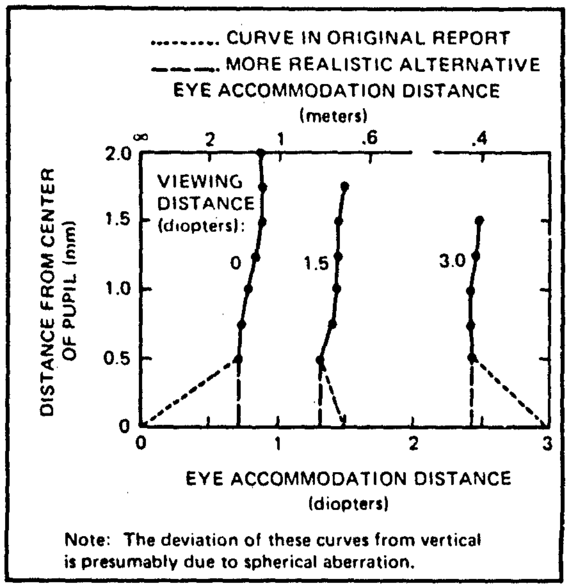

Figure 3.4-1. Spherical Aberration of the Eye. The average dioptric power for 10 eyes (seven subjects) summarized in this figure changed very little over a distance of 0.5 to 2.0 mm from the center of the pupil, indicating very little spherical aberration was present (Ref. 7,C). There was somewhat more irregularity in the curves for the individual eyes.

No measurements were made less than 0.5 mm from the center of the pupil. In the original publication the author assumed that the center of the eye pupil was in focus for the distance to the target, and he extended the curves down to these points. Actually, the eye seldom accommodates exactly to the target distance unless it happens to match the resting position of accommodation (Section 3.6.2). The best available estimate on the accommodation distance for the center of the eye pupil in these studies is therefore the measured accommodation 0.5 mm from the center.

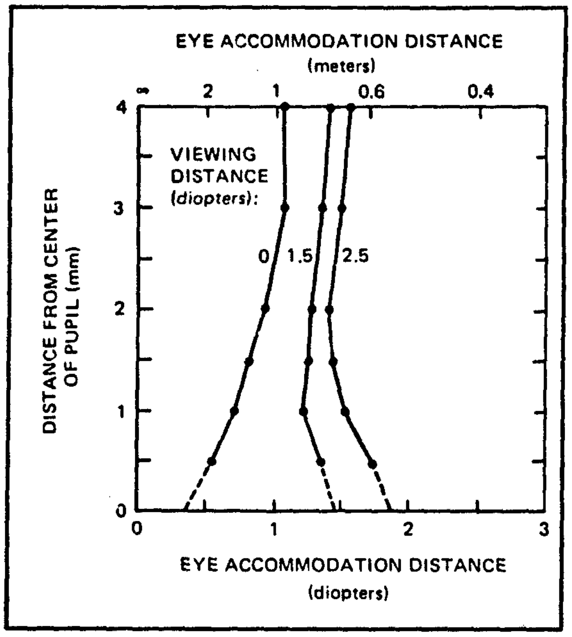

Figure 3.4-2. Spherical Aberration of the Eye. This figure shows the average dioptric power measured across the pupils on 12 eyes (11 subjects) (Ref. 8,C). As in Figure 3.4-1, it is very difficult to determine if the values given for the refractive power at the center of the pupil are valid. They are apparently projections of the test measurements, which started at 0.5 mm.

This curve shows considerably more spherical aberration for the eye than Figure 3.4-1.

3.4.2 COMA

When *coma* is present, the image of a point located off the optical axis appears comet-shaped. Coma in a display results in a blurred image and as a result, a reduction in image quality as measured by a resolving power test or a modulation transfer function test. From the point of view of the user, there is no established requirement for a separate limit on the amount of coma. (Ref. 1)

3.4.3 ASTIGMATISM

Oblique or radial *astigmatism* is an aberration in which an object point located off the optical axis is imaged as a radial line at one distance from the lens and as a line perpendicular to the radial at another distance. The astigmatism produced by a cylindrical lens has a similar effect except that the orientation of one of the lines matches the axis of the cylinder; it occurs over the entire field rather than only at off-axis points; and it is not an abberration. (Ref. 1)

The impact of astigmatism can be measured with grating targets oriented at right angles to each other. For visual measurements, resolution readings should be taken without refocusing the display, and ideally by an individual who is unable to change his accommodation.

The presence of astigmatism, whether as an aberration in the display or as a result of cylindrical power in either the display or the display user's eye, requires the user to choose between two different accommodation distances to obtain the best image. It is likely that this leads to frequent shifts in accommodation as he fixates first on an edge oriented in one direction and then on an edge oriented in another direction. This conflict from having more than one best accommodation may be a significant factor in the severe discomfort caused by relatively small amounts of astigmatism in the eye. For example, astigmatism of more than 0.5 to 1.0 diopter generally requires correction to prevent visual discomfort, while several diopters of spherical focus error, though it may be distressing and make the world appear very fuzzy, generally does not cause discomfort (Ref. 9). There is no known evaluation of the extent to which this is a problem in displays.

3.4.4 FIELD CURVATURE

The aberration known formally as "field curvature" should not be confused with the curved appearance of the image produced by many aerial image displays. This phenomenon is discussed in Section 3.4.5.

When all other aberrations are zero, field curvature is the magnitude by which the image fails to fall on a plane (Ref. 10). For a flat projection screen display, the result of field curvature is evident in the variation in image quality across the screen, and this effectively sets a design limit. For an aerial image display, the design limit derives directly from the fact that if the field curvature exceeds the depth of field, the image will by definition be degraded. The factors that affect depth of field are discussed briefly in Sections 3.8.2 and 3.8.5.

For part of the image field to be out of focus is disturbing for some display users, even though they don't need to look at features in the defocused area. It is not obvious why this occurs, since much normal visual experience is with scenes in which most of the objects are at different distances and can therefore not be in focus simultaneously.

Field curvature tolerances are tighter for large exit pupil displays intended to be used *binocularly* than for ordinary small exit pupil displays (Ref. 11).

A problem that has much the same impact as field curvature is tilt of the object plane relative to the imagery. This occurs with microscopes such as the Bausch and Lomb Zoom 70 and Zoom 240 when operated in the *monoscopic* mode because the two optical axes converge about 10 degrees at the imagery (Ref. 12). The object plane for each axis is therefore tilted 5 degrees from the imagery plane. If the amount of tilt is greater than the depth of field, at least part of the field is out of focus.

3.4.5 DISTORTION AND IMAGE CURVATURE

Distortion is the change in shape of the displayed image relative to the original object. The direction of the distortion is usually described as either pincushion or barrel, defined as in Figure 3.4-3 below. Since distortion changes only the shape of features in the imagery and not how well the user can see them, there is no basis for objectively derived design limits. In most situations, the only significant limit is what the intended users will find acceptable.

Differences in distortion between the images presented to the two eyes in a binocular display are more serious than the amount of distortion. These differences cause a *disparity* between the two images that can be very deleterious. This effect can be especially serious in a *biocular* display, where the disparity may vary with head movement (Ref. 11). Disparity tolerance is treated in Section 3.7.4.

Many aerial image displays produce a strong impression that the edges of the image field are curved toward or away from the user. The preferred term for this phenomenon, which is not an aberration in the usual sense of the term, is *image curvature.* This distinguishes it from field curvature, which is an aberration and is discussed in Section 3.4.4

Distortion is likely to be more of a problem in stereo than in monocular displays. Even though the distortion is the same in the two optical trains of a stereo display, the user will often displace the two images from the centers of the fields by moving the members of the stereo pair closer or farther apart, with the result that the two images will be distorted differently. This will introduce disparity that will probably make the stereo image appear curved and which may interfere with registering them in stereo.

Image curvature occurs even when only one eye is in use, which rules out *lateral disparity* as a cause (Sections 3.7.4.4 and 5.1). At least a portion of image curvature in a typical aerial image display is probably due to distortion. Referring to Figure 3.4-3 below, the shrinkage of details at the edge of the field in barrel distortion is perceptually equivalent to looking down on a hill, and the expansion in pincushion distortion is much like looking into a dish.

Tolerance for image curvature is much lower for a moving image. Many users, though not all, will adapt to a relatively large amount of image curvature in a static image. However, movement of the imagery will make the curvature obvious again.

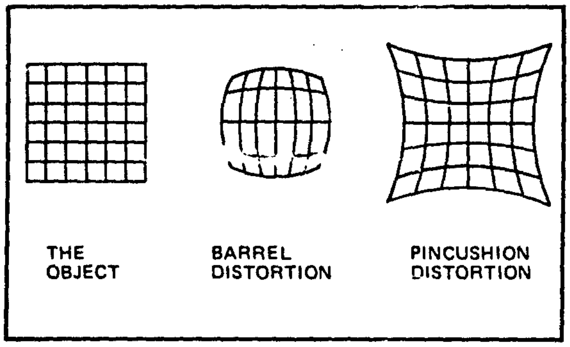

Figure 3.4-3. Barrel and Pincushion Distortion

3.4.6 CHROMATIC ABERRATION

There are no user-based data to support a specific limit on chromatic aberration in a display, but if color fringes can be seen in the image the chromatic aberration is definitely excessive.

The relatively large chromatic aberration of the eye is illustrated in the next figure. For a significant portion of the population, the cues provided by chromatic aberration contribute to the process of accommodation, apparently by providing the eye with information on the direction of the accommodative error (Ref. 12, also Section 3.2.8). If the light is made monochromatic, they will have difficulty accommodating properly, at least until they learn to use some other type of cue.

Compensation of the chromatic aberration of the eye by incorporating equal but opposite chromatic aberration into the display has been suggested as a way to increase what the user can see in the display. Lenses have been constructed that compensate for the chromatic aberration of the eye (Ref. 4). In very limited testing this kind of lens increased the ability of subjects to resolve large, low-contrast details but not small, high-contrast details (Ref. 14,D). It is not possible to estimate whether this result would occur in other viewing situations. This kind of lens is also reported to improve the ability of operators to make color matches in a split-field visual colorimeter, apparently by eliminating color fringes at the border between the two colors (Ref. 4).

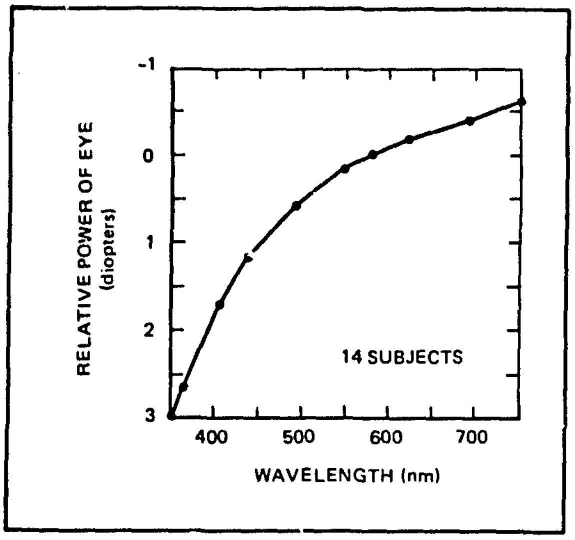

Figure 3.4-4. Chromatic Aberration of the Eye. The refractive power of the eye is greater for short wavelengths than for longer ones (Ref. 15,B). As a result, a normally sighted individual may be nearsighted for a blue object.

The curve here has been arbitrarily shifted so that a wavelength of 578 nm corresponds to a value of 0 diopter.

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3.5 DISPLAY FIELD SIZE

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SECTION 3.5 DISPLAY FIELD SIZE

Many factors influence the choice of an imagery *display field* size. A large field is desirable for several reasons:

- It helps the user see enough ground area at once to understand components of the target in context.
- It can partially compensate for an inadequate imagery translation system.
- Because the eyes can be redirected faster than the image can be repositioned by any imagery translation system, it facilitates the inspection of different areas on the imagery.

Too small a display field can cause specific problems:

- It can reduce visual performance (Sections 3.5.4 and 3.1.5).
- It can reduce search performance efficiency (Section 3.5.5).
- In a microscope-type display, where the image is surrounded by darkness, it may cause an undersirable sensation of tunnel vision.

Too large a display field is also undesirable. In addition to being unnecessarily expensive, it has the following drawbacks:

- It wastes power used to provide illumination, particularly in a projection display.
- It may reduce image quality because of the larger optical elements required and because of the increase in scattered light.
- It is likely to increase the distortion in the periphery of the field.
- Because *eyepiece* size is a function of *eye relief* and field size, it may increase eyepiece size to the point where *interpupillary distance* (IPD) and face clearance problems occur (Section 3.9).
- It may cause some ground areas to be skipped during search, increasing the number of targets that are missed.

With the exception of a general consensus that big is good, there is no basis at present for firm design limits on display field size. Summarizing the numbers developed in this section, extremely small fields, on the order of 5 to 10 degrees, cause problems and should be avoided except in special applications (Section 3.5.4 and 3.5.5). At the other extreme, the user imposes no upper limit on the size of a screen display; if his head is not free to turn, however, as with a binocular microscope, limitations on eye rotation will make an image field much larger than 60 degrees very difficult to use effectively (Section 3.5.3). At least under the conditions tested (Figure 3.5-20), there is no improvement in search performance as the image field size is increased beyond 54 degrees, and only a small, insignificant increase as it is increased from 36 to 54 degrees. A field of 18 degrees is clearly too small for search.

Ideally, determination of display field size should be based on an understanding of how information in an image is received and processed by the display user. As one justification of a large display field, it has been suggested (Ref. 1) that the display user builds up a mental image of a scene by sampling small segments with the central, high-resolution portion of his *visual field*, with the storage of these details somehow aided by the much lower resolution image provided by his peripheral visual field. While this concept is still theoretical, there is experimental evidence that at a minimum the peripheral visual field contributes to the search process by providing information on where next to direct the eye (Ref. 2).

The choice of a display field size depends not just on user variables, but also on how large an imagery area should be visible at one time and on what magnification will allow the essential details in the imagery to be seen. There are no known published data on this topic. However, if the minimum ground area that must be viewed on imagery of a given *scale* can be established, the graphs in Section 3.5.1 can be used to determine the combinations of field size and minimum magnification that will be adequate. (Also see the discussion Section 3.3.1.)

One technique that has been proposed for improving search performance is to provide a very small display field and move it automatically across the area being searched, thereby ensuring that the display operator will not skip any portion of the scene. The available information on this topic is included in Section 4.3.

The concern in this section is primarily with hard-copy rather than real-time imagery displays. The relationships between the many parameters involved in a real-time display, such as sensor field of view, sensor resolution, probable location of a target within the sensor field, display size, display resolution, and vehicle approach velocity, are beyond the scope of this handbook.

3.5.1 TERMS AND GEOMETRY

Two terms used in a specific way when discussing an optical display in this handbook are object space and image space, or simply object and image. For the present purpose, these are distinguished as follows:

- *Object space* or the *object*, refers to the imagery on which the display is focused. Hence distances given "in object space," "on the object," and "on the imagery" are all equal.

- *Image space*, or the *image*, refers to the image which the display forms of the object (imagery). If there are intermediate images, as in a microscope, then if these terms do not include a modifier they refer specifically to the image as seen by the display user. They are defined geometrically, therefore, by the light rays entering the eye.

Two other frequently used terms are display field and visual field. As used here, they differ as follows:

- The *display field* is determined by the optical elements and limited aperture of the display. The display field can be expressed in either object space or image space dimensions.

- The *visual field* refers to the extent of some surface or image as seen by the observer. A visual field must be given in angular units, sometimes known as *visual angle* (Figure 3.1-8), unless the distance from the eye to the surface being viewed is known and specified, in which case linear extent on the surface is also acceptable. The total visual field for the unobstructed eye is shown in Figures 3.5-8 and -9. Figures 3.5-10, -11, and -12 can be used to estimate the visual field over which details of a particular size can be resolved.

The designer usually expresses the size of a display field as linear extent in object space at a given magnification. For example, the field size of the Bausch and Lomb (B&L) Zoom 70 stereoscope when used with the 10X Wide Field (WF) eyepiece is given as 200/M mm (Ref. 3), where M is the magnification. The display user, however, experiences the field in terms of its angular size. A field of 200/M mm, for example, subtends an angle of 43.6 degrees. Graphs are included in this section to facilitate making these kinds of conversions for several different display situations (Figures 3.5-2, -3, -4 and -5).

These figures also simplify consideration of what display size will allow viewing a particular ground area. Suppose, for example, one wishes to display a ground area 200m (650 ft) wide, imaged on 1:40,000 scale photography. Figure 3.5-5 shows that this ground distance corresponds to 5.0mm (0.2 in) on the imagery. Assume that one also knows, either by analysis (Section 3.3) or through experience with this type of imagery, that the display magnification should be 30X. Referring then to Figure 3.5-3, an object field of 5.0 mm viewed at 30X requires an image field of approximately 34 degrees.

3.5.1 TERMS AND GEOMETRY (CONTINUED)

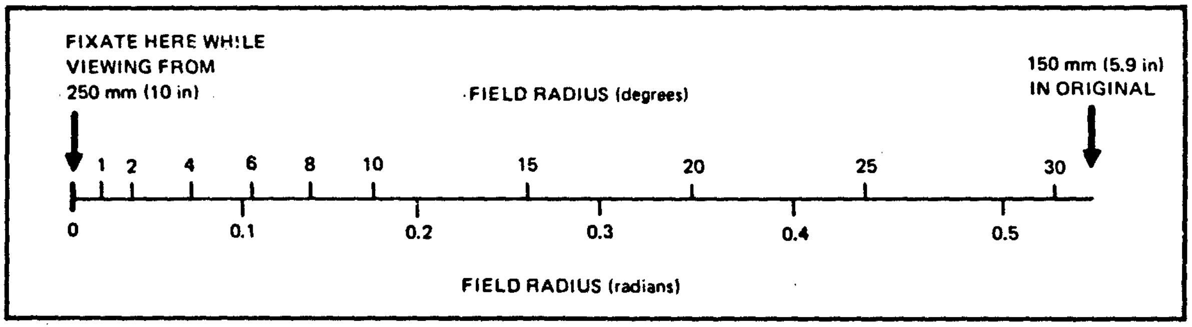


Figure 3.5-1. Image Field Size. When viewed from a distance of 250 mm (10 in), which is equivalent to a magnifying power of 1, this figure illustrates the visual angle subtended by image fields with a diameter of up to 60 degrees (Ref. 4). Because of space limitations, the radius rather than the diameter of the field is shown here.

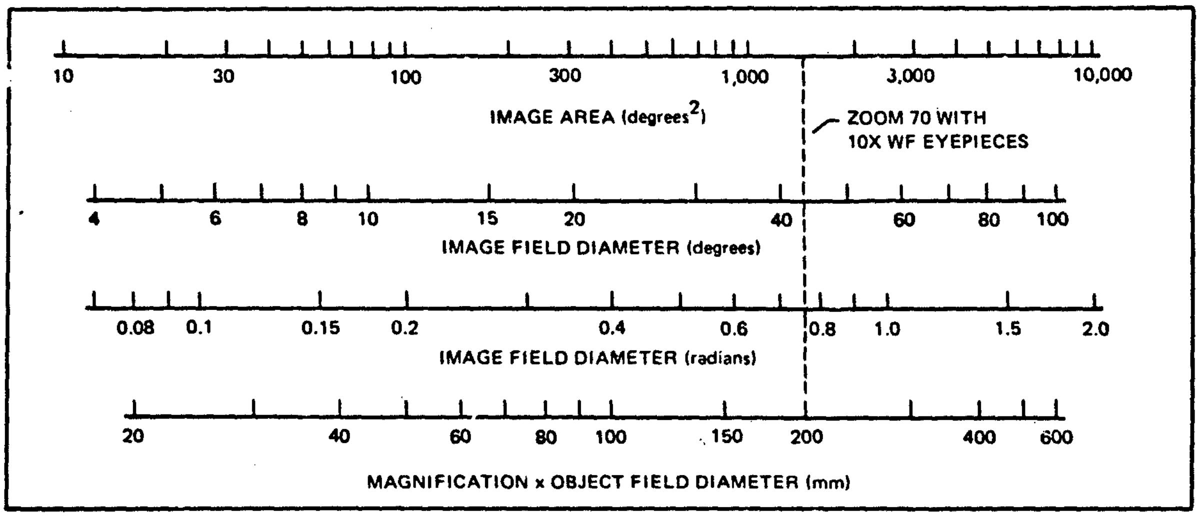


Figure 3.5-2. Typical Display Field Size Units (Ref. 5). Display field size is typically given in terms of the object field diameter, in millimeters, at a given magnification. A common Bausch and Lomb Zoom 70 microscope with a 10X Wide Field (WF) eyepiece, for example, provides an object field of 200/M, where M is the microscope magnification (Ref. 3). At a magnification of 20X, the diameter of the area visible on the object would then be 10 mm.

The user, however, experiences the display field as an image that subtends a particular visual angle, usually expressed in degrees or radians as in the two middle scales.

The upper scale (image area) is included here only to illustrate that image area increases faster than image diameter.

3.5.1 TERMS AND GEOMETRY (CONTINUED)

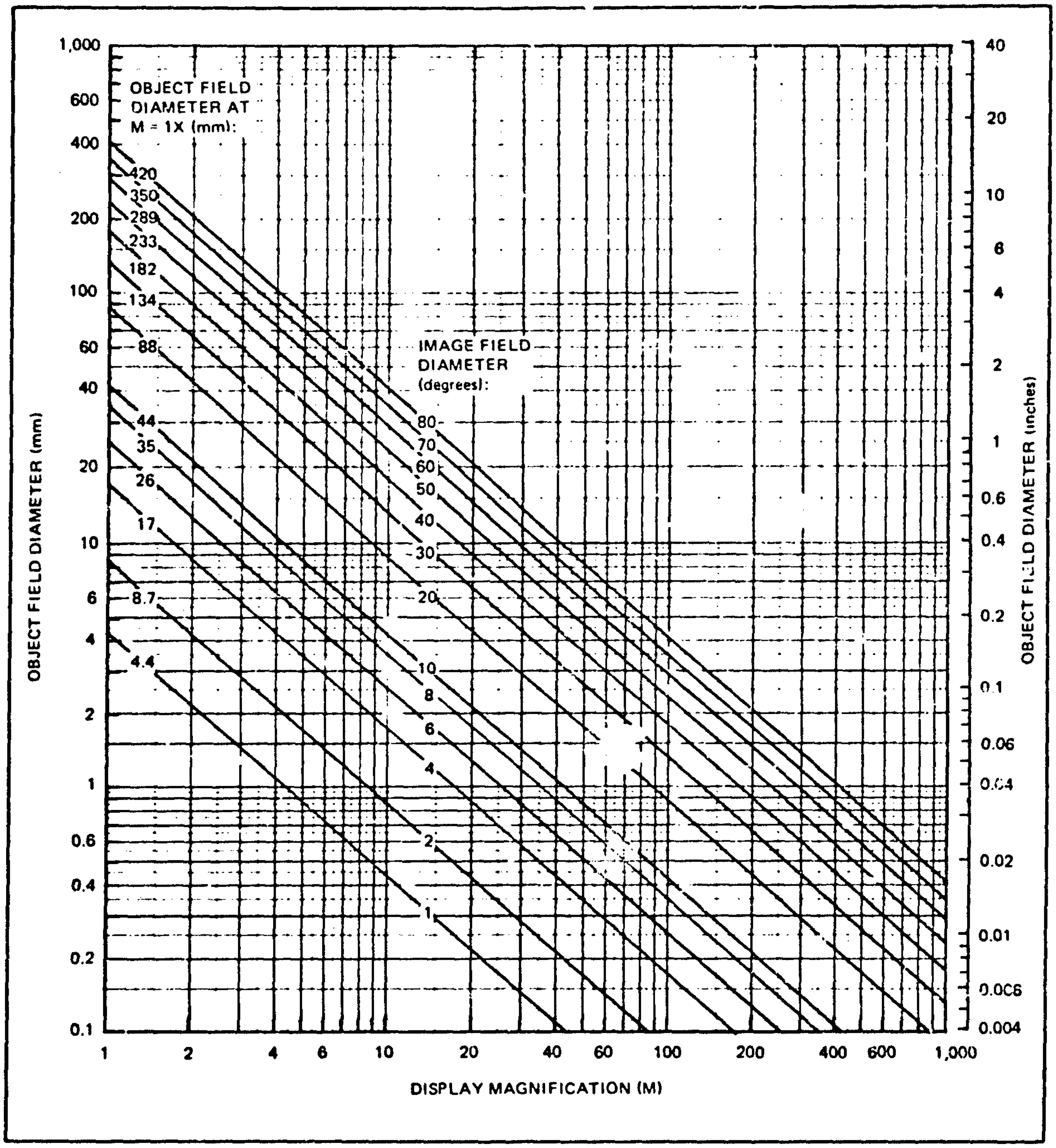


Figure 3.5-3. Relationship of Object Field Size to Image Field and Magnification (Ref. 6)

3.5.1 TERMS AND GEOMETRY (CONTINUED)

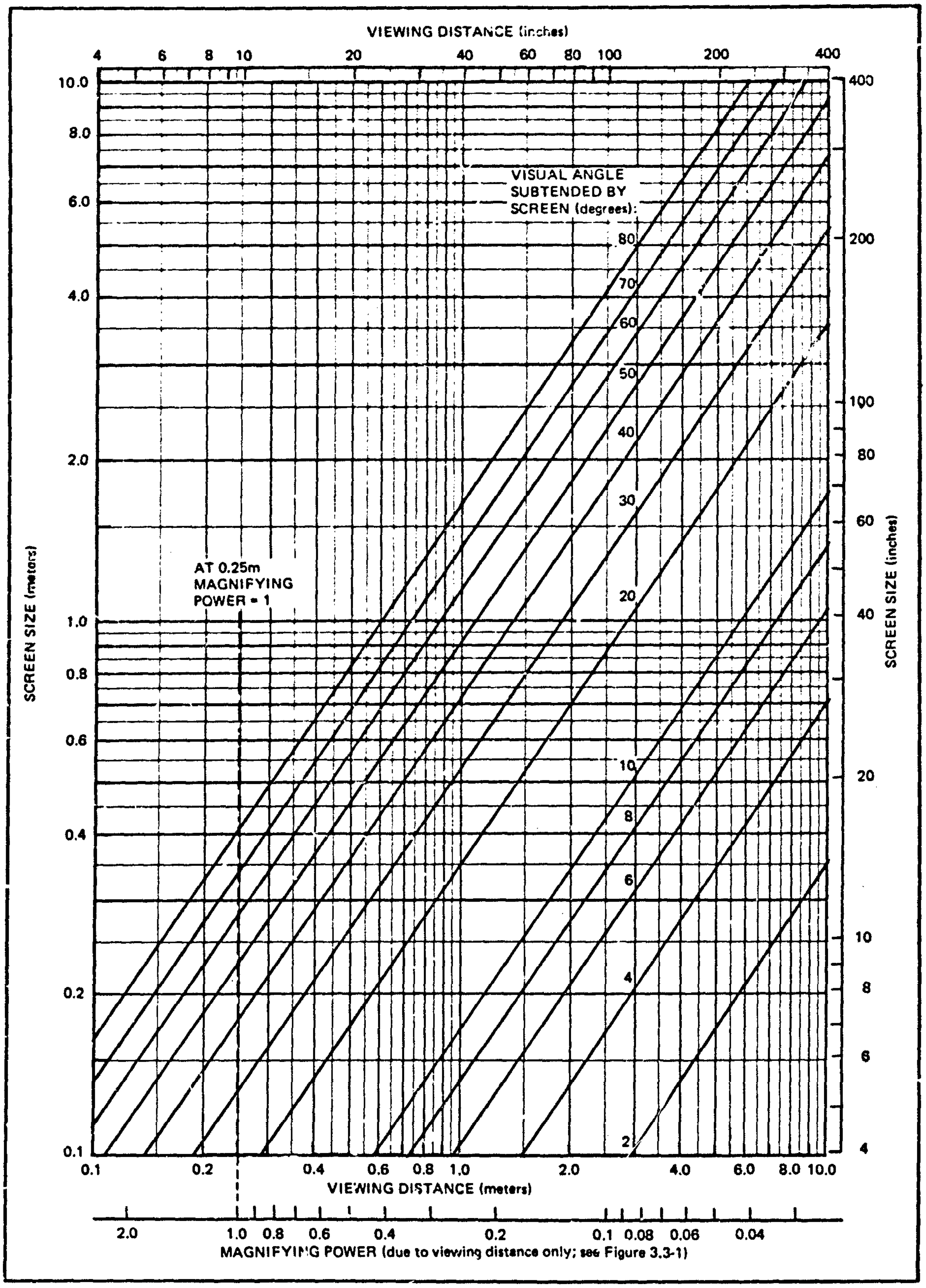


Figure 3.5-4. Impact of Viewing Distance on Image Size for Screen Displays. (continued)

3.5.1 TERMS AND GEOMETRY (CONTINUED)

Figure 3.5-4. Impact of Viewing Distance on Image Size for Screen Displays. The visual angle subtended by a display screen varies with viewing distance, as is illustrated here (Ref. 7). Note that when the magnifying power due to viewing distance is unity, a situation that occurs at the reference distance of 250 mm (10 in) (see Section 3.3), the relationship between screen size and screen visual size is the same as for object and image size at a 1X display magnification in Figure 3.5-3.

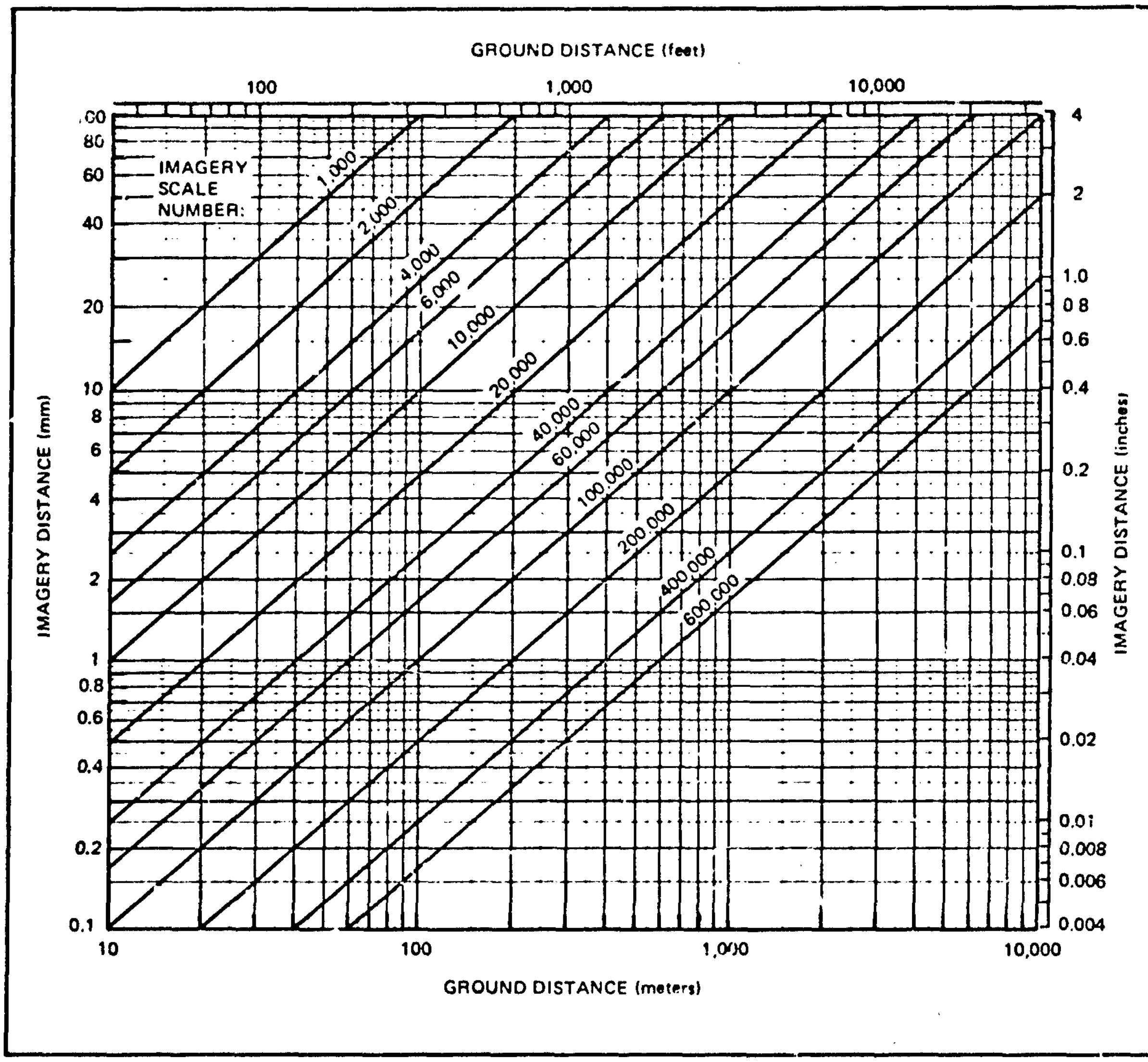


Figure 3.5-5. Relationship of Imagery To Ground Distance. This graph is included as an aid in determining the ground distance that is included in a display field of a given size.

3.5.2 VISUAL FIELD SIZE

Knowledge of the characteristics of the visual field of the eye helps in understanding how the display user makes use of the information present in the image field.

With eye orientation fixed, light can be sensed over a horizontal and vertical extent well in excess of 100 degrees. However, because of the distribution of light receptors and their neural interconnections across the retina, and possibly also because of the optical characteristics of the eye, visual ability decreases rapidly away from the fixation point. Therefore, i` the essential image details are small, the effective visual field extends less than a couple degrees from the point of fixation. A diameter of 2 to 4 degrees is sometimes used in analyses, but as the figures in this section show, the size varies with the task situation.

As a result, in order to study an image area larger than a few degrees, either the display user's eyes must change direction or the image must be moved relative to his eyes. To see details near the edge of a 50-degree-diameter field, for example, approximately 25 degrees of eye rotation relative to the display optical axis is required.

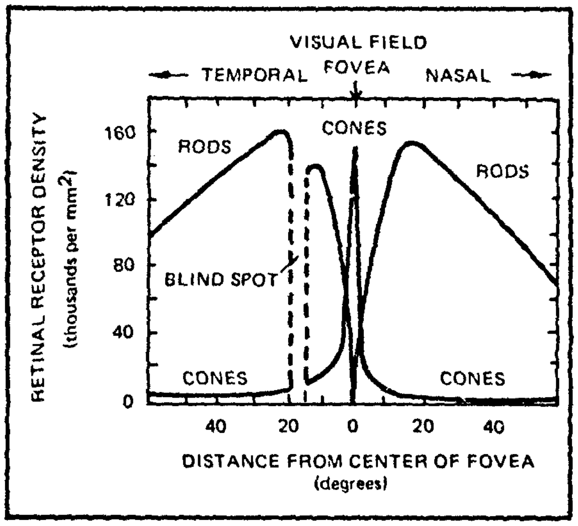


Figure 3.5-6. Distribution of Light Receptors in the Eye. Variation in ability to resolve detail across the visual field is due primarily to variation in the distribution of the two types of light receptors across the retina and to difference in their neural interconnections. The receptors that operate at the luminance levels used in imagery displays, the cones, are most numerous at the center of the fovea, which corresponds nominally to the fixation point of the eye, and decrease rapidly toward the perphery of the eye (Ref. 8, B).

The other receptors, the rods, are absent at the center of the fovea and increase to a maximum density approximately 20 degrees into the periphery. The rods function at much lower light levels than normally occur in imagery displays and can be ignored for present purposes (see *Section 3.2*).

3.5.2 VISUAL FIELD SIZE (CONTINUED)

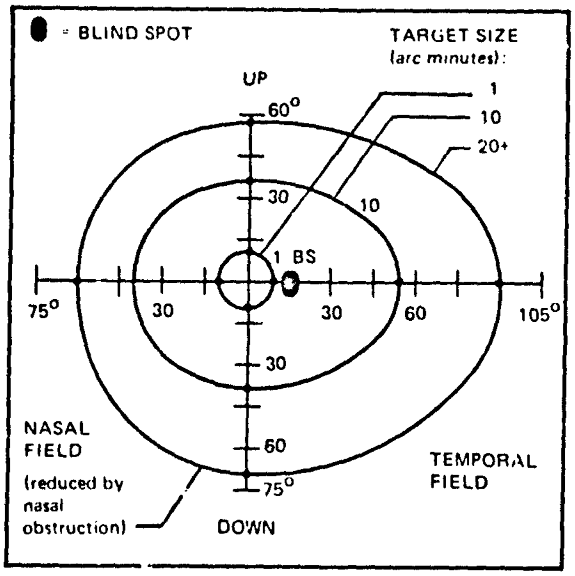


Figure 3.5-7. The Normal Achromatic Visual Field. The approximate size of the normal visual field for the right eye is illustrated. These plots are based on data from several different sources (Ref. 9,X) and are included here to illustrate general magnitudes and trends, not as design data. They were usually obtained by asking subjects whether they could see a white disk of the specified size against a dark background. These fields normally increase with an increase in any variable that increases the visiblity of a target, such as luminance, target size, and exposure time.

These curves are based on test data only at the horizontal and vertical axes of the visual field. The ellipses fitted between adjacent data points are probably realistic except for the lower left-hand quadrant, where the nose may limit the visual field.

As these curves illustrate, increasing the size of the target disc increases the area over which it can be detected and changes this area from a circle to an oval that extends farthest in the temporal direction.

The area on the retina where the optic nerve exits the eye contains no receptors and is known as the *blind spot.* Only under special viewing conditions is the observer aware of this empty region in the visual field.

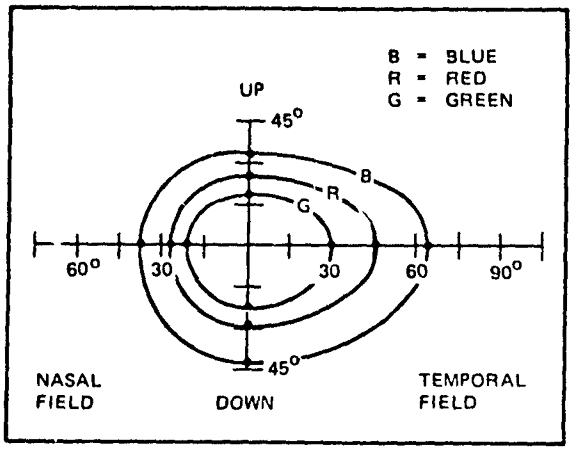


Figure 3.5-8. Normal Visual Fields for Color. What are usually referred to as normal visual fields for color, averaged across three studies, are illustrated here (Ref. 10,X). As in Figure 3.5-7, an ellipse is fitted between adjacent data points.

Because visual fields for color are affected by so many variables, this and other color field data must be evaluated carefully to determine if it is relevant before it is used in a specific design problem. Among the more important reasons for variation in color field measurements are the following:

- The task—The field for identifying the color of a target is smaller than the field for simply detecting the target. A task involving the identification of a feature of the target, such as the orientation of a grating, will yield a third field size.
- The relative radiant energy level—Visual field size for achromatic targets increases with target luminance. Proper matching of the luminance of colored targets is not simple and may not be appropriate for all purposes. In one study, the particular method used to equate green and blue targets resulted in identical visual fields for these colors (Ref. 11).

3.5.2 VISUAL FIELD SIZE (CONTINUED)

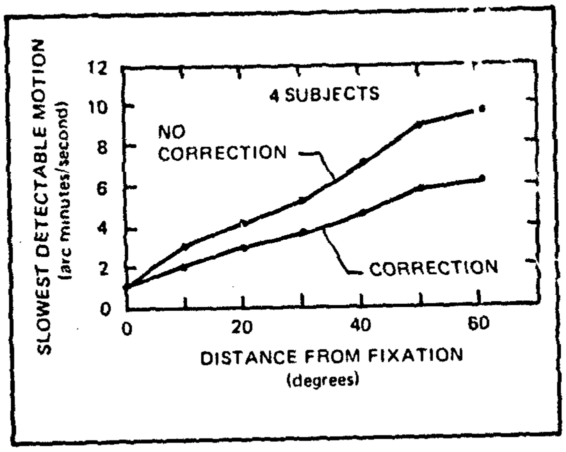


Figure 3.5-9. Correction of Peripheral Refractive Error. In most eyes, the periphery of the visual field is characterized by an increase in *refractive error* and by an increase in the *astigmatic* component of the refractive error (Ref. 12).

In order to assess the contribution of this increase in refractive error to the reduction in vision in the periphery, visual performance was first measured at several points across the visual field while the test subject used the optimum correction for that part of the visual field and tested again while he used only his normally determined spectacle correction. In the study illustrated here, the task was to detect the motion of a 1-degree-square white test target (Ref. 13,B). Although the correction did not make motion detection as good in the periphery as it was at the fixation point, it did make it better than when no special peripheral correction was used.

In a subsequent study, visual ability was measured in terms of the smallest grating that was reported to be visible and in terms of the smallest Landolt ring in which the gap could be detected (Ref. 14,B). For these tasks, the use of a peripheral refraction correction had no effect on the reduction in visual ability away from the fixation point.

3.5.2 VISUAL FIELD SIZE (CONTINUED)

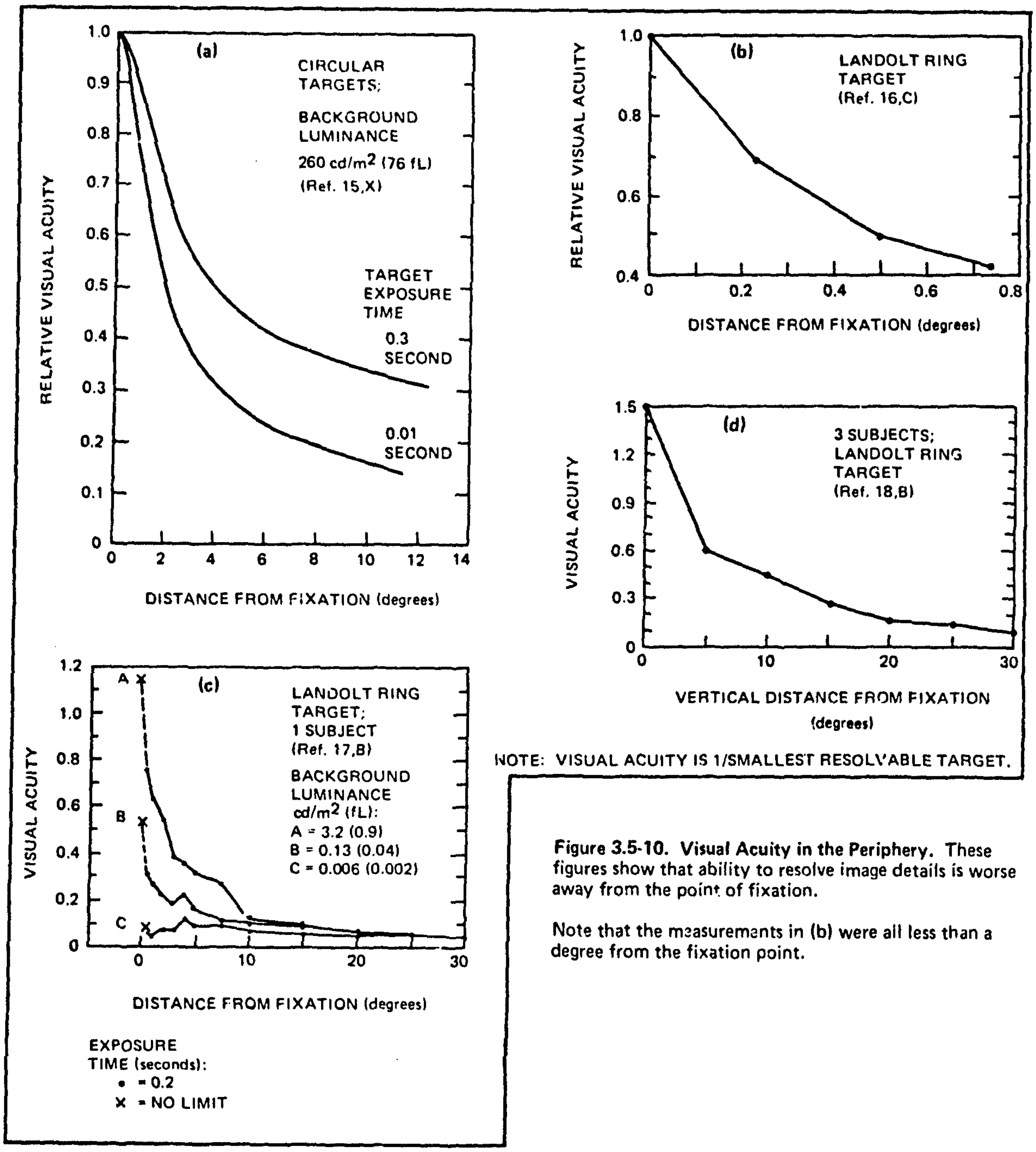


Figure 3.5-10. Visual Acuity in the Periphery. These figures show that ability to resolve image details is worse away from the point of fixation.

Note that the measurements in (b) were all less than a degree from the fixation point.

3.5.2 VISUAL FIELD SIZE (CONTINUED)

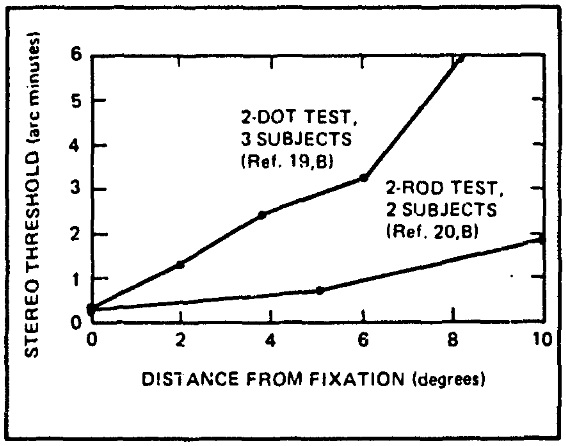


Figure 3.5-11. Stereo Acuity in the Periphery. This figure illustrates the fact that ability to distinguish differences in distance is also worse as a function of distance from the fixation point.

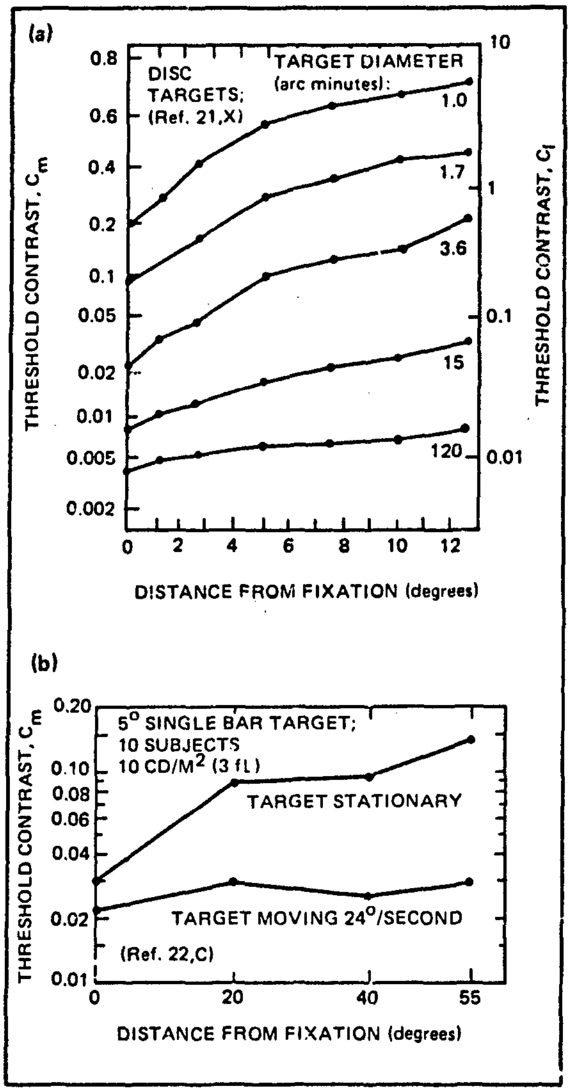


Figure 3.5-12. Contrast Sensitivity in the Periphery. These figures illustrate that the ability to distinguish small differences in luminance between a target and its background also decreases with distance away from the fixation point, at least for stationary targets. Part (a) of this figure is based on the same experimental techniques as Figure 3.1-16. Background luminance was 257 cd/m^2 (75 fL) and target duration was 0.33 second.

Part (b) shows that sensitivity for a moving target tends to remain constant into the periphery.

3.5.3 EYE ROTATION GEOMETRY

RECOMMENDATION:

In an aerial image binocular display with small exit pupils, do not expect the operator to make efficient use of an image field larger than 60 degrees.

Because the eye does not rotate around the eye entrance pupil, alignment problems can occur when the user of a microscope type of display turns his eye to look at various portions of the image field. Within limits, most users are not aware of the lateral head movements they make to compensate.

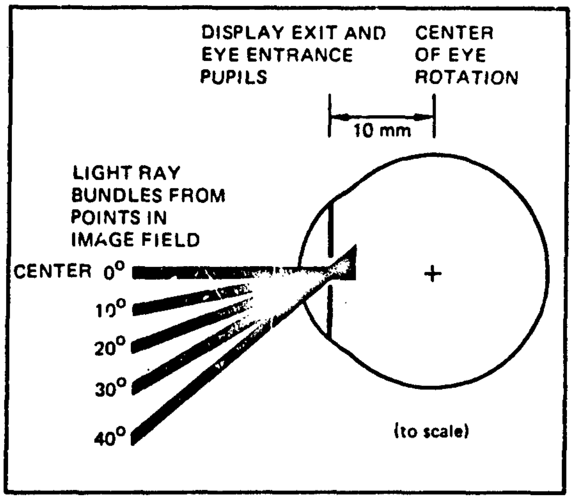


Figure 3.5-13. Eye Orientation Display Optical Axis. The center of rotation of the eye is approximately 13 mm behind the front surface of the cornea (Ref. 23), which places it approximately 10 mm behind the entrance pupil of the eye. As a result, when the user of a microscope type of display turns his eye to look at an off-axis portion of the image, the microscope exit pupil is no longer centered in his eye entrance pupil.

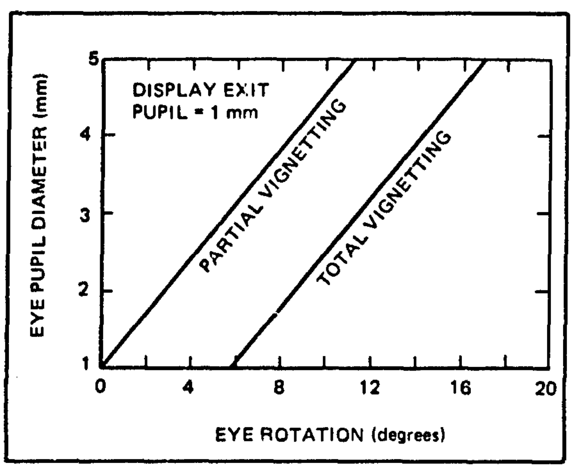


Figure 3.5-14. Vignetting as Eye Rotates. Because of the situation illustrated in the previous figure, if the microscope user turns his eye too far while keeping his head position fixed, some or all of the light from the microscope will no longer enter his eye. These two curves illustrate the amount of eye rotation at which this condition, known as *vignetting*, begins and becomes total (Ref. 24). Taking a typical eye pupil diameter of 3 mm as an example, vignetting would start with an eye rotation of 5.7 degrees and would be total with a rotation of 11.3 degrees.

3.5.3 EYE ROTATION GEOMETRY (CONTINUED)

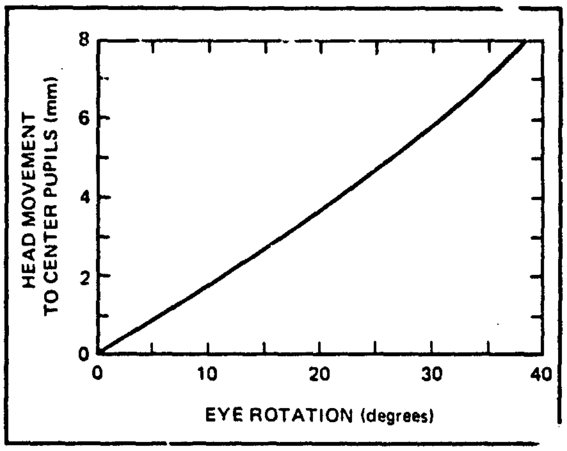


Figure 3.5-15. Head Movement Required to Compensate for Pupil Movement. In order to prevent vignetting as the eye is turned, the display user must move his head to compensate. Thi: figure illustrates the amount of head movement required to keep his pupils centered (Ref. 25). As an example, to turn from the center to the edge of a 50-degree diameter image field would require ab›ut 4.5 mm of head movement. Most display users make these compensating movements automatically and without ever becoming aware of them.

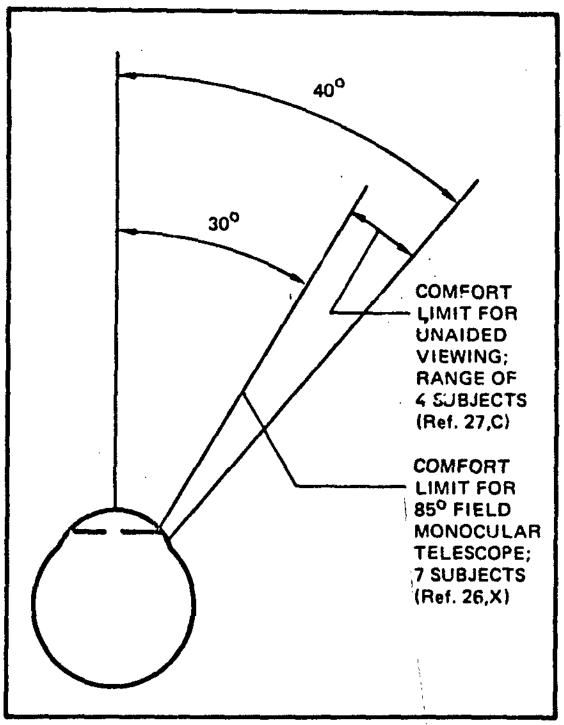


Figure 3.5-16. Eye Rotation Li‹ ›s. In unaided viewing, or whe‹ viewing a projection sc‹ ›n, the ability to rotate the head eliminates the need for la‹ ›e eye rotations within the head. However, with a binocular display that requires each eye to be at a relatively fixed distance from the eyepieces, head rotation is virtually eliminated. As a result, useful field size is at least partially limited by how far the eyes can rotate comfortably. The very limited information available on this topic is summarized here.

The author of the study with the monocular telescope states ". . . eye rotation beyond 30 degrees, while physically possible, was uncomfortable; usually the subject preferred to rotate his head. . . beyond the 30-degree eye-rotation angle. . . ." Apparently this was a general observation, not based on any direct measurements on each of the subjects.

For the four subjects, head position was fixed and they were asked to indicate the limits for comfortable prolonged viewing of an imaginary rear projection screen. Data were collected for each eye separately, without moving the head, and the smaller values in each direction were averaged. The range of average values for the four subjects is illustrated.

3.5.4 DISPLAY FIELD SIZE AND VISION

The available data suggest that display field size may affect visual performance, but only when the field is much smaller than would be found in most imagery displays. Additional data on this topic are summarized in Section 3.1.5.

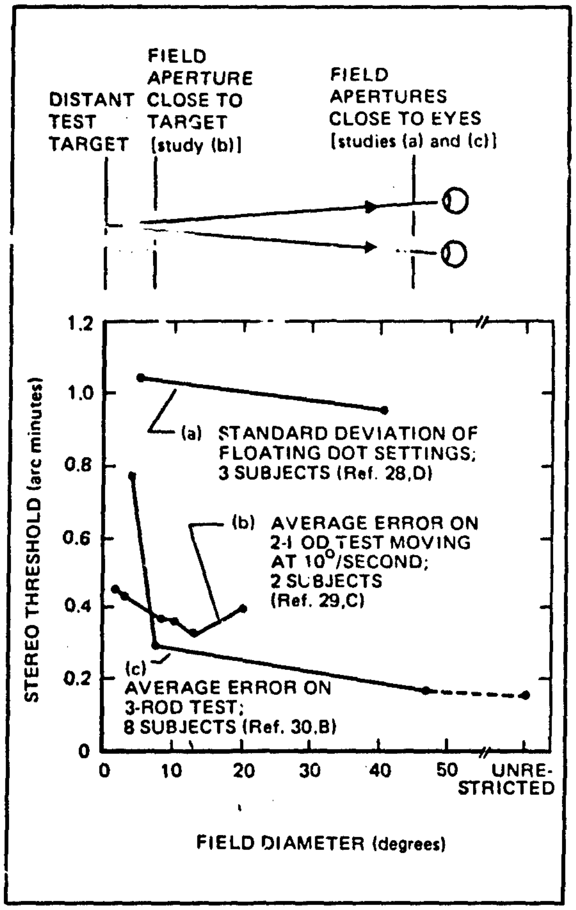


Figure 3.5-17. Field Size and Stereo Acuity. Although the studies illustrated provide some evidence that extremely small fields can reduce ability to distinguish differences in depth, there is no indication of any significant variation over the range of field sizes of concern to the display designer.

The variation in visual performance in Study (b) may be due to aperture size, or it may be due to target exposure time which varied along with aperture size. Whichever factor caused the variation in performance with apertures smaller than 10 degrees, there was little if any improvement as the field was increased from 10 degrees to 20 degrees.

3.5.5 DISPLAY FIELD SIZE AND SEARCH PERFORMANCE

RECOMMENDATION:

For a display that will be used for search, provide a display field with a diameter of at least 36 degrees, with a preferred minimum of 45 to 55 degrees.

The very limited data available on image field size and search performance are summarized below. The first figure suggests that the image-field diameter should be at least 9 degrees and the second suggests that it should be at least 34 degrees but probably need not be more than 54 degrees.

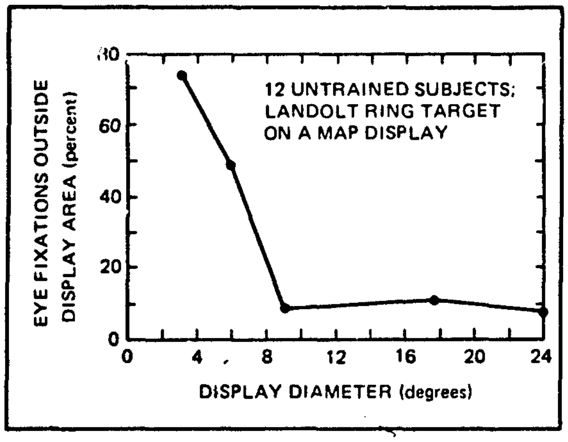


Figure 3.5-18. Visual Search Behavior with Small Display Fields. With extremely small fields, visual search efficiency may suffer because of time lost while looking outside the display area. In the experiment illustrated, this effect occurred with fields smaller than 9 degrees (Ref. 31,B).

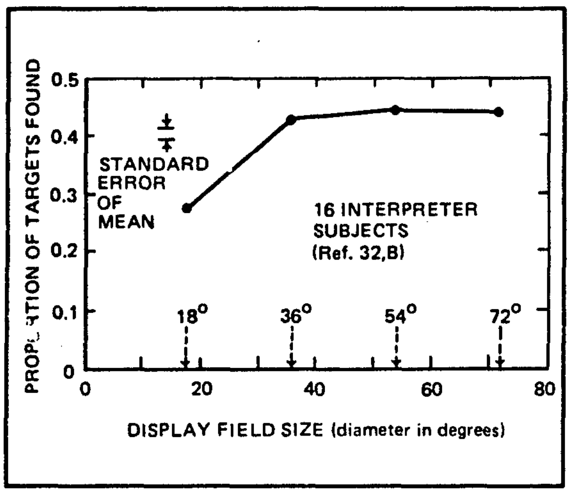


Figure 3.5-19. Field Size and Search Performance. A high quality experimental *microstereoscope* with a 72-degree image field was used to measure the impact of field size on search performance. Sixteen interpreters searched for a range of different sized targets, such as electronic sites, transformer substations, active construction site, missile sites, and air fields on small-scale, high-resolution imagery. The imagery was not in stereo, so two copies were made and mounted in registry on the two film stages in order to provide a binocular monoscopic viewing situation.

As the graph illustrates, there was a large increase in target detection success, from 27.6 to 42.8 percent as the field was enlarged from 18 degrees to 36 degrees. This change was statistically significant at $P < .01$. With a further enlargement of the field to 54 degrees, performance increased to 44.2 percent, a change that was too small to be statistically significant.

The interpreters who served as test subjects in this experiment were accustomed to microscopes utilizing Bausch and Lomb 10X WF eyepieces, which have a field of approximately 44 degrees (Section 3.5.1). It is possible that this experience prevented their taking full advantage of the larger fields used in the test.

The display used in this experiment incorporated an excellent manual imagery translation system, at least for the purposes of the test. Absence of an adequate imagery translation capability would probably make a large image field more important.

1. This concept was suggested to the author by John Merritt of Human Factors Research, Goleta, California.

2. Williams, L. G. Studies of extrafoveal discrimination and detection. In *Visual Search*, National Research Council/ National Academy of Sciences, Washington, D.C., 1973, pp. 77-92.

3. *Zoom 70 Stereoscope Model II Instruction Manual* (1st ed.). Bausch and Lomb, Rochester, New York, no date.

4. The field diameter in millimeters at 250 mm is 500 tan $\theta/2$, where θ is the field diameter in degrees.

5. The object field diameter x magnification is 500 tan $\theta/2$, where θ is the image field diameter in degrees.

6. The object field diameter in millimeters is (500/M) tan $\theta/2$, where M is magnification and θ is the image field diameter.

7. Magnifying power (MP) is 0.25/VD, where VD is viewing distance in meters.

   Screen size in degrees is 2 arctan (SS/2) (MP/0.25), where SS is screen size in meters and MP is magnifying power.

8. Osterberg, G. Topography of the layer of rods and cones in the human retina. *Acta Ophthal. Suppl.*, Vol. 61, 1935, pp. 1-102.

   This plot of Osterberg's data is adapted from Figure 29 of Pirenne, M. H. *Vision and the Eye*. Chapman and Hall, London, 1948.

9. The points in Figure 3.5-7 were obtained from a curve fitted visually to the data in Table XIV-5 of Ref. 10.

   Also see: Harrington, D. O. *The Visual Fields*. Mosby, St. Louis, 1964. See Table 2, p. 116.

10. Borish, I. M. *Clinical Refraction* (3rd ed.). Professional Press, Chicago, Illinois, 1970. See Tables XIV-2, -3, -4, and -5, each of which contain data.

11. Berk, M. A critical evaluation of color perimetry. *Arch. of Ophthal.*, Vol. 63, 1960, pp. 966-977. This study has no quality rating because it is too difficult to determine how radiance was equated.

12. Lotmar, W. and Lotmar, T. Peripheral astigmatism in the human eye: Experimental data and theoretical model predictions. *J. Opt. Soc. Am.*, Vol. 64, 1974, pp. 510-513.

    Millodot, M. and Lamont, A. Refraction of the periphery of the eye. *J. Opt. Soc. Am.*, Vol. 64, No. 1, 1974, pp. 110-111.

13. Johnson, C. A. and Leibowitz, H. W. Practice, refractive error and feedback as factors influencing peripheral motion thresholds. *Perception and Psychophysics*, Vol. 15, 1974, pp. 276-280.

14. Millidot, M. Leibowitz, H. W., Johnson, C. A. and Lamont, A. Effect of peripheral dioptrics on visual acuity. *Vision Research*, in press, 1975.

15. Blackwell, H. R. and Moldauer, A. B. *Detection Thresholds for Point Sources in the Near Periphery*. Project 2455, University of Michigan Engineering Research Institute, 1958.

    Taylor, J. H. *Contrast Thresholds as a Function of Retinal Position and Target Size for the Light-Adapted Eye.* REF. 61-10, Scripps Institution of Oceanography, 1961.

    Both cited in Grether, W. F. and Baker, C. A. Visual presentation of information. Chapter 3 in Van Cott, H. P. and Kinkade, R. G. (Ed.), *Human Engineering Guide to Equipment Design*. Government Printing Office, Washington, D.C., 1972.

16. Jones, L. A. and Higgins, G. C. Photographic granularity and graininess. III. Some characteristics of the visual system of importance in the evaluation of graininess and granularity. *J. Opt. Soc. Am.*, Vol. 37, 1947, pp. 217-263.

17. Mandelbaum, J. and Sloan, L. L. Peripheral visual acuity. *Am. J. Ophthal.*, Vol. 30, 1949. pp. 581-588.

18. Millodot, M. and Lamont, A. Peripheral visual acuity in the vertical plane. *Vision Res.*, Vol. 14, 1974, pp. 1497-1498.

19. Rawlings, S. C. and Shipley, T. Stereoscopic acuity and horizontal angular distance from fixation. *J. Opt. Soc. Am.*, Vol. 59, 1969, pp. 991-993. The values plotted are the mean setting errors for the 24 trials for each of the three subjects at each angular distance from fixation.

20. Blakemore, C. The range and scope of binocular depth discrimination in man. *J. Physiol.*, Vol. 211, 1970, pp. 599-622.

21. Original source is Blackwell and Moldauer (Ref. 15); data cited in Taylor, J. H. Use of visual performance data in visibility research. *Appl. Optics*, Vol. 3, No. 5, 1964, pp. 562-569.

22. Rogers, J. G. Peripheral contrast thresholds for moving targets. *Human Factors*, Vol. 14, No. 3, 1972, pp. 199-205.

23. For purposes of spectacle design, the center of rotation has usually been taken as 13 mm behind the cornea. See, for example, p. 67 of Fry, G. A., The eye and vision. Chapter 1 of Kingslake, R. (Ed.), *Applied Optics and Optical Engineering* (Vol. II). Academic Press, New York, 1965.

The exact value averages slightly more than 13 mm and varies among individuals and within an individual as a function of eye rotation. See Section 3.1.1 and Fry, G. A., and Hill, W. W. The center of rotation of the eye, *Am. J. Optom.*, Vol. 39, No. 11, 1962, pp. 581-595.

24. Assuming an eye entrance pupil to center of rotation separation of 10 mm, vignetting begins at an eye rotation, in degrees, of arc tan $(p_e/20)$ - arc tan $(p_i/20)$ and is complete at a rotation of arc tan $(p_e/20)$ + arc tan $(p_i/20)$, where p_e is the eye entrance pupil and p_i the instrument exit pupil, both in millimeters.

25. Assuming an eye entrance pupil to center of rotation separation of 10 mm, the head movement required to keep the eye entrance pupil stationary is 10 tan ϕ, where ϕ is eye rotation in degrees.

26. Spiro, I. J. Eye location for a wide-field large-exit-pupil optical system. *J. Opt. Soc. Am.*, Vol. 51, No. 1, 1961, pp. 103-104. The X rating on this study results from the fact that the author did not report the test conditions.

27. Unpublished study by the senior author in 1972. Four subjects who did not wear spectacles were tested. Each kept his head fixed while turning each eye, one at a time, left and right as far as he felt would be comfortable for prolonged viewing of a screen-type display. Eye rotation was calculated from the extreme fixation point reported and the four rotation angles for each subject were averaged. The arrow in the figure indicates the range of average values for the four subjects.

28. Kraft, C. L., Elworth, C. L. and Diederich, P. *Influence of Optical Field Flatness, Field of View and Reticle Brightness on Floating Dot Reticle Placement.* Document D180-19055-1, The Boeing Company, Seattle, Washington, 1968. Stereo aerial photographs were projected on a screen at 3m (9 ft) with polarizing filters on the projectors and before the subject's eyes in order to present one of the two photos to each eye. Because of the large variability in the data, there was one chance in four (0.25) that the stereo acuity difference between the two fields of view was due to chance. The distance scale could only be read by the experimenter to a precision of 1 arc minute.

29. Lit, A. and Vicars, W. M. Stereoacuity for oscillating targets exposed through apertures of various horizontal extents. *Perception and Psychophysics*, Vol. 8, 1970, pp. 348-352.

30. Luria, S. M. *Stereoscopic and Resolution Acuity With Varying Field of View.* Report 557, U.S. Naval Submarine Medical Center, Groton, Conn., 1968 (AD 685229). The 3-rod Howard Dolman test was 5.5m (18 ft) from the subject and the apertures were 0.15m (0.5 ft) away. Visual acuity was also measured in this study but did not vary as a function of field size.

31. Enoch, J. M. Effect of the size of a complex display upon visual search. *J. Opt. Soc. Am.*, Vol. 49, No. 3, 1959, pp. 280-286.

32. Farrell, R. J. and Anderson, C. D. *The Effect of Display Field Size on Interpreter Performance.* Boeing Document D180-19056-1, The Boeing Company, 1973.

3.6 VIEWING DISTANCE

3.6.1 Accommodative Range of the Eye

3.6.2 Resting Position of Accommodation (RPA)

3.6.3 Preferred Microscope Focus Setting

3.6.4 Visual Performance and Viewing Distance

3.6.5 Screen Displays

RECOMMENDATIONS

Provide an image distance in a binocular aerial image display that is compatible with the eye convergence angle (Section 3.7.4.2).

Provide an image distance in an aerial image display of 0.5 to 1.5 diopters (2.0 to 0.67m, or 80 to 26 in).

The minimum viewing distance for real-image displays such as rear screen projectors is 0.40m (16 in). To maintain best vision the maximum is 2m (80 in). Group displays may require greater distances. If the user must reach controls on the display the maximum is 0.71m (28 in). (Section 3.6.7.)

The display *viewing distance*, or separation between the display user's eye and the image being viewed, is important because it determines the eye *accommodation* required to focus the image on the *retina*. For *screen displays*, though not for *aerial image displays*, viewing distance also has an effect on the relative size of the retinal image (see *magnifying power* in Figure 3.3-1).

The image experienced by the user of a screen display is fixed in space at an obvious location, the screen, and there is no question about how viewing distance is measured. Because the specification of viewing distance is less apparent in an aerial image display, it is defined in Figure 3.6-1.

Some of the variables that affect selection of a best display viewing distance are discussed in this section. Some of these, such as microscope focus preference data (Section 3.6.3), apply only to aerial image displays. The special features of a screen display that may require it to be placed at a particular distance are discussed in Section 3.6.5.

As Figure 3.6-1 illustrates, the user of an aerial image display can place the image in such a display at whatever viewing distance he chooses simply by turning the focus knob. There are, however, several reasons why the designer of an aerial image display may need to fix the image distance:

- This may be the only image distance for which the display is *parfocal*, or remains in focus, as the magnification is changed (Section 3.8).
- In a display that incorporates a television camera tube in order to provide a television display of the aerial image, either at the display or at a remote location, the image must be in focus on the face of the camera tube.
- If a reticle is present, it must be at the same optical distance as the image.
- In theory, at least, this is the image distance for which the optical design should provide the best image quality. However, with most common types of aerial-image displays, large variations in image distance have little or no effect on image quality and it is adequate for the designer to simply assume that the image plane is at any convenient distance.

One drawback of fixing image distance in an aerial image display is that almost all spectacle wearers will then be forced to use their spectacles with the display. (The percentage of users who wear spectacles is discussed in Section 3.9.5.)

In a *binocular* display, image distance interacts closely with the convergence angle between the optical path to each eye. This subject is treated in Section 3.7.4.2.

As is mentioned in Section 1.2, the discussion and analyses in this handbook are limited to *emmetropic* individuals (those with normal sight) unless some other group is explicitly mentioned. The most distant point of accommodation for an emmetrope is approximately infinity, or 0 diopter (see Figure 3.8-2).

With the exception of Figures 3.8-9 and -10, there is only a little information available on visual ability when target distance and eye accommodation distance do not match. The kind of information that is available is illustrated by Figure 3.6-2.

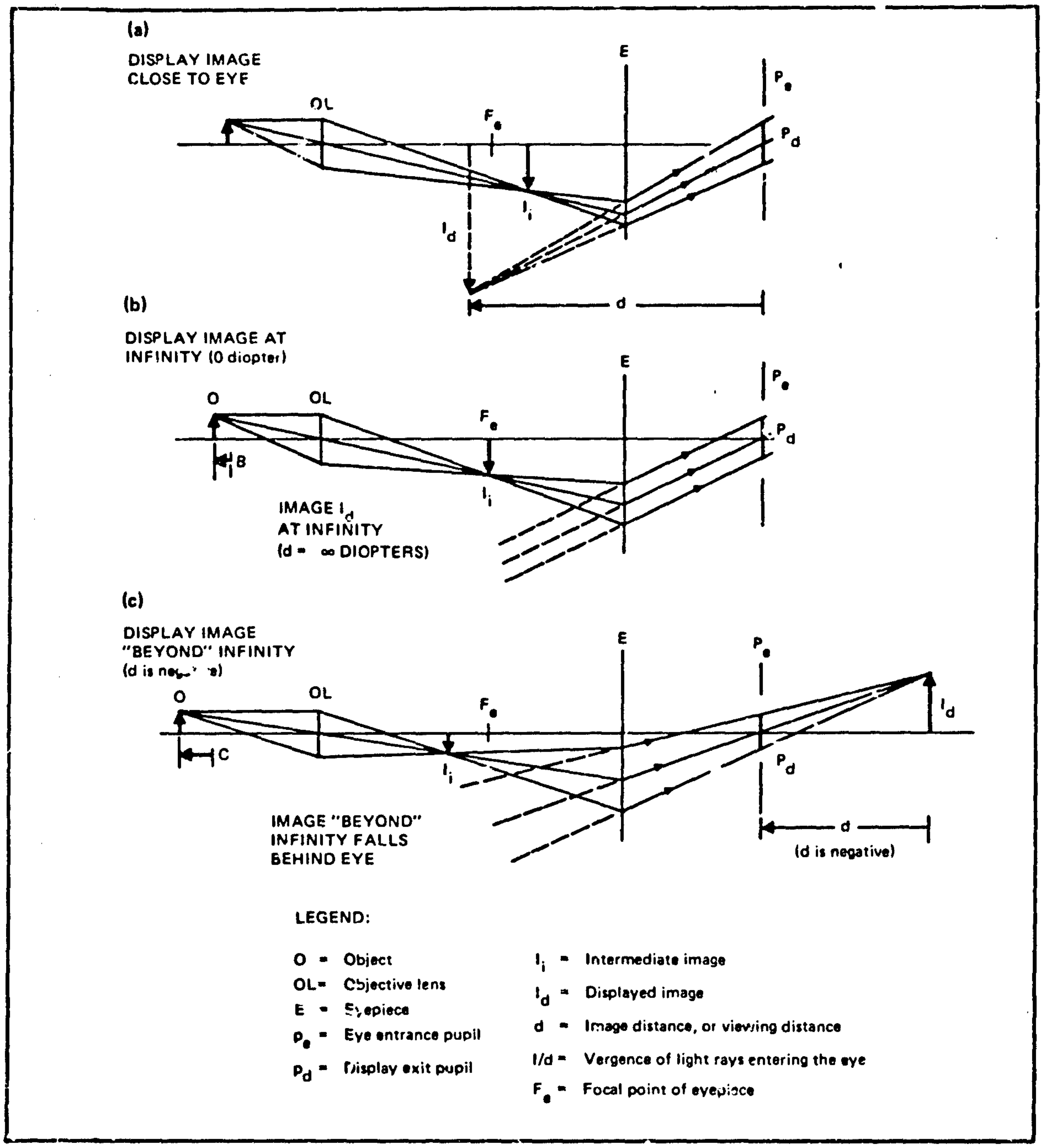


Figure 3.6-1. Image Distance in an Aerial Image Display (continued)

SECTION 3.6 VIEWING DISTANCE

Figure 3.6-1. Image Distance in an Aerial Image Display. In an aerial image display, the amount of eye *accommodation* required to focus the image on the *retina*, and hence the image or *viewing distance*, depends on the *vergence* of the light rays in the ray bundle from a single point in the object being viewed as these rays enter the eye. *Vergence* is the angular relationship between the rays of light from a single object point. Vergence is usually expressed in *diopters*, or 1 divided by the apparent distance in meters to the source of the light rays. For light rays arriving from a distance of 1m (39.37 in), the vergence is 1 diopter (D). From a distance of 0.2m, the value is 1/0.2, or 5 D. If a lens has been used so that the rays in the bundle are parallel and therefore seem to come from an infinite distance, the vergence is 1/∞, or 0 D. If a lens has been used so that the rays are converging rather than diverging as they enter the eye, vergence is defined in terms of the distance to the point where they would intersect if not intercepted by the eye. In this handbook, distances in the direction the light is traveling are taken as negative, so that the vergence of converging light rays is negative. For example, if the rays would intersect 4m behind the eye, the vergence is 1/-4, or -0.25 D. (The sign convention used with spectacles is discussed as part of the definition of *refractive error* in the glossary, Section 8.0.)

This figure illustrates how the vergence of the light rays entering the eye from an aerial image display such as a microscope varies with the focus setting of the display. Each of the three parts of the figure shows, for a single focus condition, the paths of the principal (central) and marginal members of the ray bundle that passes from a point on the object to a small area on the retina. In the process, this bundle forms an *intermediate image*, I_i, somewhere near the focal point, F_e, of the eyepiece, E.

In part (a) the intermediate image is to the right of F_e. As a result, the light rays from a single object point are diverging as they enter the eye. By projecting these to the left, it is possible to determine their apparent (effective) source at the display image I_d, and hence the viewing distance, d. The vergence and the viewing distance in diopters are 1/d. The proper eye accommodation is also 1/d diopter.

In part (b), the display focus control has moved the object to the left, increasing its separation from the objective lens, OL, by a distance shown as arrow B. This moves the intermediate image to the left so that it coincides with the focal point of the eyepiece. The light rays in the bundle from a single object point are now parallel as they enter the eye, the image is apparently at infinity, and the image distance is 1/∞ = 0 diopter. The proper eye accommodation is also 0 diopter.

In part (c), the object to objective lens distance has been increased by an additional amount, C. This places the intermediate image to the left of F_e and results in a bundle of light rays that converges as it enters the eye. Since the apparent source, or point of intersection, of the light rays is to the right, the value of d and the vergence in diopters are both negative. Only a hyperopic (farsighted) eye is capable of accommodating properly for converging light rays (Figure 3.8-2).

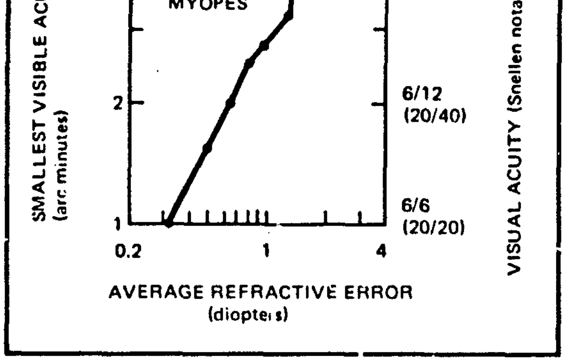


Figure 3.6-2. Visual Ability and Refractive Error. This figure illustrates visual ability measured in the *refraction* clinic as a function of the amount of *refractive error* for *myopes* (Ref. 1,X). (See Figure 3.8-2 for a discussion of this term.) For *astigmatic* eyes, the refractive errors in the two meridians were averaged. The test target distance was probably 5 to 6m (16 to 20 ft.). Visual performance was probably measured with standard clinical tests, using targets like the Snellen E illustrated in Figure 3.1-11.

The right-hand side of the graph gives visual ability in terms of the common *Snellen visual acuity* notation. Because of the potential confusion involved with this and similar units for describing visual performance (Ref. 2), these units should not be used in technical publications for any purpose beyond noting that a test subject had normal ability to resolve details on a typical medical eye test chart.

SECTION 3.6 VIEWING DISTANCE

3.6.1 ACCOMMODATIVE RANGE OF THE EYE

This section summarizes data on the ability of individuals to change the accommodation, or focus distance, of their eyes.

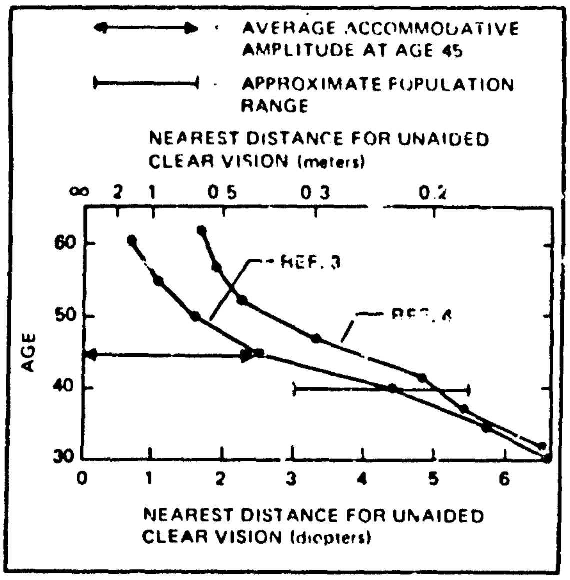


Figure 3.6-3. Accommodative Amplitude and Age. The *accommodative amplitude*, or range of distances to which an individual can focus his eyes, decreases with age. As these two curves show, specific values vary, largely because of differences in measurement technique. Because of this and because of the large population range within a single age group, which seems to remain fairly constant at 2.5 to 3.5 diopters over the age range shown here (Ref. 3), age can be used to obtain only an approximate estimate of an individual's accommodative amplitude.

Accommodative amplitude data are plotted here for *emmetropes* (individuals whose eyes, at minimum *refractive power* yield good vision for objects at infinity—see Figure 3.8-2). However, these same dioptric ranges would apply, with appropriate lateral shifts, for *myopes* (individuals whose eyes, at minimum refractive power, are focused for objects considerably closer than infinity) and for *hyperopes* (individuals whose eyes, at minimum refractive power, are focused for objects considerably beyond infinity). As an example averaging the two curves in the figure indicates that an average 40-year old individual has a 4.7-diopter accommodative amplitude. If this individual is emmetropic, he will be able to focus on objects located at any distance from 0 to 4.7 diopters (infinity to 0.21m). If he is 3 diopters myopic, he will be able to focus on objects at any distance from 3 to 7.7 diopters (0.33 to 0.13m). If he is 3 diopters hyperopic, he will be able to focus on objects at any distance from -3 diopters (beyond infinity) to 1.7 diopters (0.59m). (NOTE: Elsewhere in this handbook, the discussion is usually limited to emmetropes and fully corrected myopes and hyperopes.)

The reduction in accommodative amplitude with age generally begins to cause problems with tasks requiring fine visual discrimination of close objects somewhere in the 40 to 50-year age range. The term applied to this condition is *presbyopia*. Emmetropes and hyperopes will require a positive corrective lens in order to see clearly at near distances, and may wear this in the form of reading glasses or as a separate correction in the lower part of each spectacle lens, as in *bifocals*. Myopes may have less difficulty with presbyopia because, depending on their refractive error, they may be able to see nearby objects adequately simply by removing their spectacles. Otherwise, they will also require an additional, less-negative, correction for performing near visual tasks.

SECTION 3.6 VIEWING DISTANCE

3.6.1 ACCOMMODATIVE RANGE OF THE EYE (CONTINUED)

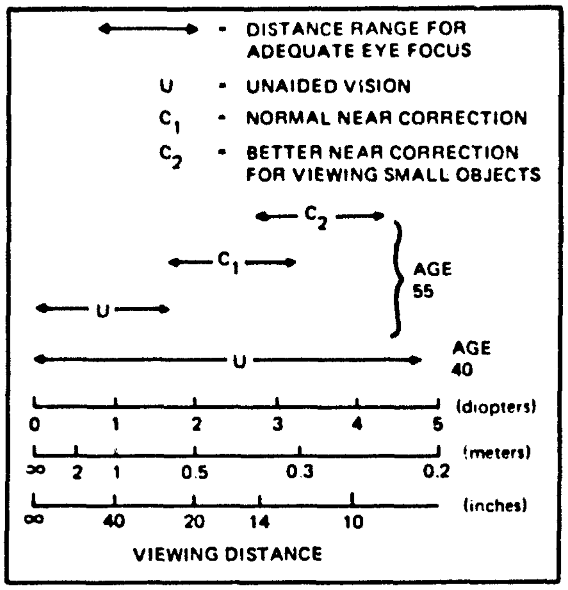


Figure 3.6-4. Use of Spectacles to Compensate for Loss of Accommodative Amplitude. As is mentioned in Figure 3.6-3, the loss in accommodative amplitude with age will at some point cause problems for the individual performing a near visual task. If a display is to be used by older individuals, this may also place some restrictions on the best viewing distance.

This figure shows the viewing distance range acceptable for two average individuals, aged 40 and 55. Figure 3.6-3 indicates that they will have an accommodative amplitude of 4.7 and 1.6 diopters, respectively. The 40-year-old individual will therefore be able to focus on objects as close as 0.21m (8.4 in). The 55-year-old individual, however, will be limited to an unaided distance of 0.62m (25 in). The unaided focus range for each individual is shown here as U.

For nearby tasks such as reading or viewing imagery or a display screen, the 55-year-old will require spectacles containing positive lenses. The amount of the correction is usually selected to move the individual's accommodative amplitude range closer so that it is centered on the distance where best near vision is required (Ref. 5). The most commonly used distance is about 0.4m (16 in). As C_1 in the figure shows, this leaves the individual with a near point of about 0.3m (12 in). If an individual such as an interpreter prefers the larger retinal image obtained with a closer distance, a positive lens with more refractive power can be used. For example, C_2 would allow clear focus at about 0.25m (10 in). However, this leaves a gap between the accommodative range for near and far vision. If any objects, such as a second display, must be viewed at this distance, an additional spectacle correction will be required.

3.6.2 RESTING POSITION OF ACCOMMODATION

The eye has a preferred focus distance, known as the resting position of accommodation (RPA) (Ref. 6). When viewing a target, the accommodation in use is generally a compromise between the viewing distance to the target and the RPA. Factors that reduce vision, such as a reduction in scene luminance or elimination of scene details and factors that reduce the impact of a focus error on image quality, such as a small pupil, tend to result in an accommodation closer to the RPA and farther from the target.

In theory, placing the image in either a screen or an aerial image display at an individual's RPA will reduce visual fatigue because it minimizes the effort required to keep the image in focus. Some of the available data on average RPA values are summarized in Figures 3.6-5 and -6 below.

As Figure 3.6-5 shows, the RPA varies widely among individuals. It must also vary within an individual over age, particularly past an age of about 40. If it is possible to provide each individual with a different viewing distance, it might be desirable to do so, at least within the limitations of keeping a reasonable match to eye convergence angle as is described in Section 3.7.4.2.

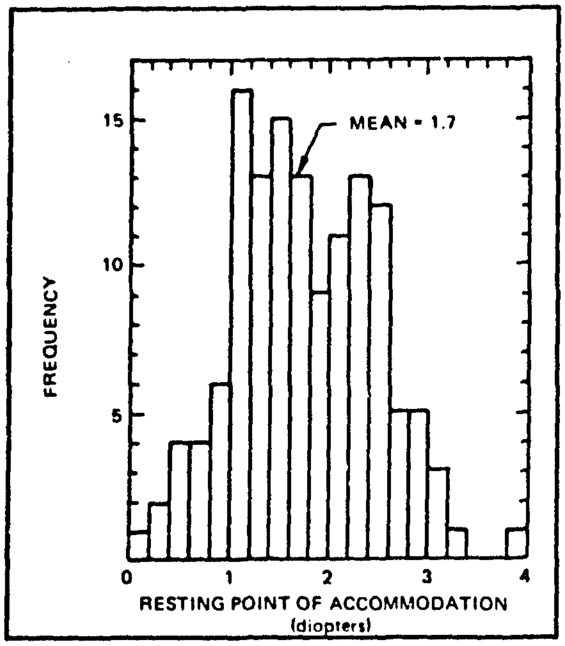


Figure 3.6-5. Resting Position of Accommodation. This figure shows the frequency distribution of resting position of accommodation (RPA) values measured in total darkness on 124 college-age observers (Ref. 7,B). The standard deviation of these values is 0.7 diopter.

The effect of age on the RPA can be seen in another study, where young adults had a similar average of 1.7 diopter, but presbyopes had an average of only 0.8 diopter (Ref. 8,X). The value obtained for presbyopes would, of course, vary with accommodative amplitude (Figure 3.6-3).

3.6.2 RESTING POSITION OF ACCOMMODATION (CONTINUED)

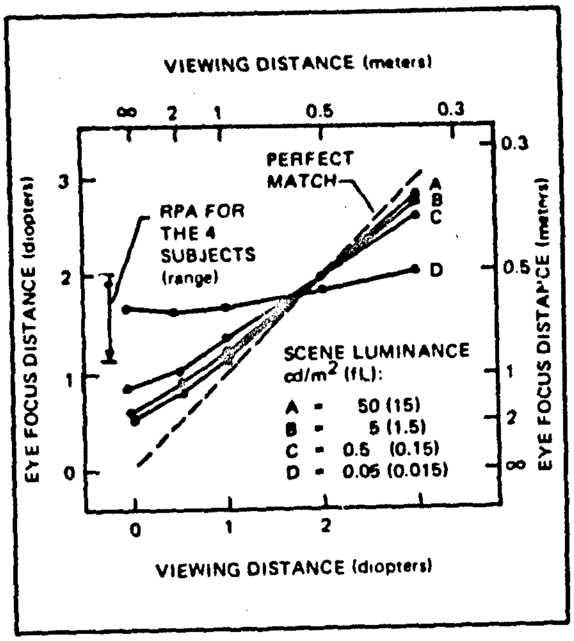


Figure 3.6-6. Impact of Luminance on Accommodative Error. The eye generally accommodates to a distance intermediate between the scene being viewed and the resting position of accommodation (RPA). As these curves illustrate, the error increases markedly at low illumination levels. (Ref. 9,C). This finding helps explain why visual performance under very low illumination conditions is best for a target at a distance that matches the subject's RPA (Figure 3.6-10).

3.6.3 PREFERRED MICROSCOPE FOCUS SETTING

The focus settings made by microscope users provide an indication of the viewing distance they find most satisfactory and to a limited extent predict how a microscope type of imagery display will be adjusted. The tendency is to focus to an image distance considerably closer than infinity, a phenomenon that has been referred to as *instrument myopia* (Ref. 10). There is strong evidence that instrument myopia is due to the resting point of accommodation phenomenon discussed in Section 3.6.2 (Ref. 6).

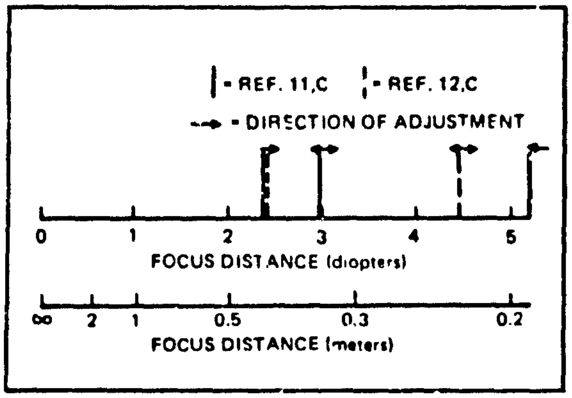


Figure 3.6-7. Focus Settings for Monocular Microscopes. Subjects tended to focus monocular microscopes so that the image distance was several diopters closer than infinity. If they were required to approach their final setting from a particular direction, without reversals, the final setting was displaced toward their starting point. This finding has a direct design application. For example, if a viewing distance near infinity is desirable, the focusing mechanism and instructions should require the display user to start with the image beyond optical infinity. If he then moves it closer until it is in focus, it should be as close to infinity as he can accept.

Although it is not illustrated, in Ref. 11 the variation among subjects was approximately 35 percent greater when they started with an image that was too close and moved it in only one direction than when they started with it too distant.

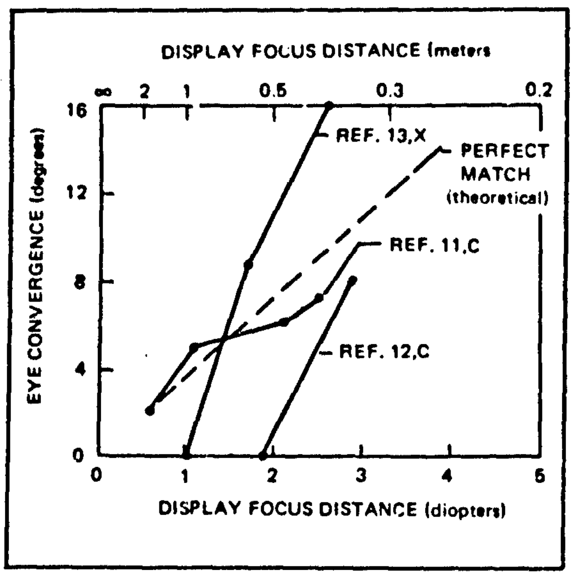
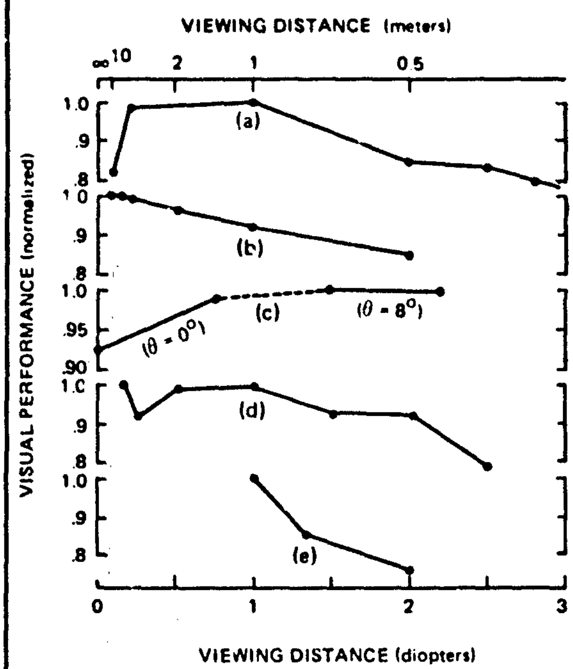


Figure 3.6-8. Focus Settings for Binocular Microscopes. This figure illustrates how focus settings of binocular microscopes varied with the convergence angle between the eyepieces. This variation approximated the theoretically correct relationship between eye convergence and viewing distance indicated by the broken line. (See Section 3.7.4.2.)

3.6.4 VISUAL PERFORMANCE AND VIEWING DISTANCE

This section summarizes the best of the available studies on the relationship between viewing distance and visual performance.



VISUAL FUNCTION MEASURED	TYPE OF TEST (Figure 3.2-11)	SUBJECTS	SOURCE
(a) VISUAL ACUITY	CHECKER BOARD	400 YOUNG ADULTS	REF. 14,B
(b) VISUAL ACUITY	COBB 2-BAR TEST	7 ADULTS	REF. 15,3
(c) STEREO ABILITY	CL STEREO TEST (Figure 5.1.11)	32 SELECTED ADULTS	REF. 16,B
(d) STEREO ACUITY	2 VERTICAL BARS	3	REF. 17,C
(e) STEREO ACUITY	2 VERTICAL BARS	3	REF. 18,C

Figure 3.6-9. Variation in Vision with Viewing Distance. The best of the many studies relating visual performance to viewing distance are summarized here. Curve (c) shows that portion of the data from Figure 3.7-13 in which there was no indication of any reduction in performance because the convergence angle, θ did not match the viewing distance.

Although these studies are not in full agreement, they strongly suggest a reduction in vision as the target moves either too close or too far away.

The point at which visual performance begins to drop as viewing distance is reduced is not clearly defined, but it appears to be somewhere between 1 and 2 diopters (1 and 0.5m). It is important to note that the subjects in all of these studies still had the ability to focus their eyes over a wide range of distances. If they had been extremely presbyopic (see Figure 3.6-3) their visual performance would have dropped much faster as the target moved closer.

The two largest studies, (a) and (c), indicated a drop in visual performance as the viewing distance approached optical infinity, while two others, (b) and (d), did not. This discrepancy may reflect differences in how adequately the test subjects were corrected for distant vision. That is, spectacles are generally prescribed on the basis of performance on an acuity test located at a distance of 0.20 to 0.16 diopter (4.9 to 6.1m, or 16 to 20 ft). This fact, in combination with the "least minus/most plus" rule for prescribing spectacles, results in many individuals having a maximum distance for clear vision that is one to several tenths of a diopter short of infinity (Ref. 19).

3.6.4 VISUAL PERFORMANCE AND VIEWING DISTANCE (CONTINUED)

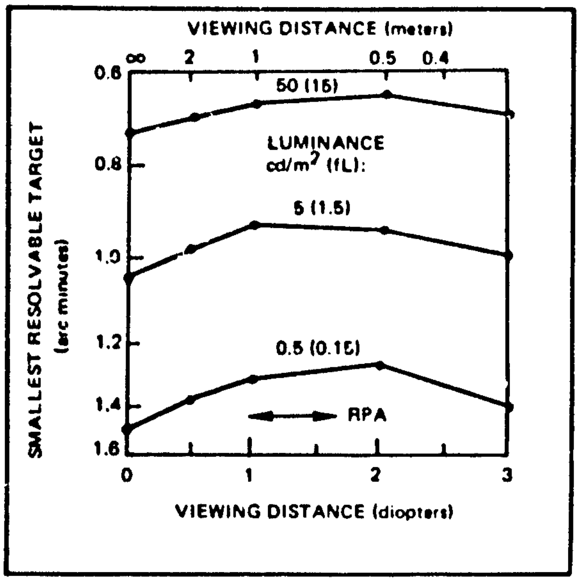


Figure 3.6-10. Variation in the Impact of Viewing Distance with Luminance. The impact of viewing distance on vision varies with other parameters, such as scene luminance. In the experiment illustrated (Ref. 9,C), the four subjects had resting positions of accommodation (RPA, Figure 3.6-5) ranging from 1 to 2 diopters and their visual acuity was generally best in this region. The effect of viewing distance was not constant, however, being considerably larger at the lower luminance levels. The implication for imagery displays is that viewing distance becomes more important as the luminance is lowered.

3.6.5 SCREEN DISPLAYS

The data discussed in the previous portions of Section 3.6 apply to screen displays such as CRT's and rear screen projectors just as they do to aerial image displays. That is, the range of viewing distance for best vision is 0.67 to 2.0m (26 to 80 in). However, viewing distance for screen displays deserves special attention because they introduce complications not present with aerial image displays. It is usually physically more difficult to adjust viewing distance for a real display, and such adjustment causes changes in apparent image size and quality that may not be desirable.

Several factors affect selection of the viewing distance for screen displays. First, the nearest point for comfortable prolonged visual work is classically quoted as 0.40m (16 in) (Ref. 20). Justifying this precise value is difficult, particularly since young adults can easily work with visual materials at much closer distances. However, reading spectacles for presbyopes are generally prescribed to provide good vision at this distance and it is therefore a reasonable minimum if many individuals over age 40 to 45 are to use the display (see Figures 3.6-3 and -4).

A second consideration in determining viewing distance is the quality of the image. The display should be far enough from the user so that the irrelevant details such as the scan lines on a CRT or the grain on a projection screen are not objectionable, but it should not be so far away that information is no longer visible. Section 3.1 describes some of the visual parameters that are useful in making this type of analysis, and Section 4.4 illustrates its application to CRT displays.

If the operator must adjust controls located adjacent to the display, the maximum distance is limited to approximately 0.71m (28 in). (For some precise limits, refer to Section 6.1.5). In some cases, difficulties in providing adequate illumination will limit display size and, in turn, maximum useful viewing distance.

SECTION 3.6 REFERENCES

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5. This discussion of the relationship of accommodative amplitude to spectacle lens prescription is considerably simplified. For example, it ignores the fact that accommodative amplitude varies with many parameters, such as measurement technique and the health of the test subject. In addition, spectacle lenses power is generally adjusted so that the patient need not work for extended periods at his extreme near point. For a treatment of some of the factors involved, see Borish, I. M. (Ed.), *Clinical Refraction* (3rd ed.). Professional Press, Chicago, 1970, pp. 923-928.

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   Hennessy, R. T. Instrument myopia. *J. Opt. Soc. Am.*, Vol. 65, 1975, pp. 1114-1120.

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10. Kassel, in study I of Ref. 11, states that this term was first applied to this phenomenon by Schober. Much of the early work in this area was done in the 1940's in Germany and Italy.

    Many of the references appear in: Mellerio, J. Ocular refraction at low illuminations. *Vision Res.*, Vol. 6, 1966, pp. 217-237. This is an excellent review of work prior to 1965.

11. Kassell, R. Die Instrumentmyopie beim sehen durch monokulare und stereoskopische Mikroskope. Thesis, Institut fur medizinische Optik der Univeritat Munchen, 1967. Translated by Booth, J., The Boeing Company, 1970. This material is summarized in Schober, H.A.W., Dehler, H., and Kassel, R., Accommodation during observations with optical instruments. *J. Opt. Soc. Am.*, Vol. 60, 1970, pp. 103-107. A total of 13 subjects were tested. Interpretation of the curve in Figure 3.6-8 is complicated by the fact that the different convergence angles were obtained by changing the interpupillary setting of the microscope; as a result each data point on the curve represents a different group of subjects.

12. Shimojima, T. Eye accommodation when looking into the microscope – I. *Jap. J. Clin. Ophthal.*, Vol. 21, 1967, pp. 985-990. The data in Figure 3.6-8 represent an average for adjustment in the two directions.

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SECTION 3.7 BINOCULAR VIEWING

The term *binocular* applies to any viewing situation and to any display that involves the use of both eyes. Binocular displays fall into two distinct classes:

- Devices that produce a single image seen by both eyes; these include most *screen displays*.

- Devices that produce two separate images, one for each eye; these include most binocular *aerial image displays*.

While some parts of this section apply to any binocular display, the principal concern is with the design limits that should be placed on the location of and differences between the two images produced by the second class of binocular display.

The design recommendations in this document are based, insofar as possible, on quantitative data collected under controlled conditions. In most instances, this means visual performance data. Little direct reference is made to problems referred to generally as visual fatigue or visual discomfort. There is no question that such problems are real and potentially serious (Ref. 1), and it is even likely that they are frequently caused by poor design or adjustment of the display features treated in this section, especially for interpreters working for extended periods at tasks such as search or mapping. The difficulty is that although many attempts have been made, there is no adequate test data relating visual fatigue or discomfort to specific features of the viewing situation in a way that allows display design limits to be set (Ref. 2).

SECTION 3.7 BINOCULAR VIEWING

3.7.1 TERMINOLOGY

There is considerable confusion in the literature about the meaning of many of the terms that serve to differentiate types of displays and describe their characteristics. Therefore, certain of the terms essential to the development of design limits for binocular displays are defined below. (Others appear in the Glossary.) Where possible these definitions have been adapted from recognized authorities (Ref. 3).

The first group of terms concerns types of displays. Several different versions of binocular displays are illustrated in Figure 3.7-1.

- *Ocular*–A general term referring either to an eyepiece or to the eye.
- *Monocular*–A single eyepiece, or involving only one eye.
- *Binocular*–Both eyes; any optical system or viewing situation that involves both eyes.
- *Biocular*–A specific type of binocular optical system in which both eyes share an optical element with a single axis of symmetry (Ref. 4). In Figure 3.7.1, (b), (c), and (d) illustrate typical variations. Biocular displays which also have large exit pupils, such as (c) and (d), can present special image registration problems if distortion and image location change differently for the two eyes as they move within the exit pupil (Ref. 5).

A second group of terms distinguishes between displays used to view a single piece of imagery or a stereo pair.

- *Monoscopic*–The display user views a single piece of imagery.
- *Stereoscopic*–The display user views two pieces of imagery, one with each eye, that have been collected from different orientations relative to the ground. When these are fused visually the lateral disparity causes a sensation of depth. (See Section 5.1 Ref. 6.)

The third group of terms concerns the geometric relationships between the two images in a binocular display. Two aspects of the *registration* of these two images must be considered, their alignment relative to the display user, and the amount of disparity, or unequalness, between them. In order to define these it is useful to consider the two images as consisting of many pairs of corresponding points, each pair being the representation of a single point on the ground (or on a reticle if one is present).

- *Alignment*–The position of the two images, relative to the display user, in angular units. Always specified as either lateral or vertical alignment.
- *Lateral Alignment*–The convergence angle, or angle between the *visual axes*, necessary for the display user to fixate on corresponding points in the two images. (This definition does not imply that the user is necessarily able to achieve such a convergence angle with his eyes.) For an object at infinity viewed without optical aids, the visual axes of the eyes would be parallel and the convergence angle would be zero.
- *Vertical Alignment*–The vertical position of the two images relative to each other. Vertical alignment is usually expressed as misalignment, or the deviation from a condition of perfect alignment. If there is no vertical misalignment present, when the display user *fixates* exactly on corresponding points in the two images the visual axes define a plane. (This definition does not imply that the visual axes intersect. Whether or not they intersect also depends on the lateral alignment between the two images.) The amount of vertical misalignment is the total deviation of the visual axes from this plane. It is usually expressed in angular units such as arc minutes or milliradians.
- *Disparity*–A difference in the two images. That is, some pairs of corresponding points have an alignment different than the alignment of other pairs. In a monoscopic display this could result from differences in distortion in the two optical paths or because reticle alignment differs from the alignment of the two images of the imagery. Disparity is inherent in stereo imagery, where it serves to encode differences in ground elevation (Sections 5.1.1 and 5.1.2).

A term related to this third group of terms is *phoria*. It is the angular relationship between the visual axes of the two eyes when there is no stimulus for fixation present. Phoria is a characteristic, therefore, of the individual, not the display.

Registration limits are expressed here as visual angles because that is how they are experienced by the user. They can easily be converted into other dimensions, such as lineal distance on the imagery, using the relationships discussed in Sections 3.5.1 and 5.3.1.

3.7.1 TERMINOLOGY (CONTINUED)

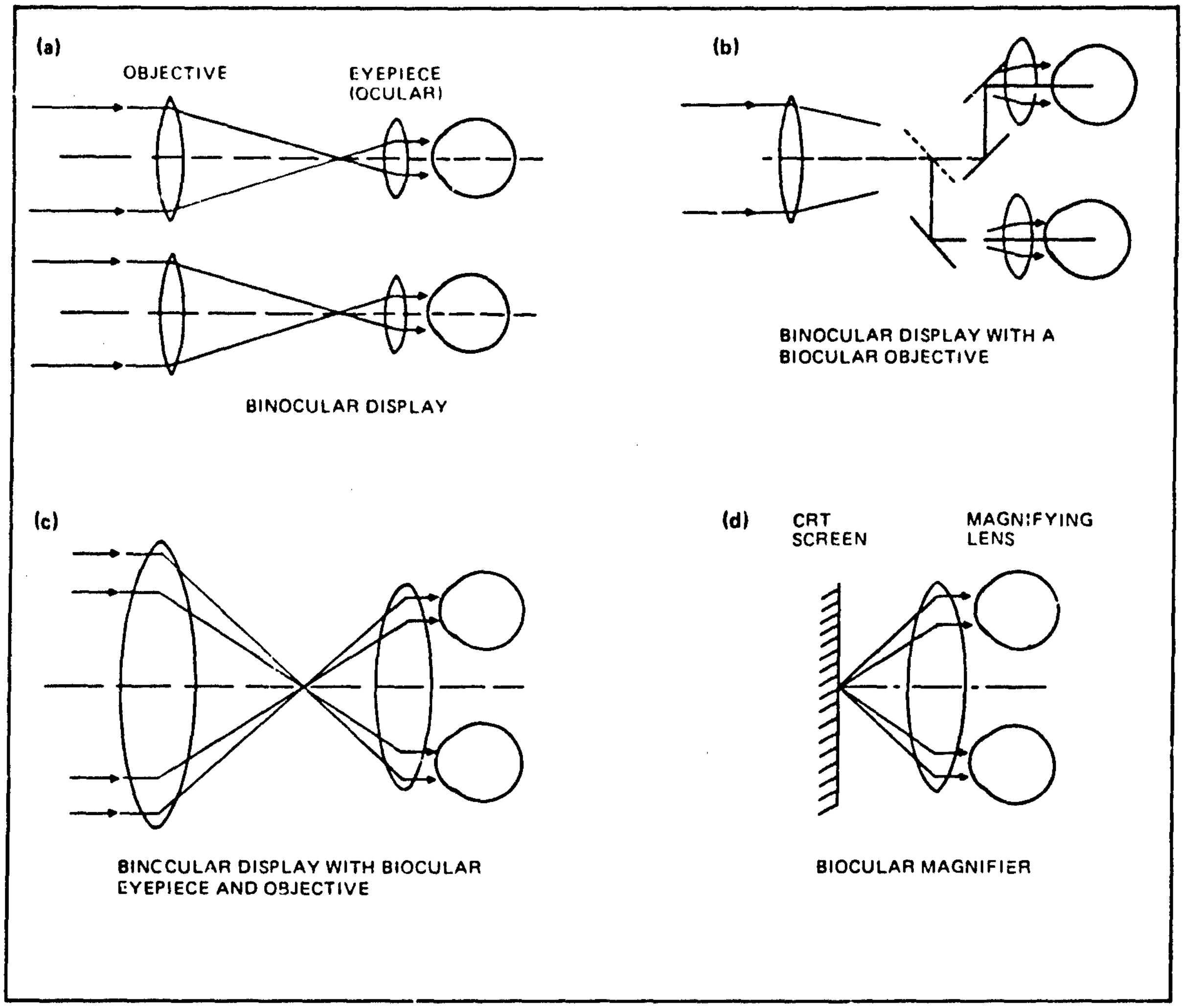

Figure 3.7-1. Preferred Titles for Typical Binocular Displays. Typical binocular displays are illustrated here in simplified form, along with the terms used to refer to them in this document (Ref. 4).

3.7.2 ADVANTAGES

The advantages of a binocular display can be summarized quickly. In addition to being more comfortable and convenient for most display users, visual performance is better when two eyes, rather than only one, are used. The reported improvement ranges from 5 to 10 percent for visual acuity (Ref. 7,X) and is approximately 40 percent for modulation sensitivity (Ref. 8,C). If illumination is limited and must be split between the two eyes, there will be some loss in visual performance (see Section 3.2). However, at typical display luminance levels this loss is considerably less than the improvement due to using both eyes (Ref. 8,C).

Whenever possible, therefore, displays should be designed for binocular viewing. The major exception is a simple display such as a tube magnifier. Much of the appeal of this type of device is due to its small size and ease of use and these advantages may be lost if sufficient optical elements are added to allow binocular use.

3.7.3 INTERPUPILLARY DISTANCE (IPD) ADJUSTMENT

RECOMMENDATION:

Provide an IPD range of at least 50 to 76 mm, with 46 to 78 mm preferred.

Provide a scale calibrated in 1.0-mm increments to indicate IPD setting. For situations where IPD is critical, such as stereo photogrammetry of color imagery, add a vernier so that the IPD setting can be repeated to within 0.1 mm (see Sections 5.2.6 and 5.3.7).

Provide a convenient, obvious means of adjusting and locking IPD.

POPULATION	SAMPLE SIZE	PERCENTILE					RANGE
		1	2.5	50	97.5	99	
AIR FORCE FLIGHT PERSONNEL (Ref. 9,B)	4057	55.5	56.6	63.2	70.7	72.1	51 – 76
ARMY DRIVERS (Ref. 10,C)	431	52.1	–	58.9	–	66.0	–
FEMALES (Ref. 11,X)	NOT GIVEN	–	53.3	63.5	71.1	–	–
IMAGE INTERPRETERS (Ref. 12,C)	61	57.2	58.4	64.9	71.4	72.6	57–73

(all dimensions are in millimeters)

Figure 3.7-2. Interpupillary Distance (IPD) Distributions. With a small exit pupil display, the interpupillary distance (IPD) must be adjustable over a range adequate for the entire population of expected users. This figure summarizes some of the available data. As the blanks indicate, equivalent points in the distribution are not always reported. In addition, IPD values outside the range shown here have been reported. For example, one former interpreter reportedly had an IPD of 46 mm (Ref. 12,X).

Based on the data shown here, the IPD range suggested by one authority (Ref. 13), 50 to 76 mm, is adequate. If the cost is not excessive, increasing this range a few millimeters is desirable because it will ensure that even the occasional very large or very small IPD user will be accommodated.

Image field size (Section 3.5) and eye relief (Section 3.9) set a lower limit on eyepiece diameter, which in turn sets a lower limit on IPD. Compromise between these variables may therefore be required.

Making the method of adjusting IPD obvious and convenient will reduce the chance of equipment damage from an improper action such as pushing directly on the ends of eyepiece tubes. A scale is desirable, and is essential if problems with chromostereopsis are to be avoided when measuring colored imagery (see Section 5.2.6 and 5.3).

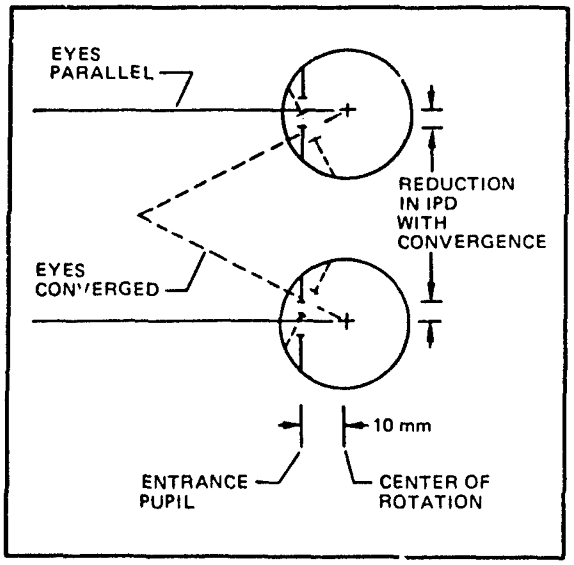

Figure 3.7-3. IPD Reduction With Eyepiece Convergence. Interpupillary distances are generally measured with the subject looking at a distant object so that his eyes are parallel. The entrance pupil of the eye is located approximately 10 mm in front of the center of rotation of the eye. As a result, when the eyes converge, the distance between the entrance pupils is decreased. The total reduction in IPD for a convergence angle of 8 degrees is approximately 1.4 mm (Ref. 14).

For critical applications, it may be necessary to consider this reduction in IPD with eye convergence. For example when measuring color imagery on a stereo comparator, the user may need to set in his particular IPD very precisely in order to minimize errors resulting from the color of the target (see Sections 5.2.6 and 5.3.7). If the comparator has converging eyepieces, a correction of the type shown here will be necessary. This could be in the form o a conversion chart, or perhaps as a second scale permanently fixed to the eyepieces that shows equivalent parallel-eye IPD instead of the actual separation between the display exit pupils.

3.7.4 IMAGE REGISTRATION IN MONOSCOPIC DISPLAYS

This section covers image registration in binocular displays used to view a single piece of imagery. Most of the test data presented here also applies to the visual situation in stereo displays, but because the two pieces of imagery in a stereo display can be moved relative to each other, the implications for display design are much different. Registration requirements for stereo displays are treated in Section 3.7.5.

Even though this section deals with design limits for monoscopic displays, stereo acuity data appear frequently. In some situations, this is because they are the only good data available. Also, stereo acuity provides one of the most sensitive indications of the ability of the two eyes to function together, and it is therefore relevant if one desires to obtain full benefit from providing an image to each eye. (See the comparison of monocular and binocular vision in Section 3.7.2.) Perhaps the primary problem with using stereo acuity data is that it may lead to more restrictive design limits than would other measurements such as binocular visual acuity; in practice this may compensate for the lack of data on visual comfort.

Vertical and lateral registration are treated separately in the sections that follow. However, the designer must keep in mind that if an image rotation capability is provided in the optical train, vertical and lateral can be interchanged. In general, the most restrictive design limit would then apply in both directions.

Several ideas relevant to the problem of developing and applying image registration design limits are treated in the paragraphs immediately following.

Considerable use is made in the following sections of test data on the maximum misregistration that will not cause a doubling of the image. This may or may not correspond to the point at which visual discomfort or blurring begin. For example, when measuring the ability of the eyes to change alignment in the refraction clinic, discomfort and image blurring usually occur well before fusion is lost (Ref. 15). On the other hand, in the experiment involving rotation tolerances for geometric targets illustrated in Figure 3.7-20, the subjects reportedly never experienced discomfort.

The frequency and duration of experience with a particular viewing situation can have a complex effect on how much of a problem it is. With time and effort, individuals can adapt to some situations that would be disruptive with brief, intermittent exposure. For example, many interpreters can view stereo imagery without optical aids (Figure 5.1-16), indicating that they are no longer bound by the normal relationship between viewing distance and eye convergence discussed in Section 3.7.5.2. Also, Figure 3.7-7 illustrates how intermittent exposure to a vertical misalignment of 17 arc minutes resulted in a drastic loss of stereo acuity, even though in another study dedicated subjects were apparently able over time to adapt to vertical misalignments 10 to 20 times as large (Ref. 16).

The obvious conclusion to be drawn from the previous paragraph is that the impact on the display user of poor image registration is reduced with continued exposure. Unfortunately, this conclusion is contradicted by the common experience that in many difficult viewing situations the sensations of visual fatigue and discomfort clearly increase with time. Perhaps the best that can be done is to simply try to provide a viewing situation that is acceptable whatever the frequency and duration of use.

When attempting to draw conclusions from experimental data, the complexity of the visual scene must be considered. Compared with a simple image containing only a few geometric shapes such as dots and lines, an image containing many details provides a stronger stimulus for fusion and increases tolerance to some kinds of misalignment. This is illustrated by Figure 3.7-20, and by the normal experience that in a floating dot stereo comparator the dot is more likely than the ground scene to appear double. With effort, this effect of image complexity can be overcome. For example, by concentrating on the floating dot it can be made to appear single and the ground scene double.

One of the most important principles, when considering limits on image disparity, is that tolerance increases with distance from the fixation point. Typical data appear in Figure 3.7-4.

3.7.4 IMAGE REGISTRATION IN MONOSCOPIC DISPLAYS (CONTINUED)

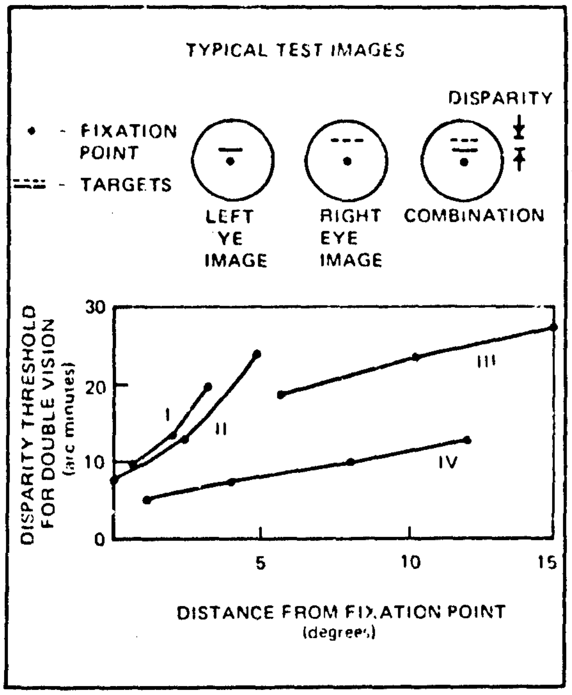

Figure 3.7-4 Variation in Disparity Tolerance With Retinal Location. The vertical disparity necessary to produce double vision is least at the fixation point, or nominal center of the *fovea*, and increases peripherally (Ref. 17,X). As the results obtained by the four different experimenters, I, II, III, and IV, illustrate, there is much disagreement on the rate of increase.

SECTION	TOPIC	COMMENTS
3.7.4.1	VERTICAL ALIGNMENT	• 10-ARC-MINUTE MAXIMUM; 5 ARC MINUTE FOR SENSITIVE USERS
3.7.4.2	CONVERGENCE ANGLE (lateral alignment)	• USE 0-10°; 2-10° PREFERRED • MATCH VIEWING DISTANCE APPROXIMATELY
3.7.4.3	VERTICAL DISPARITY	• NOT COMMON IN MONOSCOPIC DISPLAYS • 5 ARC MINUTES MAXIMUM
3.7.4.4	LATERAL DISPARITY	• NOT COMMON IN MONOSCOPIC DISPLAYS • PERCEIVED AS DEPTH • 5 ARC MINUTES MAXIMUM; LESS TO ELIMINATE DEPTH
3.7.4.5	ROTATION DIFFERENCE	• MAY BE COMMON IF EACH EYEPIECE ROTATES IMAGE • LIMIT AS VERTICAL ALIGNMENT • 0.5° IS TYPICAL MAXIMUM
3.7.4.6	SIZE (magnification) DIFFERENCE	• LIMIT AS VERTICAL ALIGNMENT • 0.8% IS TYPICAL MAXIMUM

Figure 3.7-5. Summary of Image Registration for Monoscopic Displays. For each of the six parts of Section 3.7.4, this figure lists the particular aspect of image registration discussed and summarizes the resulting conclusions.

3.7.4.1 VERTICAL ALIGNMENT IN MONOSCOPIC DISPLAYS

RECOMMENDATION:

Limit the vertical misalignment between images presented to the two eyes in a monoscopic display to 10 arc minutes. To ensure visual comfort for very sensitive users, or for tasks that place a particularly severe demand on vision, such as photogrammetry, it may be necessary to reduce this value by half.

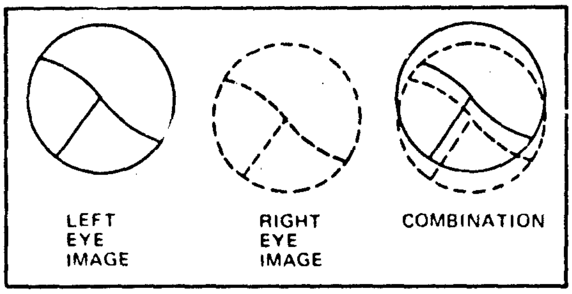

Figure 3.7-6. Vertical Misalignment. These images of a road intersection illustrate how excessive vertical misalignment in a monoscopic display results in a double image. Smaller amounts may simply result in discomfort or a blurred image.

Because the eyes do not normally change their vertical alignment, tolerances are much smaller in the vertical than in the lateral direction. In the refraction clinic, for example, blurring or doubling of the image typically occurs when vertical misalignment reaches 34 to 102 arc minutes (Ref. 18,B). In this situation, visual discomfort often occurs with a much smaller alignment error; unfortunately no specific values have been published.

To some extent, the eyes can be trained to accept an incorrect alignment. Dedicated subjects have reportedly obtained acceptable vision with up to 3 degrees of vertical misalignment (Ref. 19,C), and after a long adaptation period, a vertical misalignment of 1 degree did not degrade performance on an M-1 range finder (Ref. 20,X). Because imagery displays must provide a comfortable viewing situation and are normally used intermittently, neither these values nor the 34- to 102-arc-minute value measured in the refraction clinic provide much guidance in setting design limits.

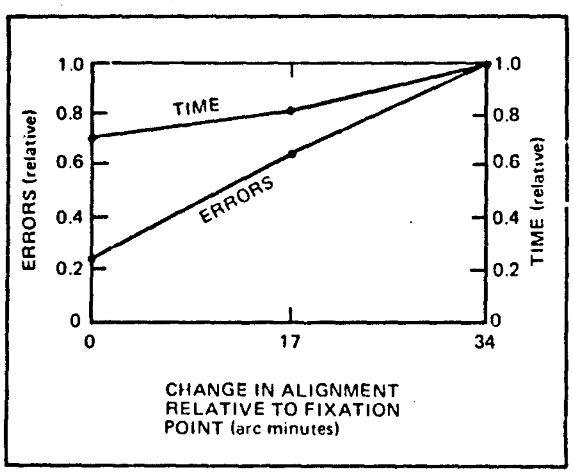

Figure 3.7-7. Reduction in Vision With Alternations in Vertical Alignment. In a study of the effect of exposure to frequent alternations in vertical alignment, subjects judged which of two diamond-shaped figures was closest (Ref. 21,C). The difference in distance corresponded to a lateral disparity of 0.2 arc minute, which is about twice the minimum that can be detected (see Figure 3.7-19). Three things occurred simultaneously at the beginning of each trial: the fixation target disappeared, the alignment changed by 17 or 34 arc minutes, and the diamonds appeared. The subjects were required to respond both quickly and accurately, and both categories of performance suffered, even with the smaller alignment change.

This study did not provide any information on the effect of continuous exposure to a vertical misalignment.

3.7.4.1 VERTICAL ALIGNMENT IN MONOSCOPIC DISPLAYS (CONTINUED)

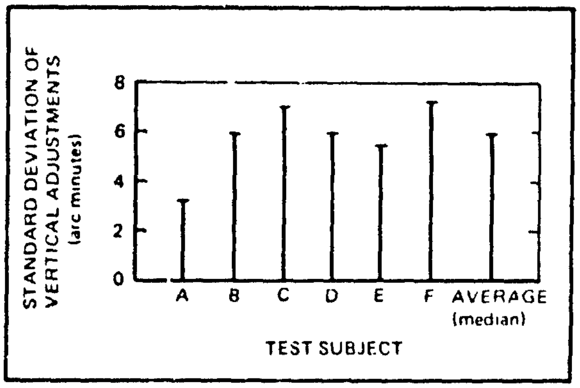

Figure 3.7-8. Variability in Vertical Alignment Settings. In the absence of good performance data on which to base design limits, it is useful to consider how much vertical misalignment display users find acceptable. The only available data are from a very preliminary study in which six subjects used a microstereoscope to view two identical photos, one before each eye (Ref. 22,D). They moved one of these freely along the vertical axis until they were satisfied with the alignment. It was not possible to measure absolute alignment errors, but the variation in the settings made by each subject yielded standard deviations ranging from 3.2 to 7.3 arc minutes, with an average (*median*) of 6.0.

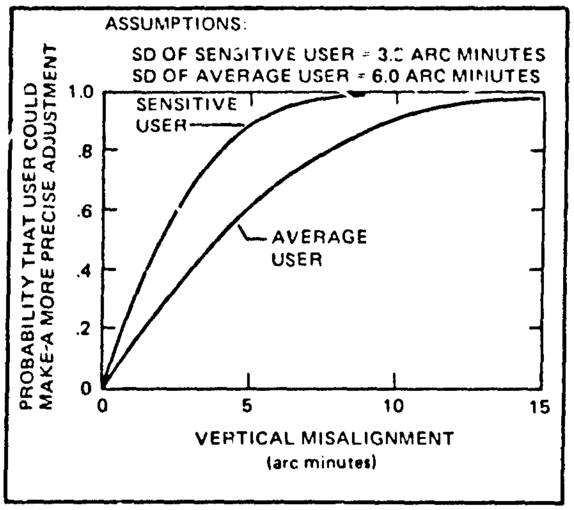

Figure 3.7-9. Estimation of Design Limits. The results summarized in the previous figure do not provide any information on either visual performance or comfort. However, they do allow an estimate of the likelihood that a typical display user could adjust vertical alignment better than any particular design limit and this in turn provides some indication of whether a particular limit is grossly inappropriate.

For the present purpose, it is reasonable to assume that vertical alignment setting errors are normally distributed. Then the average standard deviation (SD) of the settings illustrated in the previous figure, plus published tables of the normal distribution (Ref. 23), can be used to estimate the probability that a typical display user could make a setting more precise than any particular vertical misalignment allowed in the design. Extending this line of reasoning one more step, he probably wouldn't be dissatisfied with the misalignment unless he could consistently do better himself.

For example, an average user could do better than 5 arc minutes only 60 percent of the time, suggesting that this is too stringent a design limit, and he could do better than 10 arc minutes nearly 90 percent of the time, suggesting that the design limit should not exceed 10 arc minutes.

Some individuals are much more sensitive than others to vertical misalignment. The most sensitive of the six subjects, A in Figure 3.7-8, had a standard deviation of 3.2 arc minutes, approximately half the average value of 6.0. If the reasoning in the previous paragraph is valid, he would require a design limit of only 5 arc minutes.

3.7.4.2 CONVERGENCE ANGLE (LATERAL ALIGNMENT) IN MONOSCOPIC DISPLAYS

RECOMMENDATION:

Design for an eye convergence angle of 0 to 10 degrees, and preferably 2 to 10 degrees. If viewing distance is fixed (Section 3.6), use Figure 3.7-13 to select a convergence angle that matches viewing distance to within ±2.7 degrees.

This section discusses some of the factors involved in selecting a convergence angle for a binocular display. As is noted in Figure 3.7-13, a convergence angle of 0 degrees, which corresponds to parallel eyepieces, is generally easiest to build but may cause trouble for some users.

If a lateral *phoria* adjustment (Section 3.7.6) is included in the display, this is equivalent to allowing the subject to adjust the convergence angle.

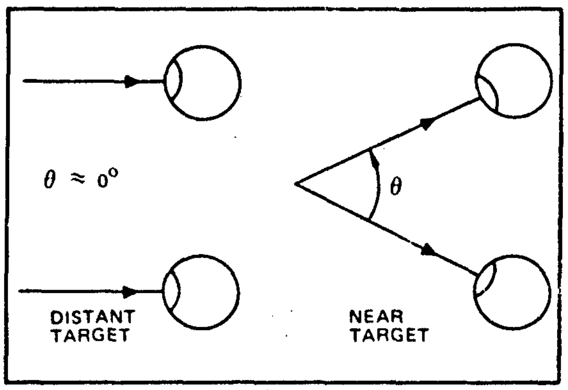

Figure 3.7-10: Eye Convergence in Normal Unaided Vision. In natural unaided viewing situations, in order for the separate images falling on the two retinas to be seen as single, or fused, the eyes must converge so that the visual axes intersect at approximately the distance of the object being viewed. If this condition is not met, *diplopia,* (double vision) will result. Normal visual experience does not involve divergence of the eyes beyond parallel.

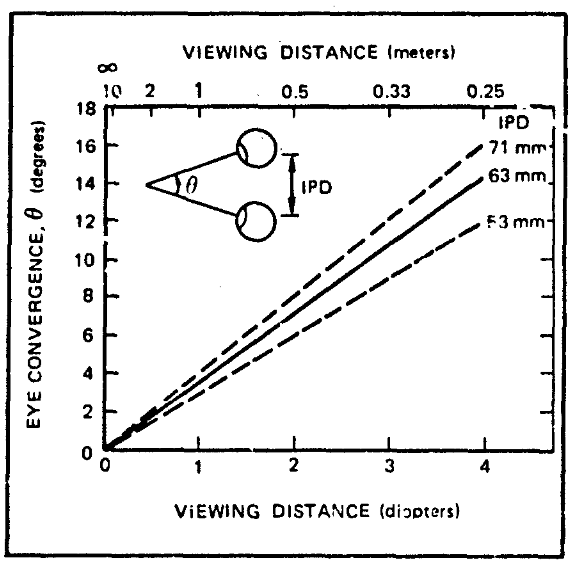

Figure 3.7-11: Relationship of Eye Convergence Angle to Viewing Distance. The correct convergence angle for single vision varies directly with viewing distance expressed in diopters (the inverse of the viewing distance in meters) and with interpupillary distance (IPD). This figure shows convergence for the nominal average and middle 95 percent of the IPD distribution in Section 3.7.3 (Ref. 24).

3.7.4.2 COVERGENCE ANGLE (LATERAL ALIGNMENT) IN MONOSCOPIC DISPLAYS (CONTINUED)

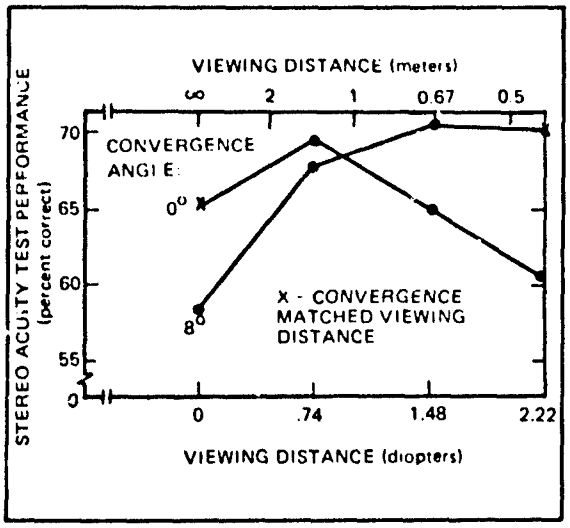

Figure 3.7.12: Effect of Convergence Angle and Viewing Distance on Visual Performance. The stereo acuity test illustrated in Figure 5.1-10 was used to assess the effect of eight combinations of eye convergence angle and viewing distance (Ref. 25,B). As can be seen in this figure, only the two viewing conditions indicated by an X involved values of these two variables that matched normal experience.

Referring to the data plotted in the figure, performance appeared to be hurt by two viewing conditions:

- When the target was at infinity (0 diopter) (probably because the subjects had difficulty focusing at that distance (Section 3.6.4))
- When the viewing distance differed from a value that matched the convergence angle by more than 0.75 diopter

Although it is not illustrated, the reduction in performance with a mismatch between convergence and target distance was greater in subjects with less than 5 diopters accommodation. This would include most individuals over 40 (see Figure 3.6-3).

Visual comfort ratings were also obtained and were nearly identical with the performance data illustrated here.

The use of a natural eye pupil in this study may have caused more sensitivity to differences in viewing distance than would occur with a display incorporating a typical small exit pupil 1 mm or less in diameter (see Figures 3.8-9 and -10).

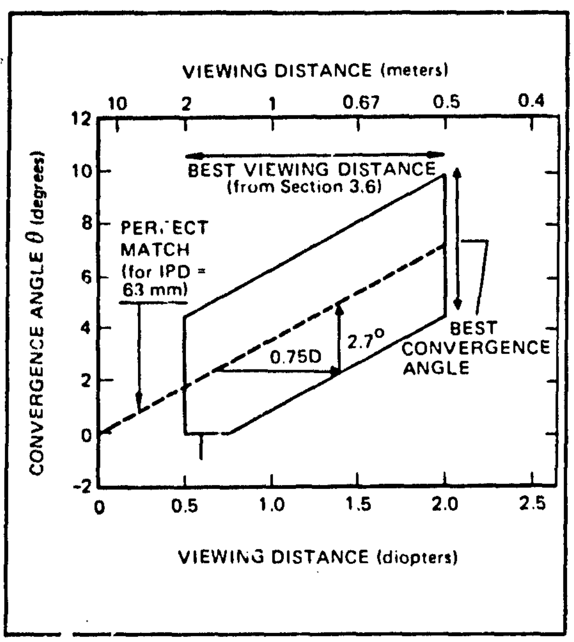

Figure 3.7-13. Convergence Angle Design Limits. The best viewing distance for a display is developed in Section 3.6 as falling between 0.5 and 2.0 diopters. The evidence summarized in the previous figure indicates that the display viewing distance should match the user's eye convergence at least to within 0.75 diopter. For an average (IPD = 63 mm) user, the 0.75-diopter (D) tolerance in distance corresponds to a 2.7-degree tolerance in convergence, resulting in the preferred design region illustrated.

A display with a convergence angle of zero is appealing because it will generally be less expensive to build and easier to align than one involving convergence. The acceptable design region illustrated will allow zero convergence so long as the design viewing distance is between 0.5 and 0.75 diopter. However, there is some very tentative evidence that a few interpreters, perhaps as many as 5 percent will have difficulty fusing the images in a zero-convergence display (Ref. 26). This suggests the desirability of providing at least a couple degrees of convergence.

Most individuals can actually diverge their eyes slightly beyond parallel (Ref. 27). Since such a condition is not a part of normal visual experience, it should be carefully avoided in a display.

3.7.4.3 VERTICAL DISPARITY IN MONOSCOPIC DISPLAYS

RECOMMENDATION:

Limit the vertical disparity between points separated by only a few degrees in a monoscopic display to 5 arc minutes. (Figure 3.7-4 can be used as a guide for relaxing this tolerance for points separated by greater distances.)

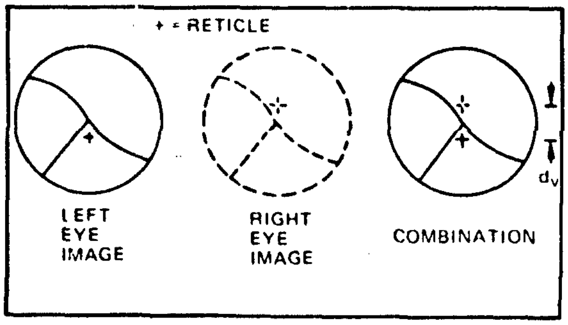

Figure 3.7-14. Vertical Disparity. Vertical disparity can generally occur in a monoscopic display only if a separate reticle is displayed to each eye or if there is a considerable difference in the distortion introduced by the two optical paths.

In the illustration, a cross reticle appears slightly higher before the right than before the left eye and this difference, d_V is the *vertical disparity*. If the vertical disparity is too large, it is not possible to fuse the two separate images (Ref. 28). Because the ground scene, in this case a road intersection, is usually the stronger stimulus for fusion, it will generally be seen as single and the reticle will blur or, as in the figure, it will be seen double. In some situations, a very small vertical disparity will even yield a sensation of depth (Ref. 29).

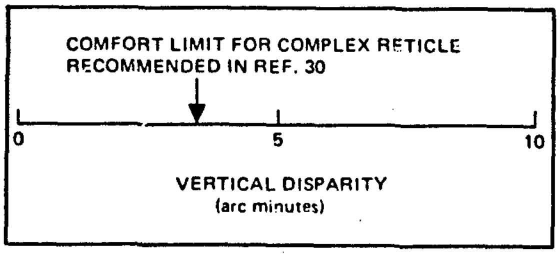

Figure 3.7-15. Comfort Limits. The only available data on the reduction of visual comfort because of vertical disparity were obtained with a complex reticle type pattern used as a head-up display in aircraft (Ref. 30,C). It was viewed against a monoscopic display of static and moving aerial imagery. Tolerance varied widely among subjects, but an extensive and informal data analysis yielded a recommendation by the authors to limit vertical disparity to 3.4 arc minutes.

3.7.4.3 VERTICAL DISPARITY IN MONOSCOPIC DISPLAYS (CONTINUED)

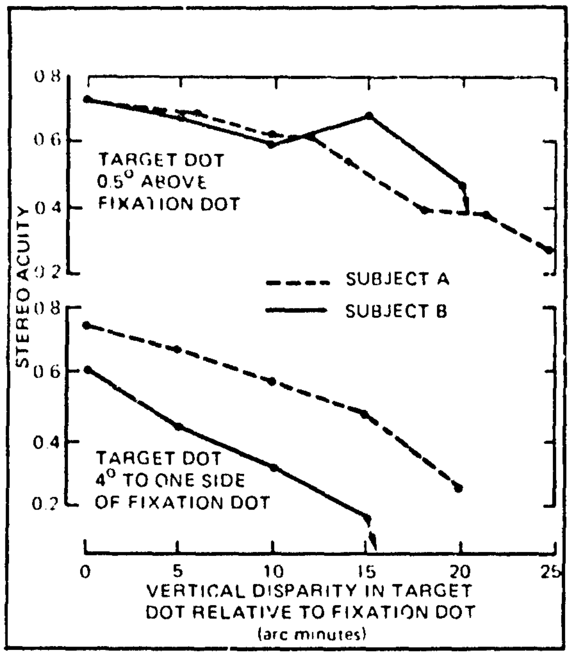

Figure 3.7-16. Ability to Discriminate Depth. This figure illustrates the loss in ability to perceive depth as vertical disparity increased (Ref. 31,C). The test consisted of two dots. In one set of trials, the target dot was 0.5 degree above the fixation dot, while in the other set, it was 4 degrees to one side.

Although the small number of subjects and small quantity of data make it difficult to decide exactly at what disparity value the loss is significant, there is even a suggestion of a loss at the smallest disparity value used, 5 arc minutes.

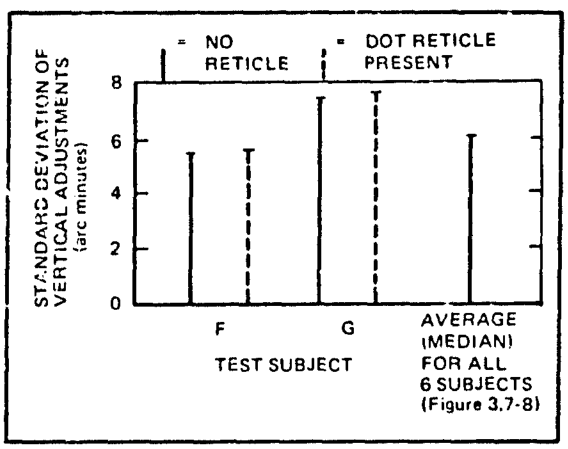

Figure 3.7-17. Variability in Vertical Disparity Settings. As in the case of vertical alignment considered in the previous section, the ability of display users to adjust out the vertical disparity in a display provides some insight into setting design limits. Two of the six subjects discussed in Figure 3.7-8, F and G, made settings both with and without a small opaque dot reticle present. Contrary to expectations, the variability of their settings was nearly the same in both situations.

Because only two of the subjects made settings with a reticle present, the best estimate for the average variability in vertical disparity adjustments is not the average for these two, but instead is the 6.0-arc-minute average for the entire six subjects.

Therefore, the comments about vertical alignment design limits in Figure 3.7-9 also apply here. Because of the additional data available on the problem of vertical disparity illustrated in Figures 3.7-15 and -16, they have somewhat less impact here.

3.7.4.4 LATERAL DISPARITY IN MONOSCOPIC DISPLAYS

RECOMMENDATION:

Limit the lateral disparity between points separated by only a few degrees in a monoscopic display to 5 arc minutes. If all sensation of depth must be avoided, reduce this limit to 1 arc minute, with a preferred limit of one-third this value, or 0.3 arc minute.

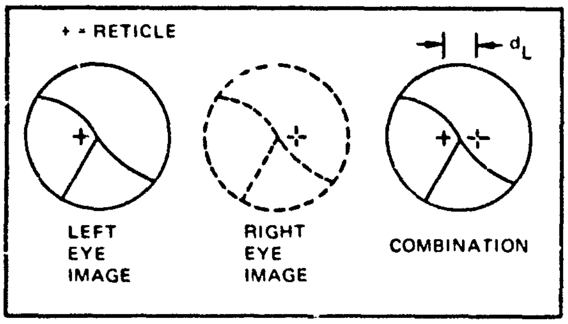

Figure 3.7-18. Lateral Disparity. Lateral disparity (d_L) is like vertical disparity (Figure 3.7-14) in that it can generally occur in a monoscopic display only if a separate reticle is displayed to each eye or if there is a considerable difference in the distortion introduced by the two optical paths. It differs from vertical disparity in that moderate amounts clearly yield the sensation of depth. (See discussion in Section 5.1.) It also differs in that considerably more lateral than vertical disparity can be tolerated before the image appears double (see Ref. 17).

As with vertical disparity, the ground scene is usually a stronger stimulus for fusion than the reticle, so it is the reticle that appears above or below the ground, or as a double image. If the images of the reticle diverge, as in the illustration, the reticle will appear to be below the surface of the ground. If the reticle images converge, the reticle will appear to be closer than the ground. A *diverging disparity* is sometimes referred to as uncrossed and a *converging* one as crossed.

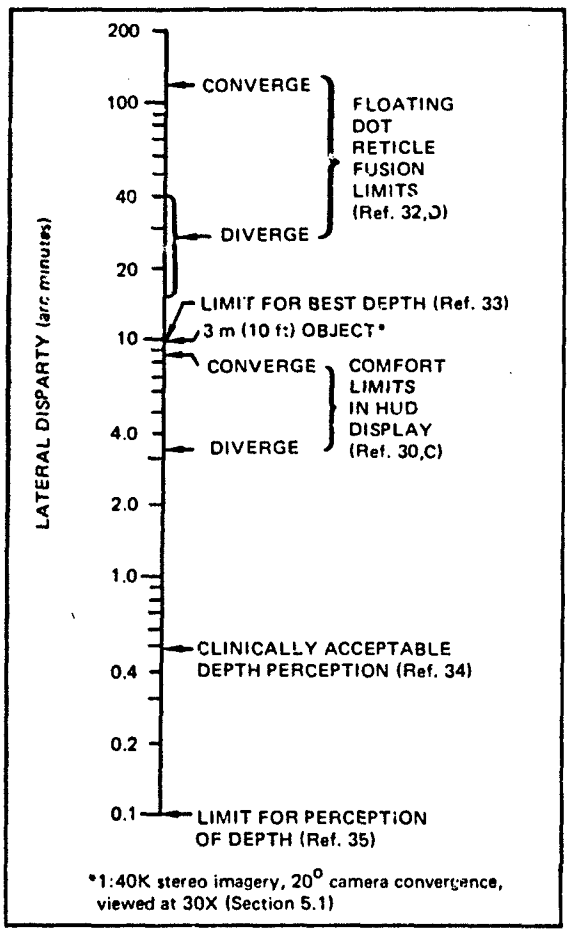

Figure 3.7-19. Effects of Specific Lateral Disparities. A single image and the sensation of depth can be obtained over an approximate range of three orders of magnitude of lateral disparity. At one extreme, under good viewing conditions, skilled individuals can discriminate a difference in depth equivalent to 0.1 arc minute and most can detect 0.5 arc minute. At the other extreme, experienced users of floating dot comparators can with effort fuse a dot reticle with more than 100 arc minutes of converging or 15 to 40 arc minutes of diverging disparity. The strongest impression of depth occurs with somewhat smaller disparities; according to one source, the upper limit for simple geometric objects is 10 arc minutes.

Design limits for imagery displays fall between these extremes and depend somewhat on the need to eliminate any sensation of depth in the image. In most situations, a converging disparity is more acceptable than a diverging one. The best available comfort limits were obtained for a display situation where the sensation of depth was neither useful nor directly harmful. This was an aircraft head up display (HUD) consisting of a complex reticle pattern viewed against a moving ground scene. Visual comfort limits were 3.4 arc minutes of diverging disparity and 8.6 arc minutes of converging disparity. (This is the same study used in Figure 3.7-15.)

Design limits based on a requirement to eliminate any sensation of depth must be considerably smaller, probably much less than 1.0 arc minute.

3.7.4.5 IMAGE ROTATION DIFFERENCE IN MONOSCOPIC DISPLAYS

RECOMMENDATION:

Limit the rotation difference between the two images in a binocular display to an amount that will not exceed the permissible vertical misalignment over the usable image field. Referring to Figure 3.7-22, if the permissible vertical misalignment is 10 arc minutes (Section 3.7.4.2), the rotation difference limit for a usable display field radius of 20 degrees is 0.5 degree.

If image rotation capability is included in the display, locate it in front of, rather than after, the optical element that splits the image for the two eyes, thereby eliminating rotation differences due to operator misadjustment. If this is impossible, at least incorporate locks on the two controls to prevent accidental rotation.

A rotation difference can occur in a monoscopic binocular display because of poor alignment or, in the case of an instrument that allows image rotation at each eyepiece, because of poor adjustment by the user. Observation suggests that with some displays such rotation differences are a serious source of visual problems.

Although there are some data on how large a rotation difference is acceptable, the best available approach in setting design limits is to consider the vertical misalignment introduced by the rotation difference.

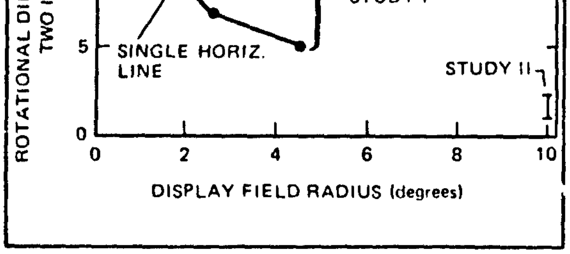

Figure 3.7-20. Tolerance for Image Rotation. The results of Study I (Ref. 36,B) illustrate how the acceptable amount of rotation difference decreases with the radius of the image field and increases with the complexity of the target. In this study, the test subject fixated at the center of the image field, and the rotation difference was increased slowly until he indicated that the target began to appear double. The subjects did not report visual discomfort at any stage of the test (Ref. 37); this might not apply to the considerably larger field typical of an imagery display. Also, their tolerance was reduced by mild stressors such as lack of sleep. A particularly interesting result of another study in this series was that rotation differences of this type are fused by the central nervous system, rather than by rotation of each eye around its visual axis as had been believed previously (Ref. 38,B).

Study II was a very limited test of how well subjects could eliminate rotation differences between members of five stereo pairs viewed in a display with a field radius of 10 degrees (Ref. 39,D). Each subject made 10 settings, and the absolute values of his errors were averaged. For the 16 subjects, the 5th and 95th percentile average errors were 1.0 and 2.2 degrees. This range is plotted here.

3.7.4.5 IMAGE ROTATION DIFFERENCE IN MONOSCOPIC DISPLAYS (CONTINUED)

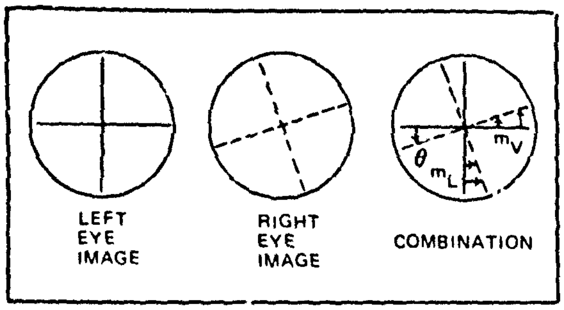

Figure 3.7-21. Image Rotation Geometry. The effect of rotating the image to one eye in a binocular display is to create vertical and lateral misalignment that increases with the rotation (θ). The display user will experience more misalignment (m_L and m_V) as he shifts his line of sight further from the center of rotation.

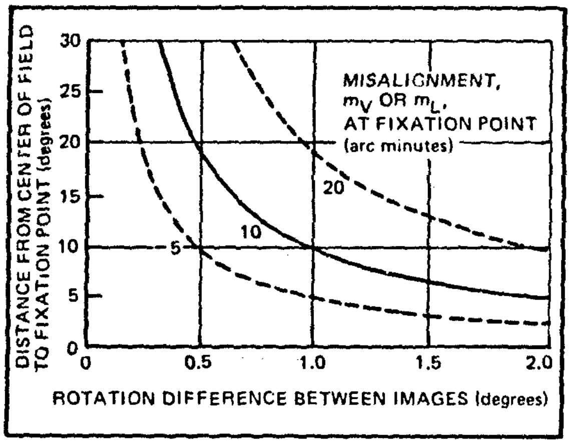

Figure 3.7-22. Conversion of Image Rotation Difference to Linear Misalignment. The usable image field is limited to the distance from the center of the field over which the vertical and lateral misalignment are acceptable. The most restrictive limitation is the 10 arc minutes developed in Section 3.7.4.1 for vertical misalignment. On this basis a rotation difference of 0.5 degree would not cause an unacceptable vertical misalignment within approximately 20 degrees of the center of the field (Ref. 40).

3.7.4.6 IMAGE SIZE DIFFERENCE (MAGNIFICATION) IN MONOSCOPIC DISPLAYS

RECOMMENDATION:

Limit the difference in size between the two images in a binocular display to an amount that will not exceed permissible vertical misalignment over the usable image field. Referring to Figure 3.7-27, if the permissible vertical misalignment is 10 arc minutes (Section 3.7.4.2), the image size difference limit for a usable display field radius of 20 degrees is 0.8 percent.

There are two ways a binocular display can cause a different size image to be presented to each eye. The most obvious cause is a difference in magnification between the two optical trains. With some instruments, an image size difference can also be caused by a difference in focus between the two optical trains. This might occur because the user has removed spectacles that provide a different correction for each eye, or because the instrument is tilted with respect to the imagery.

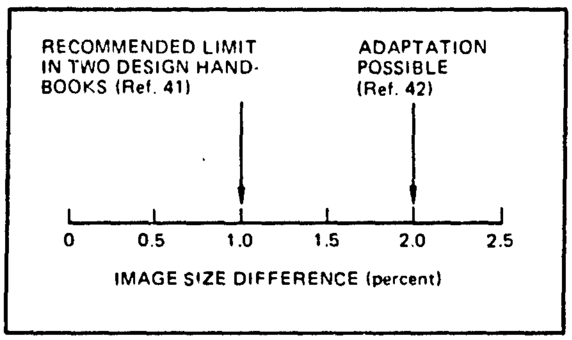

Figure 3.7-23. Other Limits on Image Size Differences. A maximum image size difference in binocular displays of 1 percent has been recommended by some authorities. Over a period of days, dedicated test subjects can adapt to image size differences of twice this amount, but only with considerable effort.

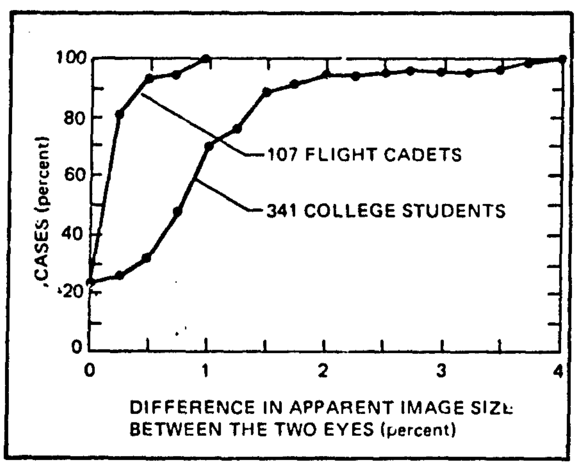

Figure 3.7-24. Normally Occurring Image Size Differences. The distribution of image size differences reported for two populations is illustrated (Ref. 43,C). A difference of 1 percent is generally considered a potential cause of visual problems in the *refraction clinic*, but much smaller differences can be troublesome (Ref. 44). For example, differences of 0.25 to 0.50 percent reportedly caused visual discomfort and serious constant and variable errors for photogrammetrists engaged in contour mapping; these problems were usually successfully eliminated by the prescription of special size correcting lenses (Ref. 45).

3.7.4.6 IMAGE SIZE DIFFERENCE (MAGNIFICATION) IN MONOSCOPIC DISPLAYS (CONTINUED)

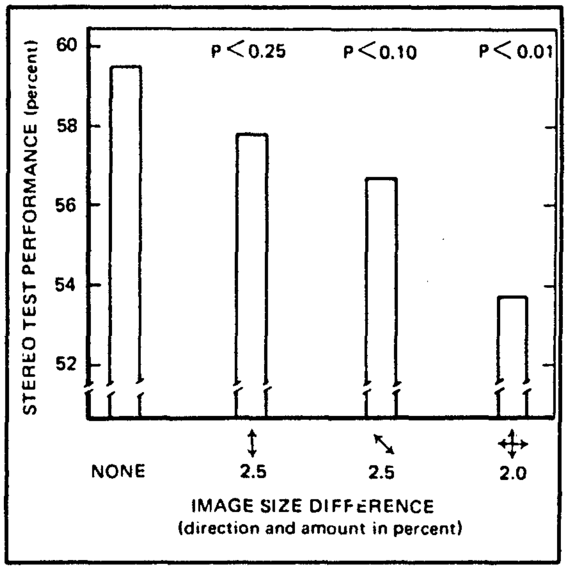

Figure 3.7-25. Reduction in Stereo Acuity With Image Size Differences in a Microstereoscope (Ref. 46,C). Image size differences reduced ability to discriminate depth in the stereo acuity test illustrated in Figure 5.1-11 and used in the study in Figure 3.7-12. A size difference along only one axis, as would occur with *anamorphic* magnification had less effect than a size difference in both directions. (P is the probability that the performance reductions observed were due to chance variation in the data.)

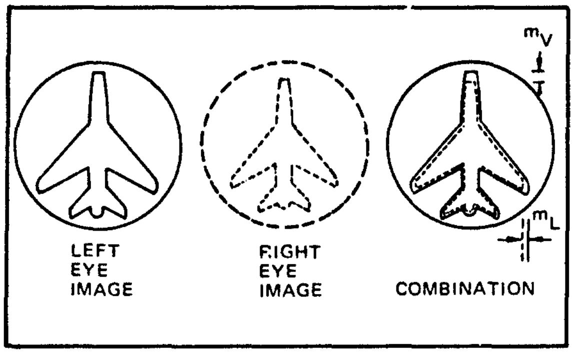

Figure 3.7-26. Geometry of Image Size Differences. A size difference between the images in a binocular display will be seen by the user as a misalignment in the vertical (m_V) and lateral (m_L) directions. The amount of this misalignment increases with the amount of the size difference and with the distance from the center of the field.

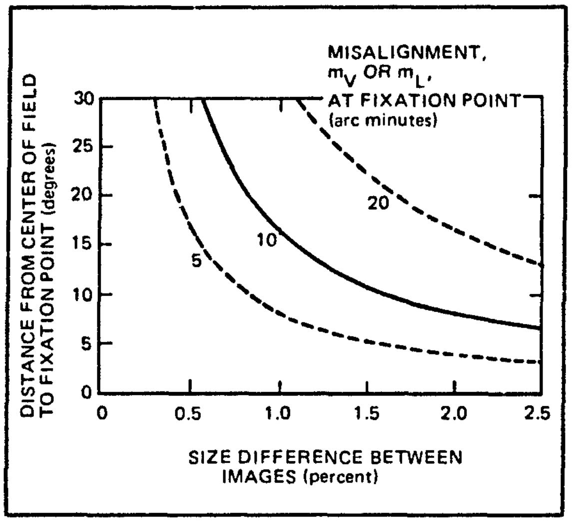

Figure 3.7-27. Conversion of Image Size Difference to Linear Misalignment. The usable image field is limited to the distance from the center of the field over which the vertical and lateral misalignment are acceptable. The most restrictive limitation is the 10 arc minutes developed in Section 3.7.4.1 for vertical misalignment. On this basis, a size difference of 0.8 percent would not cause an unacceptable vertical misalignment within approximately 20 degrees of the center of the field (Ref. 47).

3.7.5 IMAGE REGISTRATION IN STEREOSCOPIC DISPLAYS

Image registration in stereoscopic displays is considered in this section. Because the factors involved are nearly the same as those presented for monoscopic displays in Section 3.7.4, the treatment here is primarily in terms of additions and exceptions to that section.

One special problem in stereoscopic displays is distortion differences between the members of a stereo pair obtained at a high obliquity angle. Compensation for these distortions with anamorphic magnification is treated briefly in Section 5.1.4.

The discussion in the following parts of this section applies to the typical stereoscopic display in which the user can move the images of two members of the stereo pair relative to each other. If this is not possible, for example because the two pieces of imagery are permanently attached, then the more restrictive alignment limits developed for monoscopic displays in Section 3.7.4 apply.

If the stereoscopic alignment is determined by some automatic device such as an optical or electrical correlator, the additional problem of variation in alignment over time can arise. There are no directly relevant test data, but it is likely that such variations will be more troublesome than constant alignment errors of equal size. Until test data are available, the suggested design limit for variations in alignment over a short period, say a few seconds, is the 10-arc-minute value developed in Section 3.7.4.1 for vertical alignment. This limit should apply in both the vertical and lateral directions.

3.7.5.1 VERTICAL ALIGNMENT IN STEREOSCOPIC DISPLAYS

There is no good way to establish a design limit for vertical alignment of the optics in a stereoscopic display. The two images must be aligned to the same limits as in a monoscopic display, but because the display user can move them relative to each other the exact alignment of the optics is not critical. In fact, limited observation of stereo imagery set up by various interpreters indicates that small but noticeable differences in vertical alignment among individuals are common.

Ideally, the misalignment of the field edges should be small enough that it does not interfere with fusion of the imagery. There are no good data available. Because the area outside the field is dark and one of the images will always be visible in the area of overlap, this is probably a fairly weak source of interference, at least for the large field typical of imagery displays. Also, as Figure 3.7-4 illustrates, any effect decreases rapidly with distance from the fixation point and hence with distance inward from the edge of the field.

For the sake of appearances the designer will want to limit vertical misalignment to an amount that is not obvious to the user. There is no test data, but the observations on lateral alignment discussed in the next section suggest that most users would not notice a degree or so of field misalignment.

3.7.5.2 CONVERGENCE (LATERAL ALIGNMENT) ANGLE IN STEREOSCOPIC DISPLAYS

The same basic considerations apply to lateral image alignment in stereoscopic as in monoscopic displays, so the same design recommendations given in Section 3.7.4.2 apply.

However, as was noted in Section 3.7.5.1, in a typical stereoscopic display the user can move the images relative to each other in order to achieve whatever lateral alignment he desires. Limited observation indicates that the two members of a stereo pair are usually positioned by interpreters so that when they are seen fused the edge of one field is displaced laterally several degrees from the edge of the other. In one extreme case, two experienced interpreters were apparently satisfied by the stereo image obtained with one field shifted relative to the other by approximately one-third of the 40-degree display field (Ref. 48). Other than the obvious result of reducing the image area seen in stereo, there are no data to indicate what impact this kind of misalignment has on vision.

3.7.5.3 VERTICAL DISPARITY IN STEREOSCOPIC DISPLAYS

As with monoscopic displays, vertical disparity can occur in a stereoscopic display because the reticle has a different alignment than the imagery, or because of a difference in the distortion introduced by the two optical paths. Because the display user has control over vertical alignment of the imagery, significant disparity relative to a reticle will occur frequently, particularly if it is a weak stimulus for fusion such as an opaque dot. In a stereoscopic display additional disparity will result from any differences in the distortions present in the two pieces of imagery.

The design recommendations developed in Section 3.7.4.3 for monoscopic displays are the best available for stereoscopic displays.

3.7.5.4 LATERAL DISPARITY IN STEREOSCOPIC DISPLAYS

The comments in Section 3.7.5.3 concerning vertical disparity in stereoscopic displays also apply to lateral disparity, with the exception that lateral disparity will also be present because of height differences in the original ground scene. These are treated briefly in Figure 3.7-19 and at some length in Section 5.1. Lateral disparity not related to such height differences should be kept to the same limits developed in Section 3.7.4.4 for monoscopic displays.

3.7.6 PHORIA

RECOMMENDATIONS:

A phoria adjustment capability of $\pm 0.6^{\circ}$ vertically and $\pm 1.7^{\circ}$ laterally is desirable on any display used for extremely demanding visual tasks for extended periods of time, such as a high precision stereo comparator. On most other displays the available data do not justify the cost of such an adjustment. If provided, a scale to indicate the null position and the approximate amount of compensation in use is essential.

This section is notably lacking in test data from which to determine if a phoria adjustment is needed on a display. A large phoria is a well established cause of problems such as severe visual discomfort or double vision and generally requires clinical help in the form of spectacles or eye exercises. An argument against providing a phoria adjustment is that if this help is successful the individual will not need a phoria adjustment on his display, and if it is not he is unlikely to remain in such a visually demanding profession as image interpretation.

Whether smaller phorias that do not require clinical help reduce visual performance and therefore require a phoria compensation capability cannot be established from the available literature. Uncorrected phoria can cause a small error in the relative positioning of the eyes, so that the image of a single object does not fall on exactly corresponding points on the two retinas. Unfortunately, there are no test data that show whether or not this reduces visual performance (Ref. 49). In the only known study that is relevant, the one on stereo acuity summarized in Figure 3.7-12, the subjects were selected to include a typical range of lateral phorias and, with the exception of a few extreme cases, phoria had no impact on performance (Ref. 50). An additional argument against providing a phoria adjustment is the fact that with most imagery viewing tasks the display user will frequently shift his attention to other objects where he will not have the advantage of any phoria adjustment in the display.

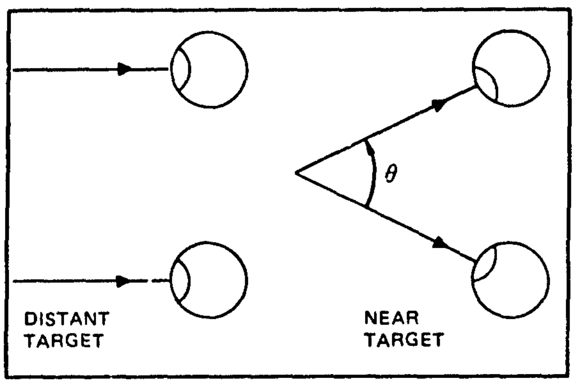

Figure 3.7-28. Normal Vision. Ideally, the balance within the sets of muscles that position the eyes is such that the visual axes intersect at the object being viewed. If this condition is not met, at least approximately, the additional effort required to maintain single vision can lead to visual discomfort, particularly with prolonged visual tasks. In extreme cases, the muscle imbalance may be sufficient to cause double vision.

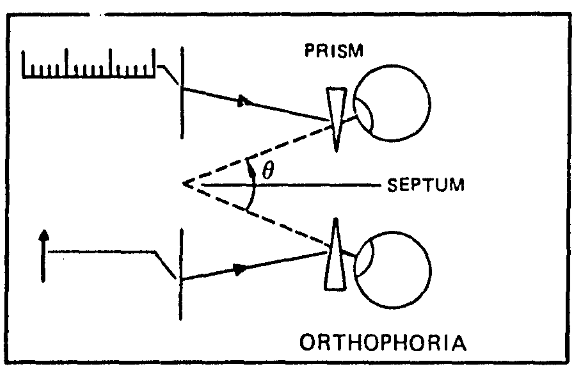

Figure 3.7-29. Measurement of Lateral Phoria. The angular relationship between the eyes in the absence of a stimulus for fusion is known as *phoria.* It can be measured by using prisms to redirect the lines of sight so that a scale appears before one eye and an index mark (↑) before the other. The position in which the test subject sees the index mark on the scale indicates the convergence angle, θ, between his eyes. If the convergence angle is correct for the distance to the scale, as in this illustration, he is said to be *orthophoric.*

3.7.6 PHORIA (CONTINUED)

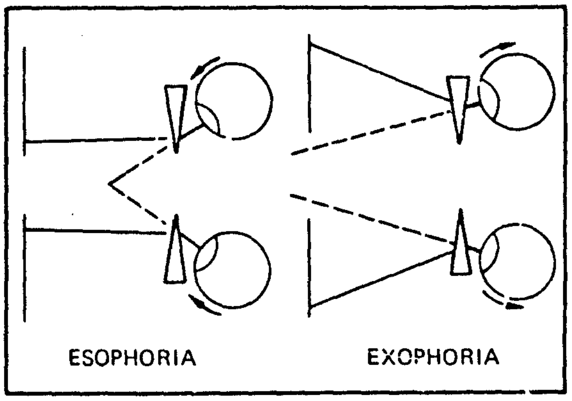

Figure 3.7-30. Lateral Phoria Types. If, in the test situation illustrated above, the individual's eyes turn inward relative to their proper position, so that the lines of sight intersect nearer than the scale, he has *esophoria*. If they turn outward, he has *exophoria*.

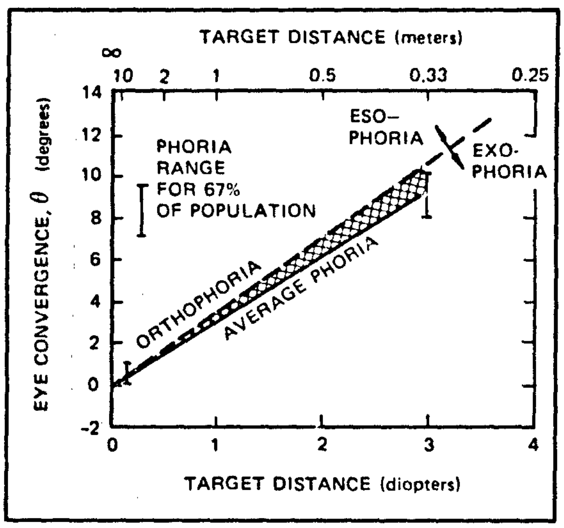

Figure 3.7-31. Distribution of Lateral Phoria. The orthophoric condition is defined by the normal relationship between target distance and convergence angle developed in Figure 3.7-11; the illustration here is for an average (IPD = 63 mm) individual.

The population tendency is toward exophoria, or inadequate convergence, particularly at the higher convergence angles required for viewing close objects (Ref. 51,X).

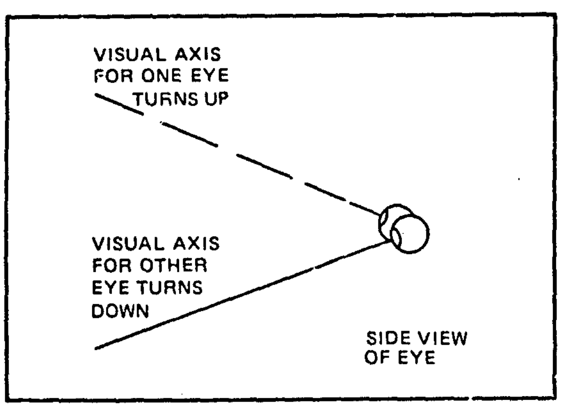

Figure 3.7-32. Vertical Phoria. If one eye tends to turn up or down relative to the other, an individual is said to have a vertical phoria.

3.7.6 PHORIA (CONTINUED)

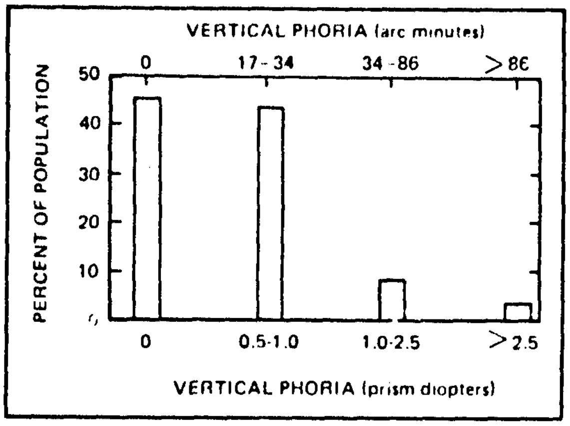

Figure 3.7-33. Distribution of Vertical Phoria (Ref. 52,X). As one would expect from the fact that the lines of the sight of the two eyes do not normally deviate vertically, vertical phorias are smaller and potentially more troublesome than lateral phorias. In general, anything over 0.6 degree is a potential source of visual problems (Ref. 53). The situation with vertical phoria is complicated by the existence of two distinct types, one of which cannot be corrected with spectacles (Ref. 54).

3.7.7 IMAGE DISTANCE

Differences in the (optical) distance to the two images in a binocular display will result if the two optical trains are not focused the same. Limited observations of experienced interpreters using common displays such as the Bausch and Lomb Zoom 70 and Zoom 240 in test situations suggest that such differences may occur frequently. There are no directly applicable data, but because such a situation sets up a conflict between the accommodative mechanism in the two eyes it is likely to contribute strongly to visual discomfort during extended periods of viewing. There is no obvious way to eliminate this problem, but providing good focus mechanisms will help. (See Section 3.8.)

3.7.8 IMAGE QUALITY

Figure 3.7-34 summarizes data indicating that stereo vision is hurt more by differences in quality between the right and left eye images than by an equivalent reduction in quality of both images. Studies with simple geometric targets have obtained exactly opposite results (Ref. 55,X). In a monoscopic display the user would of course have the option of simply viewing the better image monocularly.

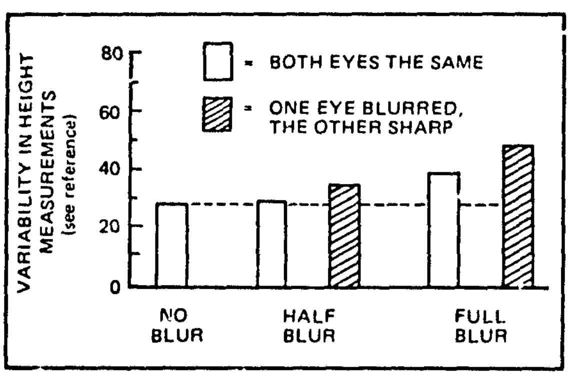

Figure 3.7-34. Impact of Image Quality Differences. Test subjects made height measurements using stereo photographs printed in focus and at two levels of blur (Ref 56,X). Five pairs were made up, one with no blur, two with one member blurred and the other not, and two with both members blurred. Performance was reported as the mean standard deviation, in micrometers, of the measurements on a particular pair. Performance was hurt more when the two eyes viewed different quality images than when both images were the same quality.

3.7.9 IMAGE LUMINANCE

RECOMMENDATION:

Limit the luminance difference between the two images in a binocular to less than 50%; a preferred limit is 25%.

The only available data on the effect of luminance differences is a limited study in which reducing the luminance of one member of a stereo pair by 50 percent reduced stereo acuity by 2.4 percent (Ref. 56,X). Whether this luminance ratio would have had a similar effect if more illumination had been available was not evaluated. On the basis of this study, the luminance difference should be less than 50 percent. How much less is necessarily arbitrary, but a value of 25 percent is certainly reasonable.

SECTION 3.7 REFERENCES

1. Refer to the discussion of asthenopia in almost any text on refraction. For example, this is covered in Chapter 9 of Ref. 54.

2. Hopkinson, R. G. and Collins, J. B. *The Ergonomics of Lighting.* McDonald, London, 1970. Although this book is concerned with illumination, the conclusions in Chapter 6, which deals with visual fatigue, are generally relevant to problems in binocular viewing also. The authors review 51 studies and note many instances where an experimenter has apparently developed a consistent technique for measuring visual fatigue, only to have other experiments fail in attempts to replicate his results. They conclude (pages 147-148) that at present there is no adequate substitute for direct subjective assessment by the individuals who will have to work in a particular viewing situation.

3. Schapero, M., Cline, D. and Hofstetter, H. W. (Ed.) *Dictionary of Visual Science* (2nd ed.) Clinton Book Co., Radnor, Pennsylvania, 1968.

   Also see Ref. 4.

4. Freeman, M. H. On the use of the term "biocular." *Optics and Laser Technology*, Vol. 5, No. 6, December 1973, pp. 266-267. One tendency is to use the term biocular to refer only to a display with a single exit pupil large enough to include both eyes. In this handbook, such devices are considered to make up only one of several classes of biocular displays.

5. Sands, P. J. Visual aberrations of afocal systems. *Optica Acta,* Vol. 18, 1971, pp. 627-636.

   Haig, G. Y. Visual aberrations of large-pupil systems. *Optica Acta,* Vol. 19, 1972, pp. 543-546.

6. Displays such as *stereomicroscopes* that provide a three-dimensional image of a real object are not the subject of this document. However, because they are normally used to view only a single object, the design recommendations for monoscopic binocular displays will generally apply.

7. Barany, E. *Acta Ophthal.* Kbh., Vol. 24, 1946, p. 634, and Horowitz, M. W. *J. Exp. Psychol.*, Vol. 39, 1949, pp. 581+, cited by Campbell and Green in Ref. 8.

8. Campbell, F. W. and Green, D. G. Monocular versus binocular visual acuity. *Nature,* Vol. 208, 1965, pp. 191-192. Results were quite consistent over the two subjects tested.

   Kristofferson, A. B. *Monocular and Binocular Detection Thresholds for Targets Varying in Size and Retinal Position,* Project Michigan Report 2144-290-T, Vision Research Laboratories, Univ. of Mich., 1958 (Also available as AD 206192.) A difference of 46 percent was obtained in this study.

9. Hertzberg, H. T. E., Daniels, G. S. and Churchill, E. *Anthropometry of Flying Personnel–1950.* WADC Technical Report 52-321, Wright Air Development Center, WPAFB, Ohio, 1954, p. 61.

10. Damon, A., Stoudt, H. W. and McFarland, R. A. *The Human Body in Equipment Design.* Harvard University Press, Cambridge, Massachusetts, 1966, p. 130.

11. Dreyfuss, H. The measure of man. In *Human Factors in Design,* Whitney Library of Design, New York, 1967, p. B1.

12. The percentile and range values in Figure 3.7-2 are based on data collected by military technicians on imagery interpreters during 1975. The value of 46mm for one former interpreter is based only on a verbal report made to the senior author and was not confirmed by measurements.

13. Military Standardization Handbook, MIL-HDBK-141. *Optical Design.* U.S. Dept. Defense, 1962.

14. The reduction in IPD with eyepiece convergence is 2 (10 sin $\theta/2$), where θ is the eyepiece convergence angle. In some instruments, the eyepiece convergence angle is not constant, but varies with the user's IPD.

15. This fact is included in the treatment of duction tests in most texts on refraction. See, for example, Figure VII-12 of Ref. 54.

16. Ogle, K. N. and Prangen, A. deH. Observations on vertical divergences and hyperphorias. *A.M.A. Arch. Ophthal.*, Vol. 49, 1953, pp. 313-334.

Also, see Ref. 19.

17. Mitchell, D. E. A review of the concept of "Panum's Fusional Areas." *Amer. J. Ophthal.*, Vol. 43, 1966, pp. 387-401. These data are from four experiments reviewed by Mitchell and summarized in his Figure 5. He notes that a double image is nearly impossible to recognize more than 10 degrees in the periphery, making measurements in this region highly variable.

18. Bureau of Visual Science. *American Optical Refraction Handbook*. American Optical Company, 1950. These data on vertical ductions are very limited but are the best that could be located and are considered realistic.

19. Crook, M. N., Anderson, E. M. S., Bishop, H. P., Hanson, J. A. and Raben, M. W. *The Misalignment of Stereoscopic Materials as a Factor in Visual Fatigue I. Vertical Misalignment*. Tufts University Institute for Psychological Research, Medford, Mass., under Office of Naval Research contract NONR-494(17), 1962.

20. According to Ref. 21 (page 845), this was the conclusion of British work during World War II. No report was cited.

21. Harker, G. S. and Henderson, A. C. Effect of vertical misalignment of optical images on depth judgments. *J. Opt. Soc. Am.*, Vol. 46, 1956, pp. 841-845. The opaque diamonds were 25 arc minutes high, 18 arc minutes wide, and had a center-to-center spacing of 36 arc minutes. They were seen against a 54-fL background at 6 meters. Exact lateral disparity was 10.7 arc seconds. Thirty young adult subjects were tested, half with a vertical alignment change each 30 seconds and half with a change each 60 seconds. Because of the way the authors reported their data, it is impossible to determine the actual percentage of errors or average response time. Making certain assumptions, the average response time was either 2, 4, or 8 seconds.

22. These data are from two very small unpublished studies. The test imagery consisted of two copies from a single high-resolution aerial negative. One copy was placed on each stage of a microstereoscope and the subject adjusted one of the two stages in the vertical direction until he was satisfied he had the best possible adjustment. The six test subjects were all familiar with viewing aerial photography. Each made 5 to 10 settings of the stage, using one or more viewing conditions as indicated in the table. The standard deviation of these settings, in arc minutes, is reported. (Two subjects, F and G, made settings both with and without a small floating dot reticle present; the data obtained with the reticle are used in Section 3.7.4.4).

DISPLAY	MAGNIFICATION	TEST SUBJECTS A	B	C	D	E	F
B&L HIGH POWER STEREO VIEWER (TWIN DYNAZOOM)	60X	4.0	5.9	7.0			
	120X	2.5			6.0		
STEREO COMPARATOR	30X					5.5	7.3
STEREO COMPARATOR WITH FLOATING DOT RETICLE	30X					5.2	6.4
	60X					6.3	9.0

23. Edwards, A. L. *Experimental Design in Psychological Research* (revised). Holt, Rinehart and Winston, New York, 1960. See Table III, p. 351.

24. Eye convergence angle, θ, is equal to 2 arc tan (D)(IPD/2), where D is the distance to the target in diopters and the IPD is expressed in meters.

Some individuals can use eye convergence angles radically different from the normal values shown in order to view stereo without optical aids (see Figure 5.1-16). However, many potential display users cannot view stereo in this manner and it therefore does not provide useful guidance in selecting convergence angle design limits.

25. Farrell, R. J., Anderson, C. D., Kraft, C. L. and Boucek, G. P., Jr. *Effects of Convergence and Accommodation on Stereopsis* Documents D180-19051-1 and D180-19051-2. The Boeing Company, Seattle, Washington, 1970. Each data point on the curves in Figure 3.7-12 represents 16 responses by each of 32 subjects. Subjects were selected to include a range of phorias, accommodative amplitudes, and spherical refractions.

Ideally, this experiment should be expanded by making a comparison between visual performance with parallel (0-degree convergence) and 2.0- to 2.5-degree convergence eyepieces at a constant viewing distance of 0.74 diopter.

26. This statement is based primarily on anecdotal evidence from engineers concerned with testing imagery displays. In the single instance observed by the editor, one interpreter out of 14 being tested on a new display was unable to obtain a single fused image on two parallel eyepiece displays.

27. Bureau of Visual Science, *Methods of Refraction and the Modern Phoropter.* American Optical Company, Southbridge, Mass., 1941. Cited in Table VIII, p. [illegible] of Ref. 18.

28. In order to obtain single vision when using both eyes, it is necessary for the light from each particular object point to fall on approximately corresponding points on the two retinas. The term "approximate" allows for the fact that a point on one retina actually corresponds to an area on the other. This area is known as Panum's fusional area; recently the average radius of this area has been referred to as the disparity threshold for diplopia, or DTD. (Diplopia means double vision.) Typical values for DTD are 5 to 15 arc minutes, although values from 2 to 30 arc minutes have been reported. Depending on the method of measurement, some experimenters have found DTD to be larger in the horizontal than the vertical direction while others have found no differences. (See the summary in Ref. 17.)

29. Lawson, E. A. Vertical disparities. *Brit. J. Psychol.* Vol. 63 1972, pp. 265-270. Approximately half of the 12 subjects reported a sensation of depth when the only disparity present in an array of geometric targets was in the vertical direction. Experience during the test was probably an important factor. Although these results are interesting, they have no obvious direct impact on display design.

30. Gold, T. Visual binocular disparity tolerances for head-up displays. *Electro-Optical Systems Design Conf., 1971 West*, 1971, pp. 399-406.

Gold, T. and Hyman, A. *Visual Requirements Study for Head-up Displays. Final Report, Phase 1.* JANAIR Report 680712, Office of Naval Research, 1970.

31. Ogle, K. N. Stereopsis and vertical disparity. *A.M.A. Arch. Opthal.*, Vol. 1955, pp. 495-504. Only two subjects were tested.

32. These values were obtained during the very small study described in Ref. 22. Subjects E and F, using the small opaque floating dot reticle in the stereo comparator, floated the dot as far above (converging dot) and as far below (diverging dot) ground level in a stereo image as was possible while still keeping the dots fused. This ability varies widely among individuals and is affected by experience.

33. Ogle, K. N. Disparity limits of stereopsis. *Arch. Opthal.*, Vol. 48, 1952, pp. 50-60. (Also, Ogle, K. N. On the limits of stereoscopic vision, *J. Exp. Psychol.*, Vol. 44, 1952, pp. 253-259.)

Similar results appear in: Blakemore, C. The range and scope of binocular depth discrimination in man. *J. Physiol.*, Vol. 211, 1970, pp. 599-622.

34. Ricciardi, C. A. *The Stereoscopic Angle and Its Relationship to the Standard Air Force Tests for Depth Perception.* USAF School Aviation Medicine Report, SAM-TR-66-70 (AD 640932), 1966. The lateral disparity that must be detected in order to pass Air Force depth perception tests is discussed. Values for three common tests are 0.53, 0.42, and 0.18 arc minute.

35. Graham, C. H. Visual space perception. Chapter 18 in Graham, C. H. (Ed.), *Vision and Visual Perception*, Wiley, New York, 1965, pp. 526-527.

36. Kertesz, A. E. Disparity detection within Panum's fusional areas. *Vision Res.*, Vol. 13, 1973, pp. 1537-1543. Two subjects were tested.

37. Kertesz, A. E. Personal communication, January 1975.

38. Kertesz, A. E. and Jones, R. W. Human cyclofusional response. *Vision Res.*, Vol. 10, 1970, pp. 891-896.

39. Kraft, C. L. *Rotational Tolerances in the Alignment of Stereo-Photographic-Transparencies.* Document D180-19057-1, The Boeing Company, Seattle, Washington, 1968.

40. This figure illustrates the relationship ϕ = arc tan (m/60A) where ϕ is the rotational difference in degrees, m is the linear misalignment in the image expressed as a visual angle in arc minutes, and A is the distance from the center of rotation expressed as a visual angle in degrees.

41. Military Standardization Handbook MIL-HDBK-141, *Optical Design.* U.S. Department of Defense, 1962. Also, Hempenius, S. A. Specifications for mirror stereoscopes. *International Arch. of Photogrammetry*, Vol. 14, 1962, pp. 45-51.

42. Morrison, L. C. Further studies on the adaptation to artificially-induced aniseikonia. *Brit. J. Physiol. Optics*, Vol. 27, No. 2, 1972, pp. 84-101.

43. Burian, H. M. Clinical significance of aniseikonia. *Arch. of Ophthal.* Vol. 29, 1943, pp. 116-133.

A difference in refractive power between the two eyes is one of several causes of naturally occurring image size differences. A difference in power of 1.0 diopter is variously estimated to cause a 1 to 2 percent size difference. See p. 507 of Ref. 44 and p. 276 of Ref. 54.

Differences in spectacle lens power can also cause image size differences and are a potential source of visual difficulties when the lenses differ by more than 0.5 diopter. (Ref. 54, Chapter 8 and particularly pp. 288 and 298.) If necessary, spectacle lens can be specially ground to eliminate these size differences, or to compensate for naturally occurring differences.

44. Duke-Elder, S. and Abrams, D. *Ophthalmic Optics and Refraction.* Vol. V of Duke-Elder, S., *System of Ophthalmology.* C. V. Mosby Company, St. Louis, 1970, p. 516. Also see pp. 228, 290, 294, 297, and 298 of Ref. 54.

45. Enoch, J. Personal communication, January 1975. Based on Dr. Enoch's work during the 1960's with an unspecified number of ACIC photogrammetrists, some of whom were at the point of changing occupations because of vision problems. In most instances, specially designed color-corrected size-compensating spectacle lenses eliminated their difficulties.

46. Kraft, C. L. *Preliminary Studies: The Influence of Moderate Aniseikonia on Stereo Perception on Horizontal Mensuration.* D180-19058-1, The Boeing Company, Seattle, Washington, 1972.

47. This figure illustrates the relationship S = 1.667 m/A, where S is the image size difference in percent and m and A are defined as for rotational differences in Ref. 40.

48. Personal experience of the senior author while using interpreters as test subjects in order to evaluate new imagery displays.

49. This phenomenon is known as fixation disparity. It has been studied extensively by Ogle (Ogle, K. N. *Researches in Binocular Vision.* Hafner, New York, 1964) and is the subject for a new vision test (Grolman, B. Binocular refraction–fixation disparity. *The Optician*, Vol. 17, September 1971, pp. 16-19). There is some evidence that it can cause a constant error in apparent depth and that this error can affect the output in certain operations, such as contour mapping (Veres, S. A. Investigation of fusion and fixation disparity limits for photogrammetry. GIMRADA report available as AD 625 217, and Veres, S. A. The effect of the fixation disparity on photogrammetric processes. *Photogram Engr.*, Vol. 300, 1964, pp. 148-153). Theoretically, in floating dot stereo mensuration such errors will cancel out and can be ignored.

50. The exceptions were two extreme esophores, who had considerable difficulty using parallel eyepieces, particularly when a near viewing distance was required. (The data for these two subjects are not included in Figure 3.7-12.) The number of extreme esophores in the population is generally very low.

51. These phoria values are weighted averages for the 7,516 subjects included in the 15 studies summarized in Table I, p. 105, of Ref. 18. Unfortunately the method of measurement was not included in this table. The table listed values for only two viewing distances; these are shown in Figure 3.7-31 along with a linear interpolation.

52. Oaks, I. W. and Oaks, L. E. Some clinical observations on vertical phorias in one thousand refractive patients. *Eye, Ear, Nose and Throat Monthly*, Vol. 15, 1936-1937, pp. 333-336. Cited in Table XII, p. 113 of Ref. 18.

53. See page 113 of Ref. 18.

54. Borish, I. M. (Ed.) *Clinical Refraction*. Professional Press, Chicago, 1970, pp. 870-871.

55. Graham, C. H. Visual perception. Chapter 23 in Stevens, S. S. *Handbook of Experimental Psychology*. Wiley, New York, 1951. The test data on which this statement is based were reported by Matsubayashi in 1938, and are summarized by Graham on page 891.

56. This work was conducted by Norma Miller at the University of Rochester's Institute of Optics. The original reports are generally unavailable, but many of the results were summarized in Anson, A. Significant findings of a stereoscope acuity study. *Photogram. Engr.*, Vol. 25, 1959, pp. 607-611.

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3.8 FOCUS MECHANISM

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SECTION 3.8 FOCUS MECHANISM

RECOMMENDATION:

Minimize the need to refocus after imagery translation or a change in magnification.

The focus controls on an *aerial image display* allow the user to obtain an image at an acceptable distance by changing the relative positions along the optical axis of the *object (imagery)*, the image and the optical elements. (Image distance for an aerial image display is defined in Figure 3.6-1.)

In some kinds of displays the user's choice of image distance is limited. For example, the screen location in a rear screen projector fixes image distance precisely, and the presence of another sensor such as a vidicon may place restrictions on it. Other reasons the designer may need to at least partially fix image distance are considered in the introduction to Section 3.6.

In many imagery viewing situations the display user adjusts focus almost continuously. While searching imagery that is moving relative to the display, he may have to focus to compensate for variations in film curl and for changes in the distance between the imagery support surface and the objective lens caused by inadequacies in the mechanical support system. Magnification changes require refocusing many displays, particularly when a different objective lens is involved. Ideally, the display will be designed so that there is no need for refocus after the imagery is translated or after magnification is changed. A display that remains in focus as magnification is changed is said to be *parfocal*. Refocusing is also frequent when the magnification is sufficient to make the blur in the imagery apparent, possibly because the user is then unable to be certain that he has the best possible image.

Ideally, the need to adjust the focus control will be reduced by constructing the display so that the image remains in focus as the imagery is moved and as the magnification is changed

Several terms are used in specific ways in this document. *Depth of field* refers to *object space* and *depth of focus* refers to corresponding quantities in *image space* (Ref. 1). Also, in many biological microscopes the display focus control moves the stage holding the object being viewed up and down. The term "stage movement" will be used here to describe the action of a focus control even though it may be the objective lens or the entire optical system that actually moves.

SECTION 3.8 FOCUS MECHANISM

3.8.1 FOCUS RANGE REQUIREMENTS

RECOMMENDATION:

Provide a display focus adjustment capability of at least ±4 diopters, and preferably ±6 diopters (Figure 3.8-3).

Allow a difference in focus of the two optical paths of a binocular display of at least 1.5 diopters, and preferably 3.5-diopters (Figure 3.8-4).

Do not allow a difference in focus in the two optical paths of a binocular display, whether introduced to compensate for differences between the operator's eyes (Figure 3.8-4) or to correct for some misalignment in the display, to cause an unacceptable difference in size of the two images (Section 3.7.4.6).

Provide a scale to indicate, at a minimum, the focus difference between the optical paths, and ideally the actual image distance in diopters.

This section considers the range of image distances that must be provided by the display focus mechanism in order to satisfy a reasonable proportion of potential users. The focus mechanism must also compensate for several variables not treated here, such as film curl, film thickness, and location of the film support surface relative to the objective lens.

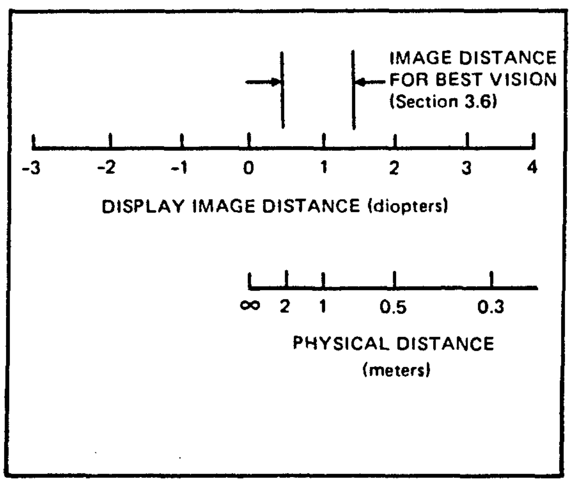


Figure 3.8-1. Optimum Image Distance for Vision. As Figure 3.8-1 illustrates, the focus control on an aerial image display moves the displayed image closer or farther away from the display user. It is better to express *image distance* in *diopters*, rather than in units of physical distance such as meters, because variations in objective lens to image distance are more directly related to the former unit. In addition, only a unit like the diopter provides a means of indicating the distance to the image as it moves away and, in a sense, goes beyond infinity. The term "diopter" is defined in the glossary (Section 8.0).

In Section 3.6 an optimum image distance for an imagery display of 0.5 to 1.5 diopters (2.0 to 0.67m) is developed. As is noted in the introduction to Section 3.6, image distance in an aerial image display varies with focus setting, but may be fixed by the presence of a reticle or a vidicon, or the requirement to maintain parfocality as magnification is changed.

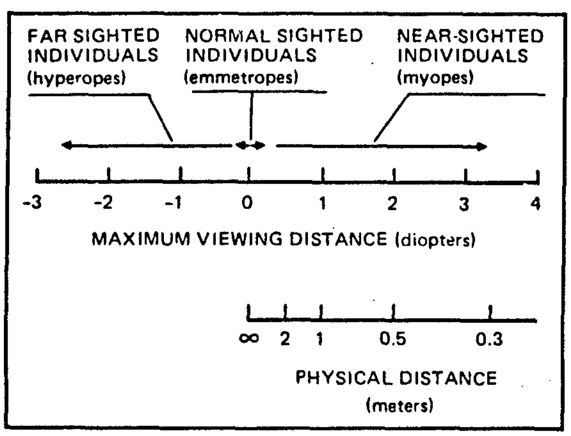


Figure 3.8-2. Maximum Viewing Distance and Refractive Error. Individuals can be characterized by the location of the most distant point at which they can maintain clear vision. The extent to which this differs from infinity is referred to as their *refractive error.*

Strictly speaking, the best image distance illustrated in the previous figure applies to normally sighted individuals or to those with refractive errors that have been successfully corrected with spectacles. If the display has been designed to provide an image at a distance of 0.5 to 1.5 diopters, individuals with an uncorrected refractive error, and those with excessive *presbyopia* (see Figure 3.6-3), will need a focus adjustment to compensate. If the imagery-to-objective lens distance must be held constant, this compensation must occur at the eyepieces.

3.8.1 FOCUS RANGE REQUIREMENTS (CONTINUED)

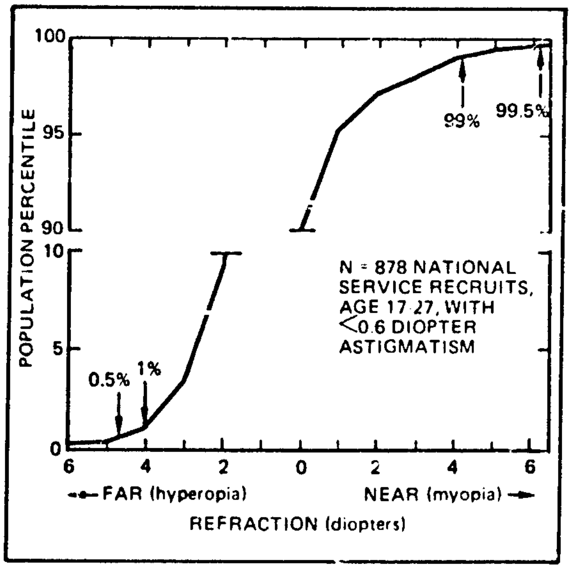


Figure 3.8-3. Distribution of Refractive Errors. While most individuals have little refractive error, a significant number have sufficient error to require compensation if they remove their spectacles when using the display. The data in Section 3.9.5 suggest that about 20 percent of the interpreters using a display would first remove their spectacles.

This curve shows the distribution of refractive errors in the general population (Ref. 2,B). It indicates that an adjustment range of ±4 diopters is required to include 98 percent of the population, and ±6 diopters to include 99 percent.

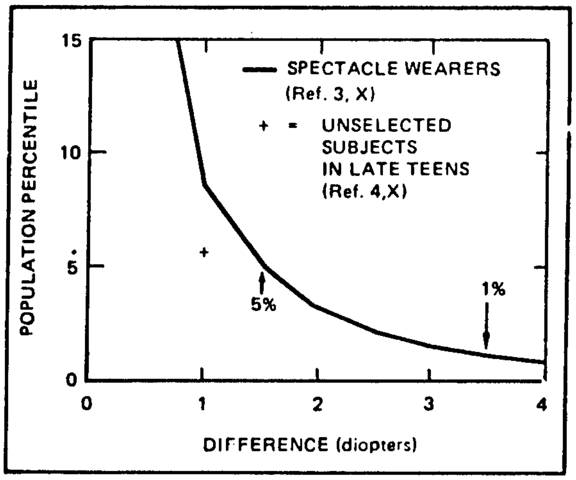


Figure 3.8-4. Refractive Differences Between the Two Eyes. Most individuals have some refractive difference between the two eyes. Assuming they don't wear spectacles to compensate, a difference in the image distance in the two optical trains of ±1.5 diopters must be available to be sure of accommodating 95 percent of potential users; ±3.5 would handle 99 percent. A range of ±3.5 diopters is suggested. This should be ample, since many individuals with this large a refractive difference will be wearing special spectacles to compensate for the resulting image size difference and they will not remove these when using the display (Section 3.7.4.6). Care should also be taken to ensure that a difference in image distance does not result in an image size difference in the display.

3.8.2 PRIMARY FOCUS CONTROL

RECOMMENDATIONS:

Use the procedure outlined in Figure 3.8-7 to establish the ratio of stage to focus control movement.

If focus control knob rotations of two or more turns will be frequent, provide a coarse focus control or a convenient, recessible crank handle.

Use a focus knob diameter of 25 to 75 mm (1 to 3 in); 50 to 62 mm (2 to 2.5 in) is preferred unless the resistance is very small (Figure 6.2-8).

Limit focus knob resistance to 11.3 g-m (16 oz-in) unless testing verifies that more resistance is acceptable (Figure 6.2-8).

Keep the ratio of resistance to upward versus downward motion less than 2:1.

Eliminate noticeable variations in resistance as the control is turned.

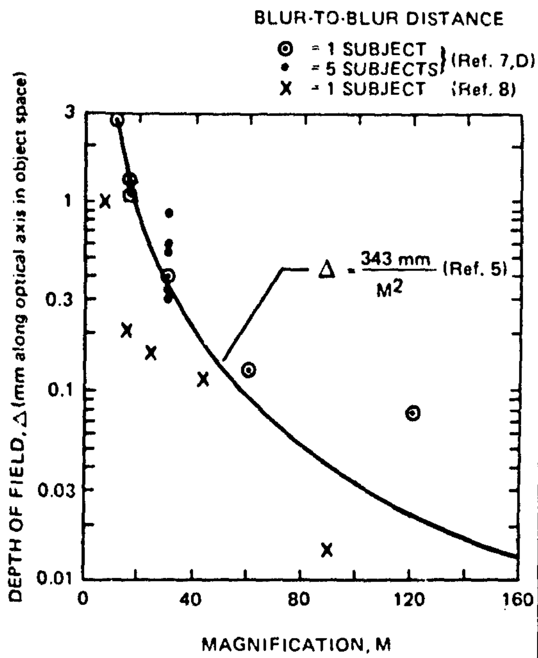
Limit backlash to twice the depth of field at the highest commonly used magnification; half this amount is preferred (Figure 3.8-8).

Do not use pushbutton-type focus controls because they interfere with focusing by bracketing (Figure 3.8-6).

The primary focus control varies the separation of the stage (imagery support surface) and the objective lens of the display. For a stereoscopic display it varies this separation for both optical trains simultaneously The stage (or objective lens) movement for a given amount of control movement must be sufficiently small that precise stage positioning is possible at high magnification and yet must not be so small that the number of control revolutions becomes excessive at low magnification or when compensating for film curl or variations in *working distance* with different objective lenses. Figure 3.8-7 provides an analytical technique for estimating the best movement ratio.

Size and maximum resistance for a focus control knob are discussed in Figure 6.2-8. A problem occurs with some focus control mechanisms that raise and lower a heavy display such as a microstereoscope relative to the imagery support surface. Unless part of the weight is supported with a spring or a counterweight, the control resistance will be much greater when raising than when lowering the display. There are no established limits on the ratio between resistance in the two directions, but experience suggests that some users will be dissatisfied with a value much larger than 2:1.

3.8.2 PRIMARY FOCUS CONTROL (CONTINUED)



$$\Delta = \frac{580 \times 10^{-6}}{NA^2} + \frac{0.146}{M \cdot NA} + \frac{250}{M^2} = \frac{343^*}{M^2} \quad \text{(Ref. 5)}$$

*THIS EQUALITY IS BASED ON THE ASSUMPTION THAT NA = 0.0034M.

Figure 3.8-5. Estimation of Depth of Field. The depth of field, Δ, of a display is the total distance the object (imagery) can move along the optical axis that still results in adequate image quality. It is necessary to consider depth of field here because it provides an estimate of how far the display user must move the stage relative to the objective lens in order to pass through the region that provides a clear image. This value is used in the analysis in Figure 3.8-7.

The value of Δ depends on *diffraction* effects, on the image quality standard imposed, and for *aerial image displays* such as microscopes, on the *accommodative amplitude* of the display user (Ref. 5). Theoretical treatment of depth of field is extensive but there is little agreement on how it should be measured (Ref. 6).

The theoretical relationship between depth of field and magnification (M), $\Delta = 343/M^2$ mm, is based on several assumptions (Ref. 5). For example, over the range of magnification illustrated, the largest portion of Δ is due to the accommodative amplitude of the display user. The value used, 4.0 diopters, is the one generally used in calculations of this type (Ref. 5). However, the data in Sections 3.6 and 3.7.4.2 suggest it may be too large by a factor of at least 2 for a *binocular* display that reduces accommodative amplitude by fixing the eye convergence angle.

The equation for depth of field also varies with the amount of blur considered acceptable in the image. The equation shown here is based on allowing a point in the object to appear as a blurred disc 2 arc minutes in diameter in the image (Ref. 5). A smaller limit on the size of this disc decreases the depth of field and a larger limit increases it.

An equation for Δ based only on magnification, such as the one shown here, is useful but requires an assumption about the relationship between magnification and *numerical aperture* (NA). The relationship used here, NA = 0.0034M, is based on microstereoscopes typically used for viewing imagery, such as the Bausch and Lomb Zoom 240, operating over a magnification range of 6 to 50X (Ref. 5). Because in most presently available displays numerical aperture does not continue to increase at this rate at higher magnifications, the equation $\Delta = 343/M^2$ probably underestimates the contribution of numerical aperture to depth of field at magnifications significantly greater than 50X.

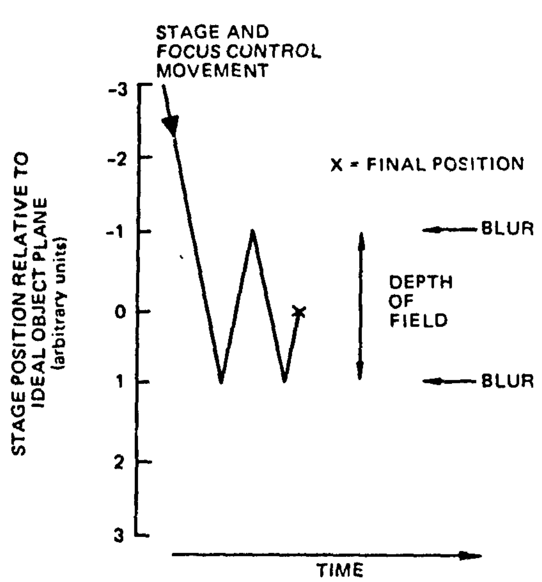


Figure 3.8-6. Focusing by Bracketing. At low magnifications the depth of field is large enough that the display user can be relatively casual about focusing. At high magnifications correct focusing is more critical and the best setting can usually be obtained by *bracketing* the depth of field. As the figure illustrates, this involves turning the focus control back and forth to establish the control settings where the image starts to blur in each direction and then using this knowledge to position the stage in the approximate center of the depth of field.

3.8.2 PRIMARY FOCUS CONTROL (CONTINUED)

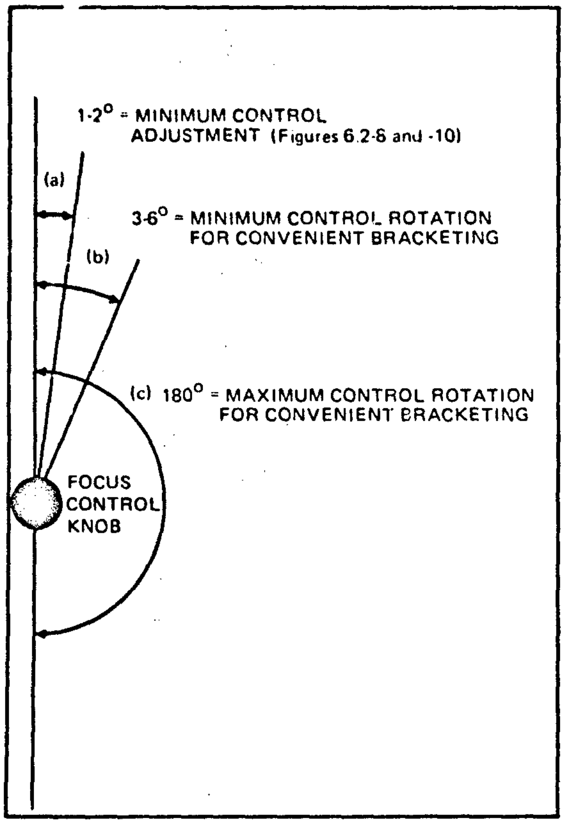


Figure 3.8-7. Determination of the Best Ratio Between Stage and Focus-Control Movement. The previous two figures provide a basis for setting limits on the ratio of stage movement to focus control rotation.

At one extreme, the smallest control setting the display user can make conveniently shown here as (a), is about 1 to 2 degrees (Figure 6.2-11). In order to use the bracketing technique of Figure 3.8-6 effectively, the control rotation to move through the depth of field should be several times this large. An increase by a factor of 3 would provide a reasonable minimum of 3 degrees rotation (b); one authority suggests 10 to 20 degrees is best (Ref. 9).

As an example, consider a display with a maximum magnification of 150X. Assuming that the curve in Figure 3.8-5 applies, the smallest depth of field for the display is 0.015 mm. This amount of stage or object movement must require at least 3 degrees of focus control rotation, and a full revolution of the control must not move the stage more than 1.8 mm.

At the other extreme, effective use of the bracketing technique requires that the display user keep his fingers in position on the control. This limits him to a comfortable rotation range estimated to be about 180 degrees. Assuming a stage to control movement ratio of 1.8 mm per revolution, the maximum stage movement possible using the bracketing technique is then 0.9 mm, which corresponds in Figure 3.8-5 to a display magnification of approximately 20X. This stage to control movement ratio would therefore allow focusing by bracketing over a magnification range of 20X to 150X.

A third consideration in the design of the focus control mechanism is the maximum stage movement required. If the display is not parfocal, this might be determined by the variation in *working distance* as magnification is changed. If the display is nearly parfocal, the maximum movement may be determined by possible variations in imagery position. Whatever the cause, if the display user must frequently turn the focus control more than about two revolutions, a coarse focus control should be provided. Alternatively, a retractable crank handle could be added to the knob; unfortunately these are seldom very satisfactory mechanically.

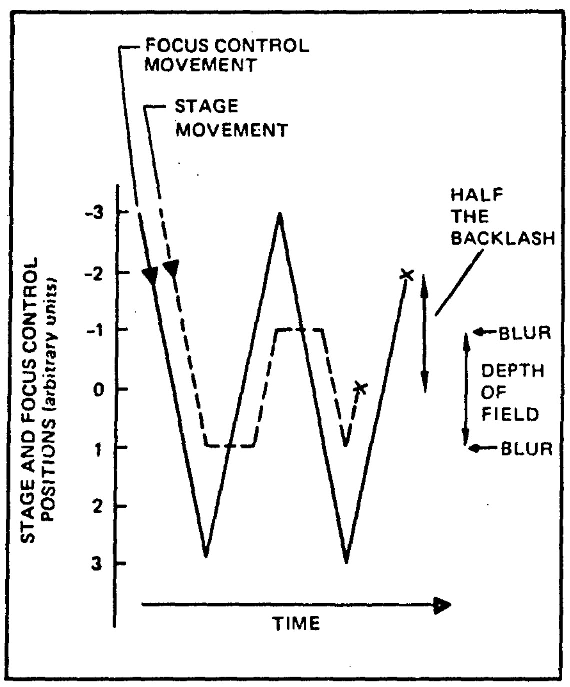


Figure 3.8-8. Impact of Backlash. *Backlash* is defined here as the maximum focus control rotation that will not cause the stage to move. As this figure shows, the stage position lags behind the control position by a distance equivalent to half the backlash.

When the display user attempts to focus by bracketing the depth of field, as in Figure 3.8-6, control movement to go from blur to blur, which is the same as going from one reversal in control movement direction to the next reversal, is increased by the amount of the backlash. Since backlash is usually a constant in terms of control movement, its impact is greatest at high magnification where focusing is more critical.

In the absence of any useful data (Ref. 10), backlash should not exceed twice the depth of field at the highest commonly used display magnification, and preferably it should be considerably less.

3.8.3 DIFFERENTIAL FOCUS CONTROL

RECOMMENDATIONS:

Provide a label to indicate the direction the image moves for a particular control input.

If the display permits, provide a scale on the differential focus control to aid users in placing the two images at the same distance.

Allow rapid image movement, with a minimum of 2.0-diopter variation in image distance per quarter turn of the focus ring on an eyepiece.

Binocular displays that provide each eye with a separate image must generally incorporate some method for varying each image distance independently, usually as a focus ring on one or both eyepieces. This serves two functions:

- For most users, it provides a means for placing the two images at the same optical distance, even though there are differences in optical path length or, in a stereoscopic display, differences in object distance.
- For those users who remove spectacles that provide a different correction for each eye, it provides a means of placing the two images at the correct relative distance. This latter group may require up to 3.5 diopters of differential focus (Figure 3.8-4).

Misuse of a differential focus control is a potential source of trouble. Most users don't require a different image distance for each eye and, although there is no data on the subject, will probably suffer if they use a display that has been adjusted so that such a difference exists. (See Section 3.7.7.) The potential for such a difference is high because a significant number of experienced display users are apparently unable to determine whether the two images are equidistant (Ref. 11).

A display user will have more difficulty placing the two images at the same distance if he cannot concentrate on the image he is focusing due to interference from the other image. If he eliminates the interference by closing one eye, he will accept an image at any distance within his accommodative range (Figure 3.6-3) and he is unlikely to set each image at the same distance.

If a user finds he must focus one eyepiece at a time, then because his *far point* is relatively fixed while his *near point* is highly variable, he will be more likely to make the images equidistant if he places each as far away as possible (Ref. 12). Most individuals are not consciously aware of the distance to an aerial image, so to use this technique the display user must be told which way to move the differential focus controls, preferably by means of labels on the controls. If the eyepieces converge, when he finishes focusing each image separately, he will probably have to move both images closer with the primary focus control in order to make the viewing distance match the eyepiece convergence angle (Figure 3.7-13).

Before implementing the focusing technique in the previous two paragraphs, it should be tested to ensure that it does not interfere with obtaining parfocality across variations in magnification. Whether it is incorporated or not, labeling on the focus controls to indicate which way they move the images is desirable.

All users would benefit by the addition of a detent or a scale like that on the eyepieces of binoculars to indicate when the images are at a particular distance. In displays where the differential focus adjustment must compensate for differences in optical path length, such a scale may not be feasible.

3.8.3 DIFFERENTIAL FOCUS CONTROL (CONTINUED)

Focusing to make the two images equidistant is made more difficult by the fact that the eye changes accommodation in response to changes in image distance, particularly when the distance varies slowly. To reduce this tendency the differential focus control should allow rapid changes in image distance. In the absence of useful test data, it is estimated that a quarter turn of an eyepiece focus ring should provide at least a 2.0-diopter change in image distance.

Action of the differential focus controls should be positive in both directions. With many of the displays commonly used for viewing imagery, rotation of the focus ring in one direction extends the eyepiece while rotation in the other direction retracts the ring but leaves the eyepiece behind, forcing the user to push it in manually. Apparently this results from reducing eyepiece clearance sufficiently to maintain adequate optical alignment. If this problem cannot be eliminated with a focusing ring type of control, it would be easier to obtain proper focus by simply sliding the eyepiece in and out manually and then locking it in place with a screw or a lockring. The design should allow one-hand operation.

3.8.4 FOCUS CONTROLS FOR REAL IMAGE DISPLAYS

The design recommendations developed in Section 3.8.2 for aerial image displays also apply to real image displays such as rear screen projectors. However, because the image distance is fixed by the screen position, the user's accommodative amplitude is no longer a factor in the depth of field, and the values in Figure 3.8-5 must be reduced accordingly. In addition, it may be appropriate to increase the allowable blur in the image to match the resolution of the screen (Δ_2 in the equation in Ref. 5).

Focusing requirements for electronic displays are discussed in Section 4.4.

3.8.5 AUTOMATIC FOCUS DEVICES

This section summarizes some of the data that may be useful in any attempt to establish design parameters for an automatic focus device. Such a device would automatically maintain a constant image distance in an aerial image display by compensating for variations in objective lens to imagery distance. At a minimum, such a device must include a focus control that allows the user to adjust image distance as on an ordinary display. Also, there is the question of how much variation in image distance around the constant value to allow. This variation includes a component due to the sensitivity limit of the device, plus relatively rapid changes in image distance due to any jerkiness or oscillatory hunting behavior in the servo mechanism. This section is concerned with design limits for this type of variation in image distance.

Design limits depend on a large number of factors. None of these are understood well enough, at least as they relate to imagery displays, to allow setting reasonable design limits. Therefore, the best recommendation that can be made at present is to limit such variations to an amount that does not have any detectable impact on display image quality or on user comfort.

Among the factors that would have to be considered in order to set specific design limits are the following:

- Image quality
- Accommodative amplitude of the operator while he is using the display (Figures 3.7-13 and 3.6-3)
- Accommodative response of the display user to an image at a fixed distance (Figure 3.8-12)
- Accommodative response of the display user to variations in image distance (Figure 3.8-13 through -16)
- Sensitivity of the user to changes in image distance (Figure 3.8-11)
- Depth of field of the display user when using the display (Figures 3.8-5, -9, -10, and -11)

Image quality, which depends both on the resolution of the imagery and on the numerical aperture and magnification of the display, must be considered because of its impact on the amount of focus error that will be noticeable.

Average accommodative amplitude as a function of age is summarized in Figure 3.6-3. In most displays, the usable accommodation range is smaller than this figure indicates because the convergence angle between the eyes is fixed. The data in Figure 3.7-13 suggest that, at least for binocular displays involving natural pupil sizes, the upper limit on the variation in image distance that can be tolerated is no more than ±0.75 diopters. Older display users might not tolerate this amount of variation. As Figure 3.8-9 illustrates, tolerance for accommodative error varies with pupil diameter.

One approach would be to limit variations in image distance to plus or minus half the depth of field of the display. This could be measured by having test subjects with good visual acuity but a very small accommodative amplitude focus the display from blur to blur (Ref. 13). Use of a high-quality resolution target would produce the smallest limits, but these might be more restrictive than necessary if they are based on looking at objects with significantly higher resolution than is available in the imagery to be viewed on the display

A design limit of plus or minus half the depth of field would be reasonable only if one could be sure that the average display focus was exactly centered between the distances at which blur occurred. This would occur only when the display user was totally successful in using a focusing technique like that illustrated in Figure 3.8-6. As Figure 3.8-11 illustrates, if the average image distance falls on either side of this position, tolerance to oscillatory variation in image distance is reduced. To compensate, a design limit of perhaps plus or minus a quarter of the depth of field would be more desirable.

Accommodation normally changes constantly, even when an object at a fixed distance that contains fine detail is being viewed. Presumably there is no need to set design limits smaller than this variation. The amplitude of this variation in accommodation is nominally 0.2 to 0.4 diopters, although as the representative data in Figures 3.8-12 and -13 illustrate, establishing a meaningful average or maximum is not currently possible.

Most of the figures in the remainder of this section illustrate data collected under test conditions where the

3.8.5 AUTOMATIC FOCUS DEVICES (CONTINUED)

optical distance to a target could be varied without any change in the size of the target. (See the discussion of the *Badal principle* in the glossary, Section 8.0, or in Ref. 14.)

One reason changes in image distance pose a problem for the display user is the existence of a well-defined latency of perhaps 0.4 second in the response of the accommodative mechanism of the eye. The available data on this topic are summarized in Figure 3.8-14.

An oscillatory variation in image distance can affect the display user in two ways. First, his eyes will attempt to change accommodation in order to track the image; this might be fatiguing in itself. Second, as the curves in Figure 3.8-15 and -16 illustrate, his accommodative response will be less than the image movement and will lag behind it, resulting in an accommodative error that varies with time (Ref. 15). There is no indication that with continued exposure to oscillatory variation in target distance at a particular frequency there will be any change in the response of the eye (Ref. 16).

One final factor that may possibly be of some relevance is the apparent change in the size of an image experienced by some individuals when the image changes in distance but not in size. An extensive review of this phenomenon is available (Ref. 17).

3.8.5 AUTOMATIC FOCUS DEVICES (CONTINUED)

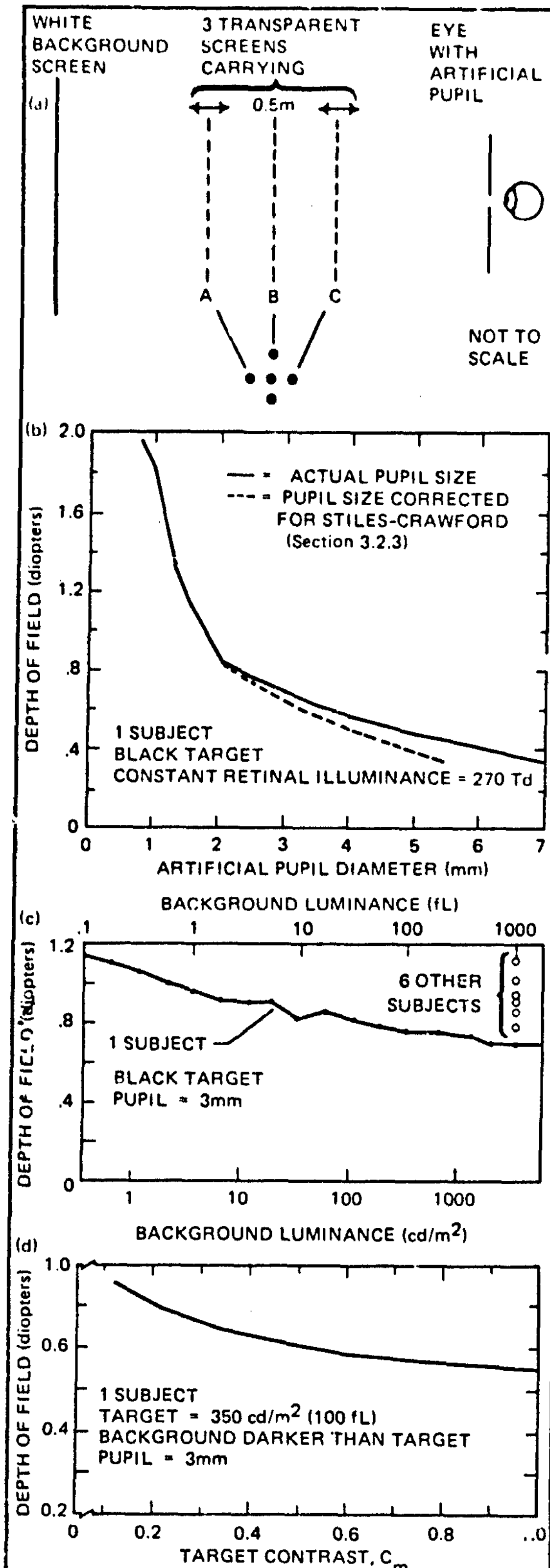


Figure 3.8-9. Depth of Field of the Eye. In the study illustrated here, the depth of field of the eye was measured by adjusting the distance to two discs, A and C in part (a) of the figure (Ref. 18,C). The spots subtended 10 arc minutes and each was approximately 20 arc minutes from its neighbors. Except when measuring the effect of target contrast, the discs were black and were viewed against a white background. To measure the effect of contrast, they were front illuminated to make them brighter than the background. Screen B, carrying three discs, was fixed at a distance of 2.0 diopters (0.5m) from the subject. Screens A and C, carrying one disc each, could be moved along the subject's visual axis. The pupil of the eye in use was dilated with drugs, and the other eye was covered.

Measurements were made by separating screens A and C until their discs appeared blurred, then moving them toward B until all five were in sharp focus. Subjects were allowed to compare the appearance of the discs by glancing quickly from one to another. With practice, measurements could be repeated to within 0.02 diopter.

The effects of changes in pupil size, background luminance, and disc contrast on depth of field are illustrated and are all in the expected direction. In (a) a smaller pupil allows a smaller bundle of light rays to enter the eye, thereby decreasing the size of the blur circle caused by a particular amount of focus error. For very small pupils there is also some blurring of the image due to diffraction, thereby reducing visibility of the target and increasing tolerance for blur caused by focus error. Parts (c) and (d) show that decreases in luminance and in contrast both increase depth of field, presumably by increasing tolerance to blur.

The importance of the test subject is illustrated in (c), which shows data collected under a single test condition for an additional six subjects. Although their larger depth of field values may be due to basic differences in their visual systems, a more likely cause is that they were less critical in their judgments of spot sharpness. This suggests that a target with finer detail might yield smaller depth of field values than illustrated here.

3.8.5 AUTOMATIC FOCUS DEVICES (CONTINUED)

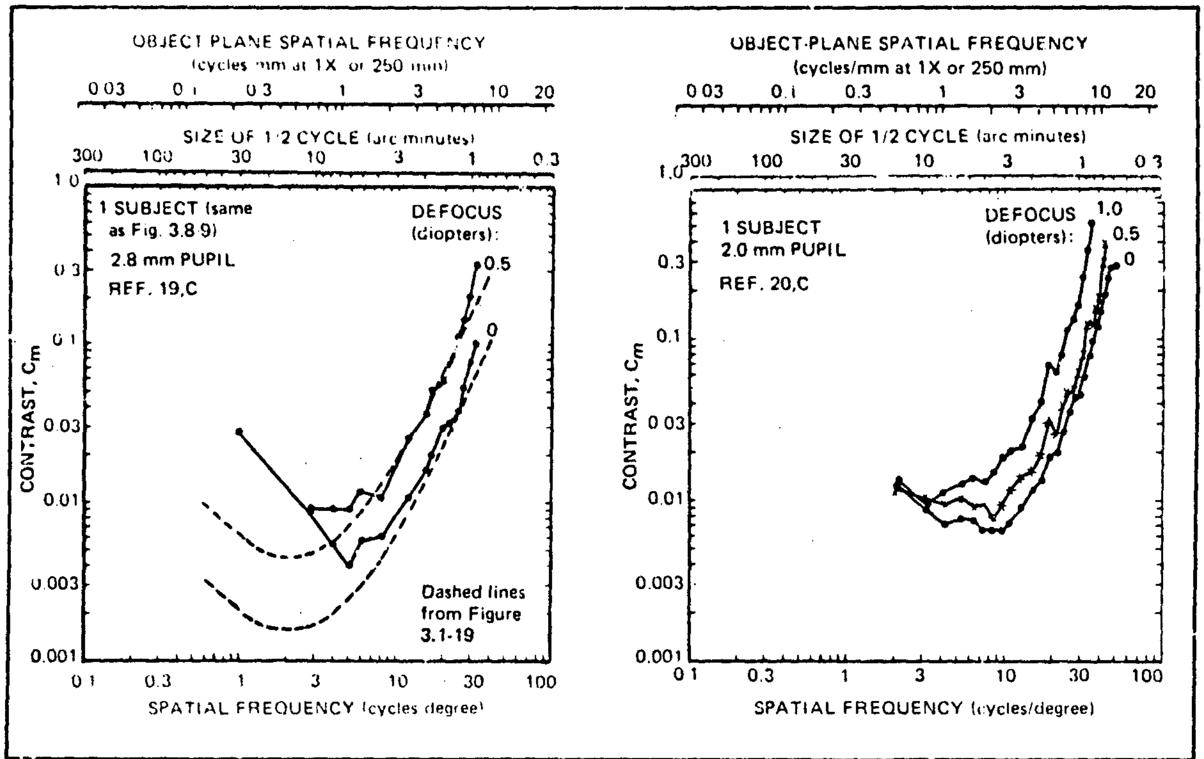


Figure 3.8-10. Effect of Focus Error on Contrast Sensitivity. Another method of estimating the depth of field of the eye is to measure contrast sensitivity with various amounts of focus error present. The technique used here was like that used in Figure 3.1-37. The target was a sinusoidal grating viewed on a CRT. The accommodation of the eye being tested was fixed with atropine.

The previous figure indicates that the depth of field of the eye with a pupil diameter of 2 to 3 mm is in excess of 0.5 diopter; this figure indicates however, that a significant reduction in visual performance capability can occur with this amount of focus error.

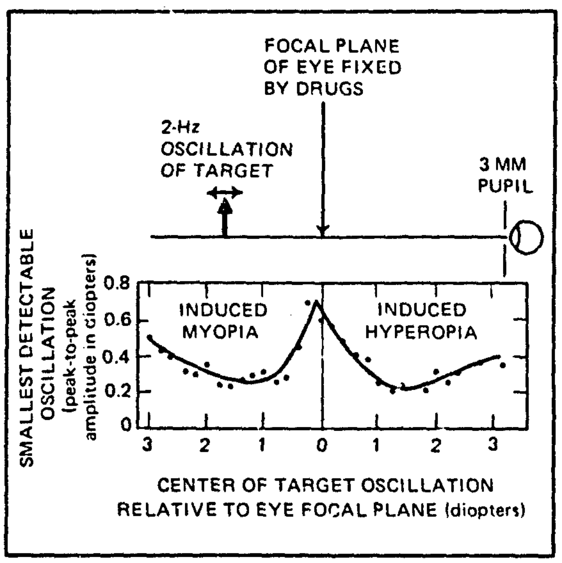


Figure 3.8-11. Detection of Target Oscillation. The amplitude of 2-Hz oscillation in target distance that was just detectable as blur is illustrated (Ref. 21). The small high-contrast test object was viewed through a 3-mm artificial pupil against a 170-cd/m^2 (50-fL) white background. Drugs were used to eliminate any changes in the accommodation of the eye that might have served as a clue.

The minimum detectable oscillation amplitude when the average image distance matched the focus distance of the eye, approximately 0.6 diopter, is very close to the depth of field of the eye with a 3-mm pupil measured in this same laboratory (Figure 3.8-9). Blur was detectable at a much smaller amplitude when the average image distance was 1 to 2 diopters away from the eye focus distance. The increase in threshold beyond 2 diopters probably resulted because the target was constantly blurred, making the oscillatory blur harder to detect.

3.8.5 AUTOMATIC FOCUS DEVICES (CONTINUED)

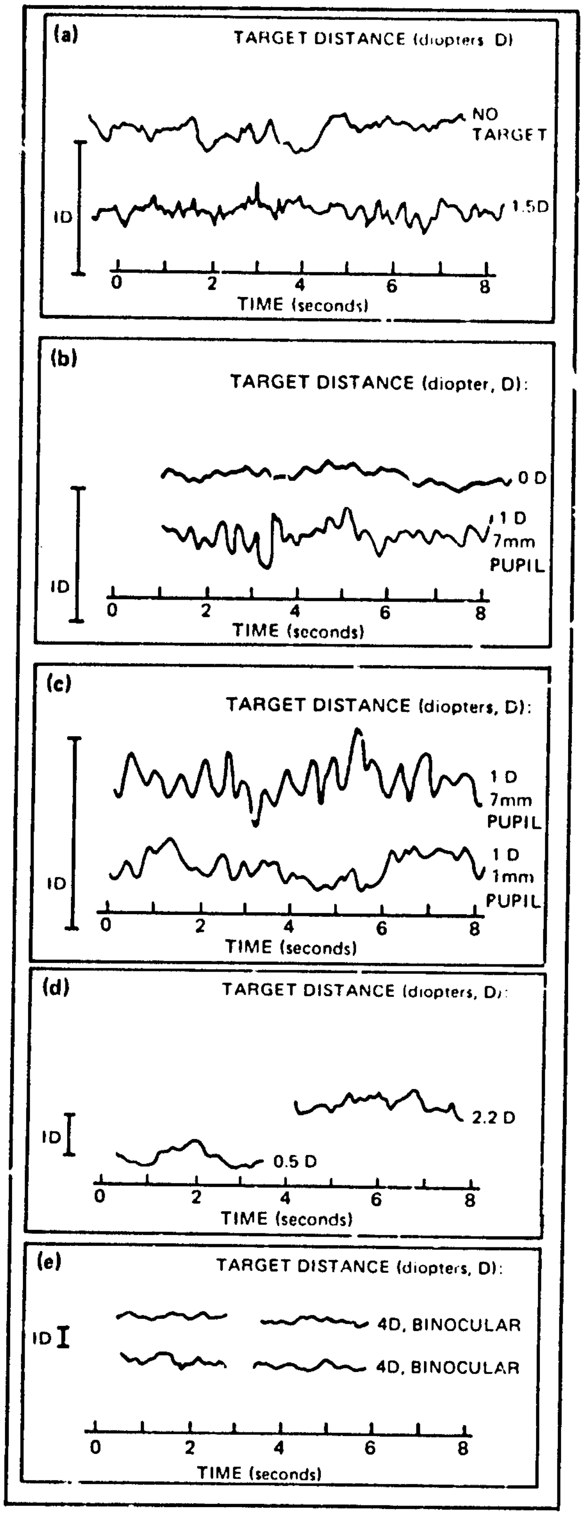


Figure 3.8-12. Normal Variation in Accommodation. The accommodation of the eye varies constantly while viewing a target at a fixed distance, even though fine details in the target remain in apparently good focus. Typical records of eye accommodation made with infrared *optometers* are illustrated. Each recording includes the distance to the target being viewed, in diopters (D), and the eye pupil diameter when known. In most cases an artificial pupil was used. At the left of each recording is a line indicating the vertical distance that corresponds to a 1-diopter change in accommodation.

The curves in (a), (b), and (c) are from a single laboratory and were collected with the eye pupil dilated with drugs.

These recordings all illustrate the approximate magnitude and frequency of naturally occurring variations in accommodation. In addition, they illustrate several specific phenomena:

(a) – Accommodation varies both with an empty visual field and with a target present (Ref. 22).

(b) – The variation is reduced when the target is at infinity (Ref. 16). (Pupil diameter was not reported for the upper curve).

(c) – There is less high-frequency variation with a small (artificial) pupil than with a large pupil (Ref. 23). The high-frequency variation with the 7-mm pupil is concentrated at 2.0 Hz.

(d) – Measurements in a second laboratory, using reduced illumination to dilate the pupil, are similar to those in the previous curves (Ref. 24).

(e) – Measurements from a third laboratory suggest that the variation in accommodation is reduced if both eyes view the target (Ref. 25).

3.8.5 AUTOMATIC FOCUS DEVICES (CONTINUED)

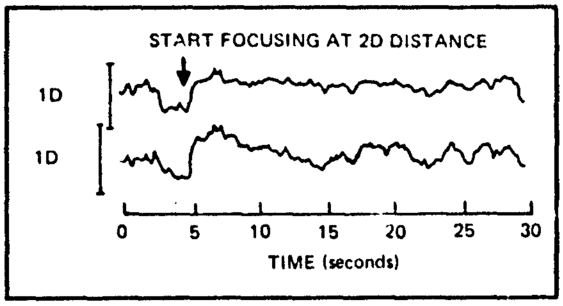


Figure 3.8-13. Similarity of Accommodation Variations in the Two Eyes. Measurements made with a double optometer indicate that the accommodation changes in the two eyes, although not identical, are very similar (Ref. 26). Four seconds into this recording, the subject was instructed to hold his focus and fixation steady on a target at a distance of 2.0 diopters. The target was viewed binocularly.

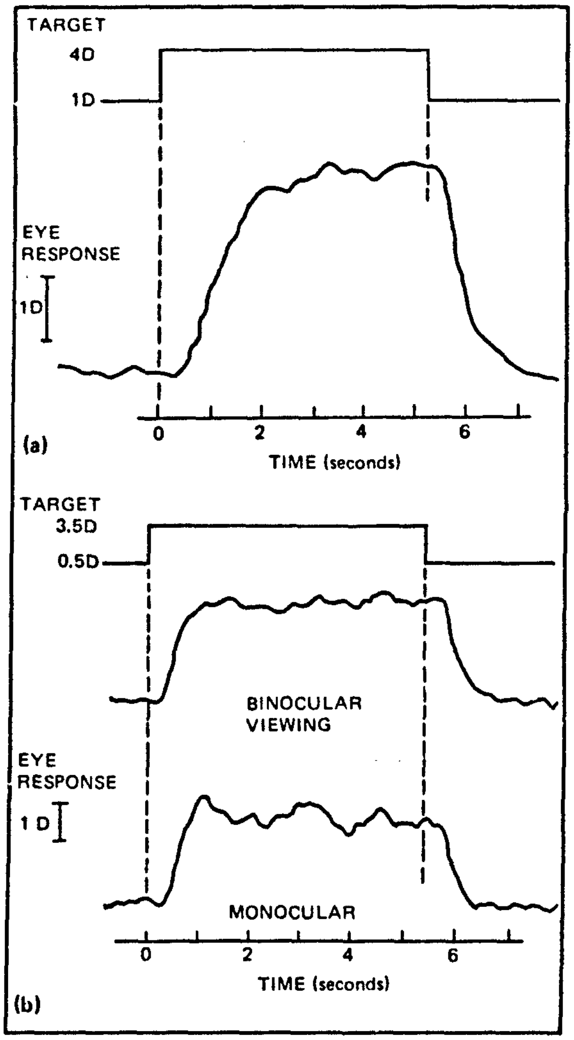


Figure 3.8-14. Abrupt Change in Target Distance. The eye does not respond immediately to an abrupt change in target distance. Instead, at least for young individuals, there is a latent period of approximately 0.4 second before the eye begins to change accommodation, and the response itself lasts for about 0.6 second more.

Typical accommodative responses to abrupt changes in target distance are illustrated. Part (a) shows the accommodative response of the eye to changes in target distance between 1 diopter and 4 diopters (Ref. 27). Part (b) provides a comparison between the accommodative responses of one eye when either one eye or both eyes view the target as it moves between 0.5 diopter and 3.5 diopters (Ref. 25).

Two other studies include specific values:

For a 2.0-diopter change in target distance, the maximum accommodation velocity was 10 diopters per second; average latency for six subjects ranged from 0.31 to 0.44 second, with an overall average of 0.39 second; average movement time was 0.6 second (Ref. 28).

For a 1.7-diopter change, average latency was 0.4 second; the average interval between the 10-percent and 90-percent points of the accommodation response was 0.7 second (Ref. 29).

3.8.5 AUTOMATIC FOCUS DEVICES (CONTINUED)

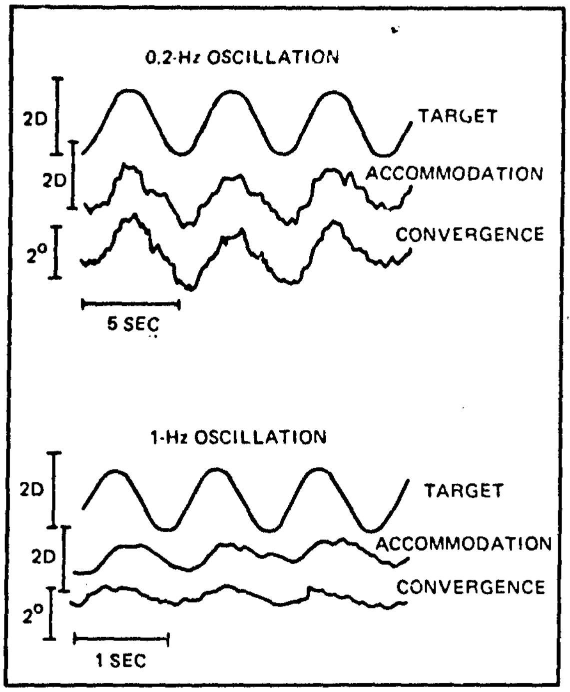


Figure 3.8-15. Oscillatory Variation in Target Distance. Accommodation responses to sinusoidal oscillation in target distance at two frequencies, 0.2 Hz and 1 Hz, are illustrated (Ref. 30). As the oscillation frequency increased, the accommodation response decreased in amplitude and lagged farther behind the target position. Specific values over a range of frequencies are summarized in the next figure.

In the study illustrated here, one eye viewed the moving target while the other viewed an empty field and was therefore free to turn. The result was an oscillatory variation in the convergence angle between the eyes similar to the variation in accommodation. In a binocular viewing situation, the convergence angle changes would be much smaller; but under some circumstances, these might be adequate to induce a sensation of oscillation in depth. Such a phenomenon has not been demonstrated.

3.8.5 AUTOMATIC FOCUS DEVICES (CONTINUED)

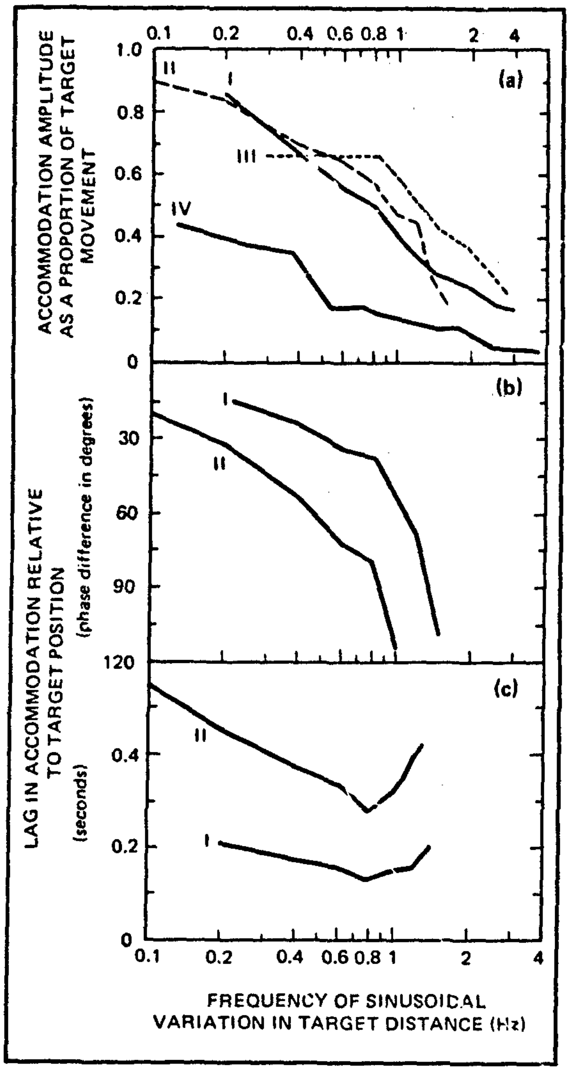


Figure 3.8-16. Effect of Target Oscillation Frequency. As both part (a) and Figure 3.8-15 illustrate, an increase in the frequency at which target distance varies causes the accommodative response of the eye to become smaller and to lag farther behind. Both of these phenomena are illustrated here, with lag expressed first as phase difference in degrees (b), and then in seconds (c) (Ref. 31).

These curves are each based on test data for monocular viewing by a single subject. The test conditions for the four studies were as follows:

I – Target amplitude of 0.85 diopter; pupil dilated by reducing room illumination (Ref. 32). These data are from the same report as Figure 3.8-15.

II – Average data for target amplitudes of 2.0 and 3.0 diopters; apparently natural pupil diameter (Ref. 33).

III – Target amplitude 0.75 diopter; pupil dilated with drugs (Ref. 34).

IV – Target amplitude 0.6 diopter; pupil dilated with drugs (Ref. 35).

In studies I and II, lag was reported in terms of phase angle in degrees, as is illustrated in (b). These data are repeated in (c) in terms of seconds (Ref. 31). In study IV, the lag reportedly varied between 0.36 and 0.50 second, but data for specific oscillation frequencies were not given.

Because these data were collected in order to increase understanding of the focusing mechanism of the eye rather than to aid display design, they must be applied with caution. For one thing, each curve is based on data from only one subject. Also, the methods by which the several authors obtained their published figures from their original recordings were only briefly described and certain assumptions (Ref. 36) are necessary in order to bring these data together here in a single graph. Particularly striking is the difference between amplitude curves III and IV in (a), which are based on measurements made by the same experimenters.

SECTION 3.8 REFERENCES

1. This distinction is generally followed, for example, in the two articles in Ref. 5.

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4. Hirsch, M. J. Anisometropia. A preliminary report of the Ojai longitudinal study. *Arch. Am. Acad. Optom.*, Vol. 44, No. 9, 1967. Cited in Borish, I. M. (Ed.), *Clinical Refraction* (3rd ed.). Professional Press, Chicago, 1970, p. 259.

5. Martin, L. C. *Technical Optics, Vol. II* (2nd ed.). Isaac Pitman & Sons, London, 1961. See pp. 14-19 and 97-99.

Courtney-Pratt, J. S. and Gregory, R. L. Microscope with enhanced depth of field and 3-D capability. *Appl. Optics*, Vol. 12, No. 10, 1973, pp. 2509-2519.

Depth of field, Δ, is the distance along the optical axis in object space over which an acceptably sharp image is obtained. It includes three terms:

- Δ_1, the Rayleigh limit of $\lambda/4$, which accounts for the effects of diffraction,
- Δ_2, due to the amount of blur acceptable in the image, and
- Δ_3, due to the change in the display user's eye accommodation.

The best approach, in the absence of useful empirical data (see Martin, p. 97), is to treat these as if they are additive.

As developed in the two referenced papers, the terms (in mm) are:

$\Delta_1 = n\lambda/NA^2 = 580 \times 10^{-6}/NA^2$, where n is the refractive index of the medium, air in this case, λ is the wavelength of light, 580 nm, and NA is the numerical aperture.

$\Delta_2 = 0.073c/M \cdot NA = 0.146/M \cdot NA$, where c, the size of the permissible circle of confusion, or blur circle, is taken to be 2 arc minutes (for c in radians, substitute 250 for 0.073), and M is the magnification.

$\Delta_3 = b^2(1/b)/M^2 = 250/M^2$, where b is both the near point of accommodation and the image distance in the microscope and is assumed to be 0.25m.

Adding these yields:

$$\Delta = \Delta_1 + \Delta_2 + \Delta_3 = \frac{580 \times 10^{-6}}{NA^2} + \frac{0.146}{M \cdot NA} + \frac{250}{M^2}$$

The best available data on the numerical aperture expected in the class of microscopes of interest are found in Hooker, R. B. *A Comparison of the Square Wave Response of the Three Microscopes Commonly Used in Photointerpretation*. RADC-TR-70-150, (AD-874 241 L), 1970. The magnifications and numerical apertures of these microscopes, for the lens configurations that gave best performance, were:

M	NA	NA/M
6	0.021	0.0035
12	0.044	0.0036
25	0.090	0.0037
50	0.149	0.0030

The average value for NA/M was 0.0034. Substituting this in the expression for Δ yields: $\Delta = 343/M^2$

Because in most displays the numerical aperture does not continue to increase as rapidly with magnification at higher magnifications, this expression will underestimate Δ in this region.

A simpler formula for depth of field, $\Delta = \lambda(n^2 - NA^2)^{1/2}/NA^2 + 250/M^2$, appears in Benford, J. R. Microscope objectives. Chapter 4 in Kingslake, R. *Applied Optics and Optical Engineering*, Vol. III. Academic Press, New York, 1965. See pp. 157 and 158.

6. See either of the two sources at the beginning of Ref. 5. Also see:

Martin, L. C. *The Theory of the Microscope*. American Elsevier, New York, 1966.

7. These data are from an unpublished study by the senior author in which subjects rotated the focus control of a binocular microscope and indicated when the transitions from blur to a sharp image and then back to blur occurred. Five individuals used a Bausch and Lomb Zoom 70 microscope, which has converging eyepieces. The two smallest values were obtained for the two older subjects who had very limited accommodative amplitude. A single subject used a Bausch and Lomb Zoom 240 at a range of magnifications and had good accommodative amplitude. All the subjects viewed high-resolution aerial photography.

8. These data were collected by R. Chaban of McBain Instruments, Chatsworth, California, in 1974. The single subject was middleaged and had good accommodative amplitude. The display had parallel eyepieces and a numerical aperture as follows:

M	Objective lens	NA
8X	1X	0.026
16X	2X	0.052
25X	1X	?
45X	1X	0.070
90X	2X	0.140

Focusing was from blur to blur using a high-contrast tri-bar resolution target of excellent quality. Older individuals with limited accommodative amplitude reportedly produced smaller values.

9. Wohl, J. G. (Ed.). *Human Factors Design Standards for the Fleet Ballistic Missile System: Volume II. Design of Equipment*, NAVWEPS-OD-18413A, U.S. Navy, 1962. (Also available as AD 048895). This authority suggests that the range of a focus control should require 10 to 20 degrees of rotation; the basis for this recommendation was not given.

10. In Figure 6.2-8, a study is cited which indicates that 20 degrees of backlash in a rotary control has little effect so long as there is a good display of the control setting. That obviously is not the situation for a focus control.

11. This statement is based on observations by the senior author. These occurred primarily during test programs when eyepieces of a microscope-type display were misadjusted to produce gross differences in image distance in order to illustrate the focus mechanism to a test subject; it was discovered later that the test subject was using the display without having removed the misadjustment.

12. This idea was suggested to the authors by Dr. Jay Enoch.

13. Bifocal wearers with good vision would generally make suitable test subjects. See Figure 3.6-3.

14. Ogle, K. N. *Optics–An Introduction for Ophthalmologists*. Charles C. Thomas, Springfield, Illinois, 1961.

Southall, J. P. C. *Mirrors, Prisms, and Lenses: A Textbook of Geometrical Optics* (3rd ed.). Peter Smith, Magnolia, Massachusetts, 1933.

15. The accommodative error, or difference between the accommodation distance of an eye viewing a target that oscillates in distance and the distance to the target, is made up of two components. One is due to the fact that the amplitude of accommodation change is less than the change in target distance, and the other is due to the fact that the response of the eye lags behind the movement of the target. The best available data are in parts (a) and (b) of Figure 3.8-16. Also, see the discussion of the resting position of accommodation in Section 3.6.2.

16. Campbell, F. W., Robson, J. G., and Westheimer, G. Fluctuations of accommodation under steady viewing conditions, *J. Physiol.*, Vol. 145, 1959, pp. 579-594. See Figure 2.

17. McReady, D. Size-distance perception and accommodation-convergence micropsia--A critique. *Vision Res*, Vol. 5, 1965, pp. 189-206.

18. Campbell, F. W. The depth of field of the human eye *Optica Acta*, Vol. 4, No. 4, 1957, pp. 157-164. The author states that paredrine hydrochloride, 2 percent, was used to dilate the pupil of the eye without interfering appreciably with accommodation.

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22. Campbell, F. W., Westheimer, G., and Robson, J. G. Significance of fluctuations of accommodation, *J. Optical Soc. Am.*, Vol. 48, 1958, p. 669.

23. See Figure 4 of Ref. 16.

24. Figure 4.1 of Ref. 30.

25. Krueger, H. An apparatus for continuous, objective measurement of refraction of the human eye. *Optica Acta*, Vol. 20, No. 4, 1973, pp. 277-285. See Figure 4 of this article.

26. Campbell, F. W. Correlation of accommodation between the two eyes, *J. Opt. Soc. Am.*, Vol. 50, No. 7, 1960, p. 738.

27. van der Wildt, G. J. and Bouman, M. A. An accommodometer: An apparatus for measuring the total accommodation response of the human eye. *Appl. Optics*, Vol. 10, 1971, pp. 1950-1958. See Figure 9.

28. Campbell, F. W. and Westheimer, G. Dynamics of accommodation responses of the human eye, *J. Physiol.*, Vol. 151, 1960, pp. 285-295. See pp. 288 and 289.

29. Page 9 of Ref. 30.

30. Yoshida, T. and Watanabe, A. *Control Mechanism of the Accommodation-Vergence Eye-Movement System in Human Eyes*. NHK Technical Monograph 21, March, 1973, Nippon Hoso Kyokai, Japan Broadcasting Corp. Technical Research Lab. (Available as NASA report N73-30062) The optical distance to a target before one eye was varied sinusoidally while the other eye viewed an empty field. Both the accommodation of the eye viewing the target and the convergence angle between the eyes were measured. The sample data shown here appeared in Figure 4.2 of the article.

31. Phase lag in seconds is L/360f, where L is phase lag in degrees and f is frequency in hertz.

32. Figure 4.3 of Ref. 30.

33. Figure 5 of Ref. 25. These data were presented normalized to a value of 1.0 at 0.1 Hz. The curves in Figure 4 of this reference suggest that the accommodation response at 0.1 Hz was actually about 0.9, so the data in Figure 5 were multiplied by this value to obtain the curve shown here.

34. The values plotted in Figure 3.8-16 were obtained by measuring the curves in Figure 8 of Ref. 16.

35. Figure 6 of Ref. 28. It is not clear why this curve is so low, since it came from the same laboratory as did Study III.

36. For example, the accommodative amplitude data of Study I were originally reported as gain in decibels. Gain was converted to the values shown here by assuming that a gain of -10 dB was equivalent to an accommodative response 0.3 times as large as the target movement. (See Section 6.6.2.)

Ref. 33 describes how the data of Study II were adjusted to remove the normalization.

3.9 EYEPIECE DESIGN

3.9.1 Exit Pupil Size

3.9.2 Eyepiece Focus

3.9.3 Surface Finish

3.9.4 Eyepiece Elevation Angle

3.9.5 Eye Relief

3.9.6 Face Clearance

SECTION 3.9 EYEPIECE DESIGN

3.9 EYEPIECE DESIGN

Most of the discussion in this section deals with *eyepieces* that have *exit pupils* sufficiently small to effectively fix the user's head position relative to the display.

3.9.1 EXIT PUPIL SIZE

A large exit pupil display would eliminate problems such as operator discomfort resulting from the need to keep head position fixed with a small exit pupil display. However, because only a small portion of the light from such a display enters the user's eyes, it may be difficult to obtain adequate luminance. Distortions can also be a problem, particularly if they vary differently in the two eyes as the head is moved within the exit pupil (Section 3.4.5 and 3.7.1)

The relationship of display exit pupil size to display *magnification* and *numerical aperture* is treated in Sections 3.3.1 and 3.3.2. The impact of display exit pupil size on image *luminance* is treated in Sections 3.2.2, 3.2.3, and 3.2.4. Information on the variation in visual performance with eye entrance pupil size appears in Section 3.1.9.

3.9.2 EYEPIECE FOCUS

Most eyepieces include provision for focusing. Design recommendations for the eyepiece focus mechanism and adjustment range appear in Sections 3.8.1 and 3.8.3.

3.9.3 SURFACE FINISH

Any eye relief distance less than 30 to 40 mm will inevitably result in some contact between spectacle lenses and the eyepiece. The last physical surface of the eyepiece should therefore incorporate a finish that will minimize the chance of scratches. In addition, non-optical surfaces should have a black, nonspecular surface to reduce the amount of stray light reflected into the user's eyes.

3.9.4 EYEPIECE ELEVATION ANGLE

Eyepiece elevation angle affects both the operator's comfort and the area over which he can position his head while using the display. These topics are treated in Section 6.1 and in greater detail in Section 6.1.3.

3.9.5 EYE RELIEF

RECOMMENDATION:

Provide a minimum eye relief, measured from the last mechanical surface of the eyepiece, of at least 20 mm. A value of 25 mm is preferred.

In order to see the entire image field, the display user must keep his eye at a distance that places the display exit pupil approximately in the plane of the entrance pupil of his eye. The eye relief, or distance from the eyepiece to the exit pupil, must be sufficient to allow this. The largest eye relief is required by spectacle wearers who must keep their spectacles on while using the display, other users being able to get by so long as they have face and eyelash clearance.

A large portion of the population wears spectacles. The data in Figure 3.9-2 suggest that 30 to 50 percent of the population aged 20 to 45 will be using spectacles (Ref. 1). Spectacle use is even more prevalent among interpreters. The following values were obtained for a sample of 90 persons (Ref. 2,B):

- No corrective lenses: 31 percent
- Wear spectacles but remove them when using microscope-type imagery displays: 20 percent
- Wear spectacles when using imagery displays: 49 percent

Provision must be made in the display for users who wear spectacles. The preferred solution is to provide adequate *eye relief*. Alternatively, it would be possible to provide each user who required spectacles for some *refractive error* that could not be removed by refocusing the display, such as *astigmatism*, with a special lens to place on top of each eyepiece. However, this raises two problems. First, there is the difficulty of supplying the lenses. Second, in most applications the display user will still need his regular spectacles on each of the frequent occasions when he looks away from the display.

Published recommendations for eye relief vary. One authority recommends 25 mm with a minimum of 20 mm for spectacle use and 12 mm without spectacles (Ref. 3,X). A second also recommends 25 mm but would allow a minimum of 15 mm to permit spectacle use (Ref. 4,X). A third suggests a minimum of 10 to 12 mm without spectacles (Ref. 5,X). Unfortunately, none cites the basis for the values.

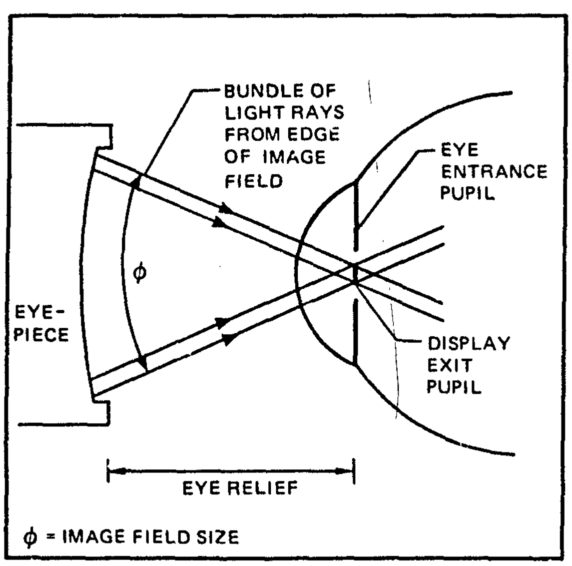


Figure 3.9-1. Eye Relief. Eye relief is the distance from the last physical surface of an eyepiece to the exit pupil. As can be seen in the figure, a small movement of the eye away from or toward the eyepiece will reduce tolerance to lateral eye movements and a larger movement will cause *vignetting*, or a cutting off of the light from the edges of the image field. The exact amounts depend on the relative sizes of the image field Section 3.5.3) the eye entrance pupil (Section 3.2.2), and the display exit pupil.

In addition to reducing the usable size of the image field, sufficient separation between the eye and display pupils could reduce image quality. There is no useful test data on this subject (Ref. 6).

This diagram also shows how eye relief and image field size (ϕ) serve to set a lower limit on eyepiece diameter.

3.9.5 EYE RELIEF (CONTINUED)

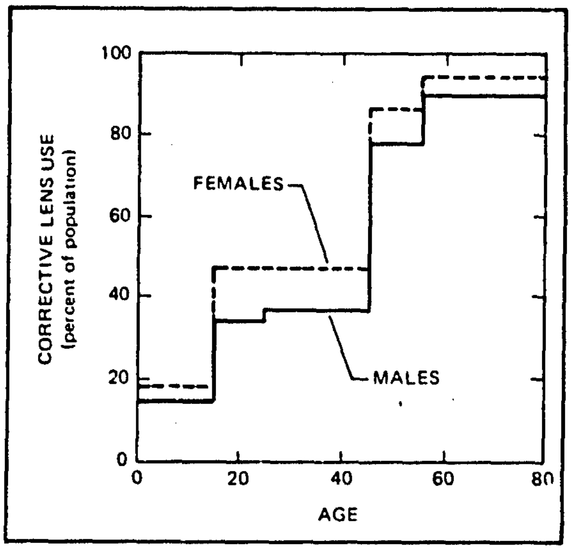
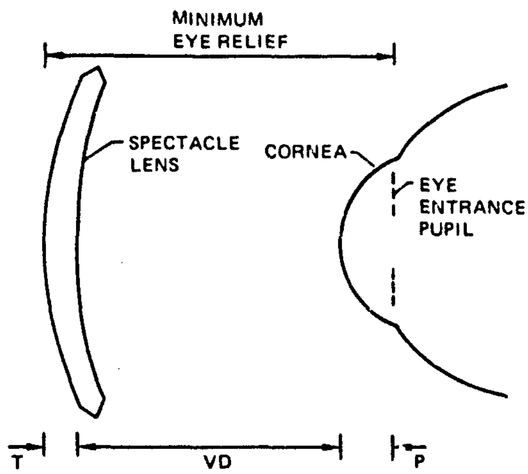


Figure 3.9-2. Age and Corrective Lens Use. This figure shows the percent of the general U.S. population who use corrective lenses (Ref. 1,A). The incidence of use climbs rapidly up to an age of about 20, after which it remains stable into the mid-forties. At this point, the gradual loss of near vision with age, known as *presbyopia* (Figure 3.6.3) causes the incidence of use to climb again.

This figure includes both spectacle and contact lens wearers. However, inclusion of the latter group has little impact on estimates of how many display users are likely to be wearing spectacles. The percent of the total sample that used contact lenses, either with or without spectacles, was:

- For age 17 to 24, 3.4 percent for males and 9.5 percent for females.
- For age 25 to 44, 1.8 percent for males and 4.2 percent for females.

3.9.5 EYE RELIEF (CONTINUED)



	SPECTACLE USER VERTEX DISTANCE PERCENTILE		
	5	50	95
SPECTACLE LENS THICKNESS (T) (Ref. 12)	2	2	2
LENS BACK VERTEX DISTANCE (VD) (Ref. 13,C)	10	14	18
CORNEA TO PUPIL DISTANCE (P) (Figure 3.1-7)	3	3	3
MINIMUM EYE RELIEF	15	19	23

NOTES: All dimensions in millimeters; 50 percentile value is an estimate

Figure 3.9-3. Determination of Minimum Eye Relief for Spectacle Wearers. Minimum eye relief with spectacles includes three measurable components, plus a relatively arbitrary clearance between the spectacle lens and the eyepiece. Two of the components, lens thickness and cornea to entrance pupil distance, are small and relatively fixed. Vertex distance (VD) has classically been taken as 12 or 13.5 mm (Ref. 9) but a range of 10 to 18 mm is more appropriate. Part of the increase may be due to the modern shift to plastic spectacle frames that place the lens farther from the eye (Ref. 10). The 18-mm value applies to a general population and may be slightly large for the present purpose. On the average, strong corrections are likely to be fitted closer to the eye than weak ones (Ref. 11). and strong corrections are also more likely to be worn while using the display.

These values suggest that an eye relief of 25 mm is desirable because it would allow 2 mm of lens clearance for a 95 percentile spectacle wearer. A value of 20 mm is acceptable but will result in a few percent of the users having difficulty because their spectacles contact the eyepiece or they are right at the point of losing the edges of the image field. This will also interfere with their effective use of a large image field. (See (Section 3.5.3)

3.9.6 FACE CLEARANCE

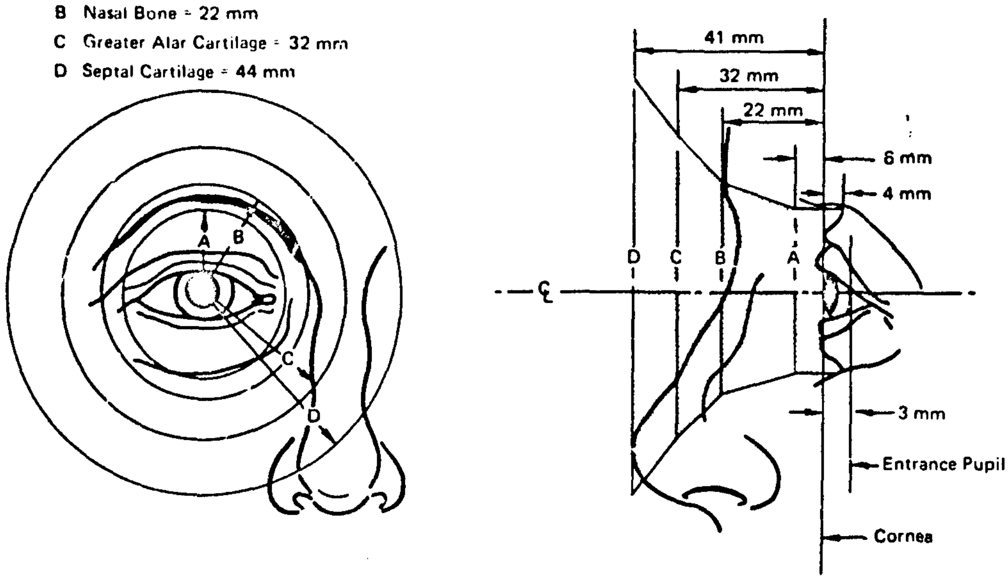


Figure 3.9-4. Anatomical Limits on Eyepiece Size (Ref. 4,X). Image field size and eye relief combine to set a minimum on eyepiece diameter (Figure 3.9-1). If the eyepieces are too large, they will strike the user's face, particularly if he has a small interpupillary distance (IPD). The problem is complicated by the fact that correlation between most body measurements is relatively low, so that some individuals with large faces and large noses will have a small IPD (Ref. 14).

The only known data on face size are illustrated. The original data source is unknown, as is the population on which they are based. Since they appeared as a requirement for the design of eye cushions for military viewing devices such as gunsights, they probably indicate average dimensions for male military personnel. If there is any doubt that clearance is adequate, the designer should build a simple mockup and test it with a number of individuals who have large faces and small IPD's. Population distributions for IPD appear in Section 3.7.1.

SECTION 3.9 REFERENCES

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2. Data collected by military personnel, 1975. A total of 6 of the 90 interpreters wore contact lenses; where these appear in the three groups listed in Section 3.9.5 is not known.

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6. Coleman, H. S. *et al* The coefficient of specific resolution of the human eye for Foucault test objects viewed through circular apertures. *J. Opt. Soc. Am.*, Vol. 39, 1949, pp. 766-770. In theory, sufficient separation between the eye and display pupils could reduce image quality. In this, the only experiment in which this was tested, image quality was not reduced when the exit pupil of a telescopic device was placed 3 mm in front of the cornea, a separation of 6 mm between the instrument exit pupil and the eye entrance pupil.

7. U.S. National Center for Health Statistics. *Binocular Visual Acuity of Adults, United States, 1960-1962.* Publication No. 1000, Series 11, No. 3, U.S. Public Health Service, 1964.

8. The Ayreshire Study Circle. An investigation into accommodation. *Brit. J. Physiol. Optics*, Vol. 16, 1960. Cited in Borish, I. M. (Ed.), *Clinical Refraction* (3rd ed.). Professional Press, Chicago, 1970, p. 170. Numerous other studies on this topic are also cited in Borish; all yielded generally similar results.

9. Duke-Elder, S. and Abrams, D. *Ophthalmic Optics and Refraction*, Vol. V of S. Duke-Elder (Ed.) *System of Ophthalmology.* C. V. Mosby, St. Louis. 1970. See p. 644.

   Davis, J. K., Fernald, H. G. and Rayner, A. W. An analysis of ophthalmic lens design. *Am. J. Optom. and Arch. Amer. Acad. Optom.*, Vol. 41, 1964, pp. 400-421.

10. Davis, J. K. The significance of the center of rotation of the eye (in 3 parts). *Optometric World*, Vol. 50, Nos. 1, 2, 3, 1963.

11. Davis, J. K., Personal communication, December 1974.

12. Minimum thickness at the center of typical glass spectacle lenses is 2.2 mm. This value may vary as materials and safety standards evolve.

13. Davis, J. K., Spitzberg, L. and Winters, F. H., Jr. *Spectacle Lens Design–Restudied.* Presented at the Annual Meeting of the Academy of Optometry, Toronto, December, 1971. This manuscript describes the development of the American Optical Company's Tillyer Masterpiece II minus cylinder lens. It will be published in shortened form in the academy's journal. The sample size for the data summarized in Figure 3.9-3 is not given.

14. Morony, W. F. and Smith, M. J. *Intercorrelations and selected descriptive statistics for 96 anthropometric measures on 1549 Naval aviation personnel.* AD 754 780. Also see Ref. 6.1-2.

PAGE

3.10 IMAGE TRANSLATION AND ROTATION

3.10.1 Geometry 3.10-1

3.10.2 Effect of Image Motion on Vision 3.10-3

3.10.3 Velocity Requirements 3.10-6

3.10.4 Control of Image Translation 3.10-9

3.10.5 Precise Image Positioning (Comparators) 3.10-12

3.10.6 Image Rotation and Interchange Between the Eyes 3.10-14

3.10.7 Control of the Direction of Image Motion 3.10-16

[redacted]

SECTION 3.10 IMAGE TRANSLATION AND ROTATION

The image translation and rotation systems are essential parts of an imagery display, providing means for the interpreter to move from place to place on the imagery and to rotate the view for optimum interpretability in mono and correct eyebase orientation in stereo.

Although good design of these functions will not directly increase what can be seen in the image, the ease and accuracy of translation and rotation will have a major impact on the amount of imagery which can be effectively covered, and will significantly affect user satisfaction with the equipment in daily use.

This is especially important in the exploitation of stereo imagery, since difficult means for positioning and rotation make stereo setup time consuming and frustrating, sometimes to the extent that stereo imagery is not used as often as it would be with more convenient equipment.

Poor design of translation and rotation functions can thus significantly reduce the usefulness of the display and the efficient exploitation of the imagery, particularly with respect to tasks such as search and stereo viewing, no matter how good the image quality of the display may be. In displays intended for searching large quantities of imagery, it is essential to provide an adequate range of image velocities, adequate control over these velocities, and freedom from noticeable irregularities in image motion. This is also true for stereo displays, where precise positioning is required to align and orient the stereo pair.

Although much of the background material in this section applies to any kind of display, the analysis and conclusions are based on displays intended for viewing permanently recorded imagery, rather than on real time displays.

One special application of image motion, not treated further, occurs with rear projection screens. Most such screens have a grain structure that reduces their resolution. As an image moves across such a screen, the eye tends to integrate over the grain, so that at low image velocities, on the order of two degrees per second or less, the screen resolution is increased.

Translation mechanism design is complicated by the extreme scarcity of data on image and imagery translation velocities actually used by interpreters. Collecting such data is difficult because, unlike display parameters such as magnification and luminance, there is no simple way to determine what velocity is in use. This kind of data would be much easier to collect if prototype displays, which generally incorporate much better translation mechanisms than are now in use and than might be economical on production units, included test points where an electrical signal that indicated image or imagery velocity could be obtained.

3.10.1 GEOMETRY

The user of a display experiences image motion in terms of the angular velocity of the image but the display designer must work in terms of the linear velocity of the imagery. Figure 3.10-1 illustrates the relationship between these two sets of units.

Figure 3.10-1. Relationship of Image to Imagery Velocity. The image velocity produced by a particular imagery velocity and display magnifying power is illustrated (Ref. I). As is discussed in Section 3.3, magnifying power is usually identical to the magnification engraved on a virtual image display such as a microscope. For screen-type displays, it is equal to display magnification only at a viewing distance of 250 mm (10 in). For other distances a correction factor is necessary. For example, at 500 mm (20 in), magnifying power is one-half the magnification, and, at 750 mm (30 in), it is one-third (see Figure 3.3-16).

3.10.1 GEOMETRY (CONTINUED)

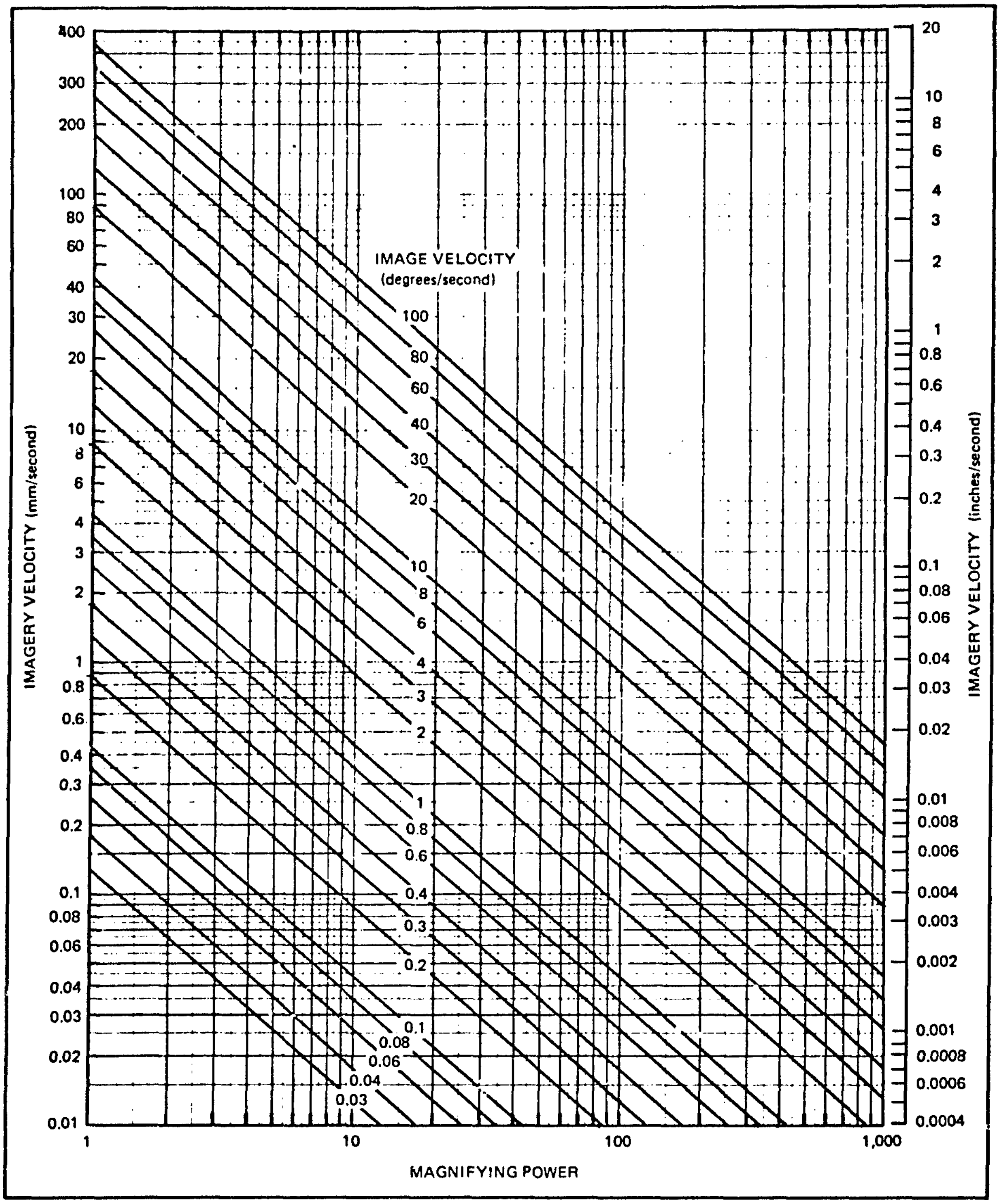

Figure 3.10-1. Relationship of Image to Imagery Velocity

3.10.2 EFFECT OF IMAGE MOTION ON VISION

Much image interpretation, particularly search, necessarily takes place while the image is moving. The effect of motion on ability to see details in an image depends on several factors:

- Image velocity
- Whether the eye can track the motion
- The amount of time available to look at each particular area in the image

The data summarized in this section illustrate that while a moving image is somewhat more difficult to see than a static one, the impact is small if the eye is able to track the image and thereby eliminate motion of the image on the retina. In most imagery display situations, this will be possible. Since the motion will be under the control of the user, it will be expected, and the eye will be able to track it smoothly, at least in the horizontal direction, up to a velocity of about 30 degrees per second (Ref. 2).

The major effect of image motion on the display user is to limit the time he can spend looking for a target. For example, with an image velocity of 20 degrees per second and an image field of 40 degrees, the longest one point on the image is visible only 2.0 seconds. Assuming each eye fixation lasts an average of 0.4 second, this allows the observer only 5 *fixations* to cover the entire image field.

The situation is complicated further with a display such as a microscope that has small exit pupils. As Figure 3.5-13 illustrates, turning his eye more than a few degrees while tracking the moving target will require the observer to move his head to compensate for the motion of his eye pupil.

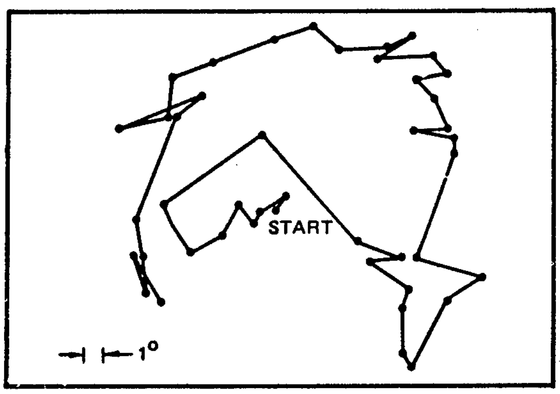

Figure 3.10-2. Eye Movements During Visual Search. In order to view an extended area, the eye typically remains at one fixation point only a few tenths of a second then moves on to the next (Ref. 3). As an example, this figure illustrates the first 45 fixation points for an observer searching for airfield symbols on a map (Ref. 4). In the interval between fixation points, the image is necessarily moving across the retina. However, these movements last only a very short time and are seldom if ever noticed by the observer.

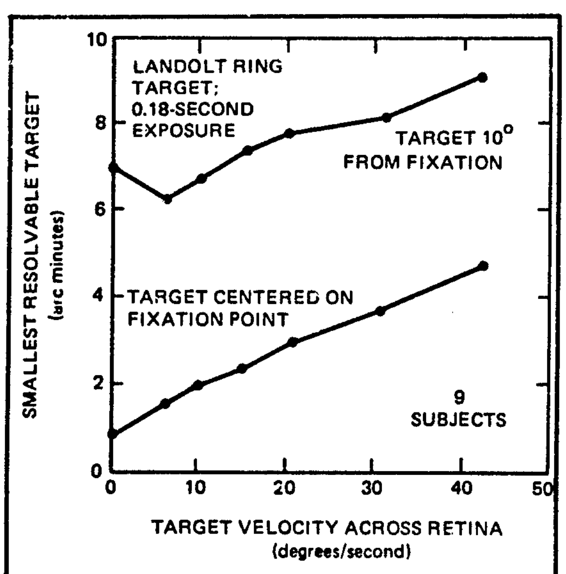

Figure 3.10-3. Vision With Image Movement on the Retina. When a target is seen only in motion relative to the fixation point of the eye, the ability to resolve details in the target is reduced, especially close to the fixation point (Ref. 5,B). The one exception occurs in the periphery of the eye, where low image velocities actually improve vision slightly.

A portion of the loss at the fixation point illustrated here is probably due not to motion directly, but to the fact that the motion of the image takes it across lower resolution portions of the visual field (see Figure 3.5-10).

Recent data on lower image velocities indicate that for exposure durations of 0.1 and 0.2 second, retinal image velocities up to about 2.5 degrees per second do not reduce ability to resolve details so long as the movement is horizontal or vertical (Ref. 6,C). Oblique motion reduces vision at 1 degree per second.

3.10.2 EFFECT OF IMAGE MOTION ON VISION (CONTINUED)

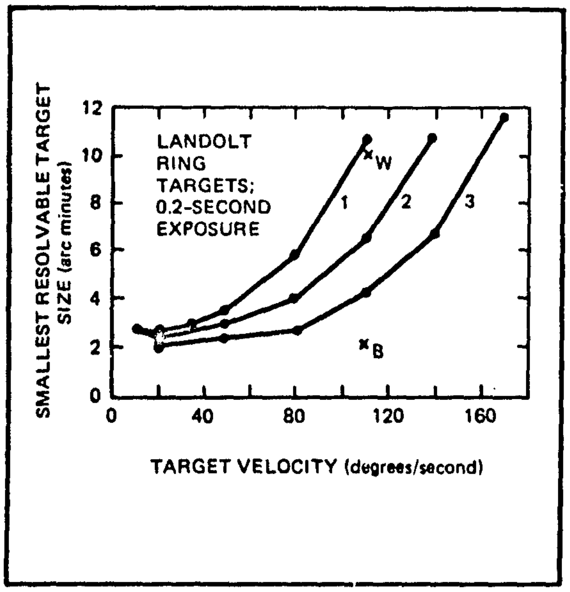

Figure 3.10-4. Vision for a Moving Target. In order to view a moving image, the observer must attempt to reduce the effect of the motion by tracking the image with his eyes during each fixation period. The ability to perform this feat, sometimes referred to as *dynamic visual acuity* (DVA), varies widely among individuals and as a function of experience. For example, the impact of target velocity on the visual ability of three groups of five to eight subjects, selected according to their ability to see a moving image, is illustrated by curves 1, 2, and 3 (Ref. 7,C). The subjects in Group 3 are obviously able to retain good vision at higher velocities than are the subjects in the other groups.

Experience has a major impact on the ability to see a moving target. In another study by the same experimenters, the average size target that could be seen by the 200 subjects at a velocity of 110 degrees per second dropped from 11 arc minutes on the first trial to 6 arc minutes on the twentieth (Ref. 8,X). There were very large differences, however, in the improvement shown by different individuals. Even though they performed nearly the same on the first trial, the 20 best subjects were able to see a 1.9-arc-minute target on the twentieth trial (B in the figure), while the 20 worst had improved only slightly (W in the figure).

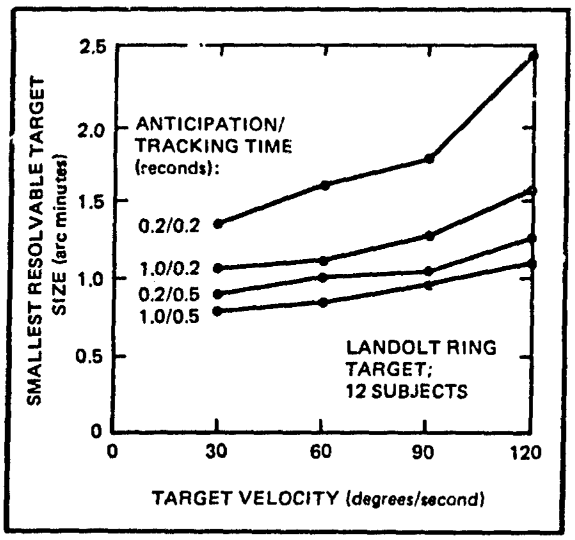

Figure 3.10-5. Impact of the Duration of Anticipation and Exposure. The ability to see a moving target is a function both of how long the target is visible to the observer and how much information he has that helps him prepare to track it. In the previous figure, the 0.2-second target exposure was preceded by a 0.2-second period when the observer could see a blurred image of the moving target. In the study illustrated here, the duration of the anticipatory period was varied to assess its effect (Ref. 9,C).

In the two bottom curves, the target remained exposed 0.5 second. Increasing the time interval during which the observer could see the target area but not the target from 0.2 to 1.0 second had only a small effect. However, as the two top curves illustrate, when the target was visible only 0.2 second, this same increase in time to get ready (anticipation time) had a very large effect.

The data represented in these four curves also suggest that the velocity of a moving image has less impact on vision than does the amount of time the observer is able to track the image.

3.10.2 EFFECT OF IMAGE MOTION ON VISION (CONTINUED)

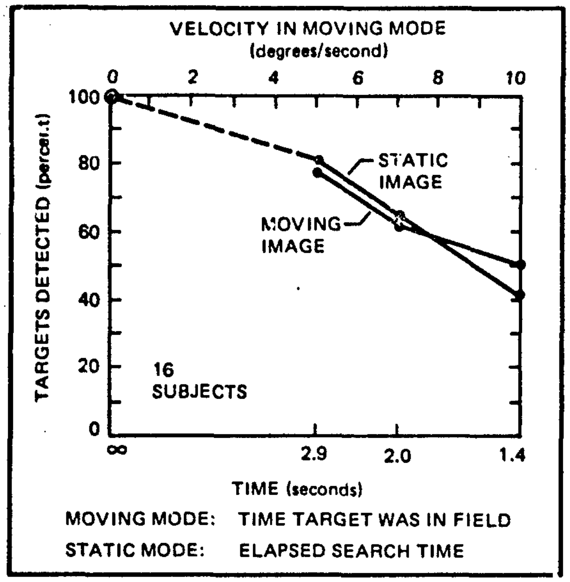

Figure 3.10-6. Search of Moving and Static Images. When search performance is compared on the basis of time spent searching, there is little difference between static and moving displays, at least for velocities up to 10 degrees per second. In the study illustrated here, subjects searched for a split ring in a 15-degree field of solid rings (Ref. 10,B). Two display modes were used, static and moving. In the static mode, the subject reported the target as soon as it was detected. The moving mode involved three velocities: 5, 7, and 10 degrees per second.

The graph shows data from both viewing modes, plotted with search time equated as shown on the bottom scale.

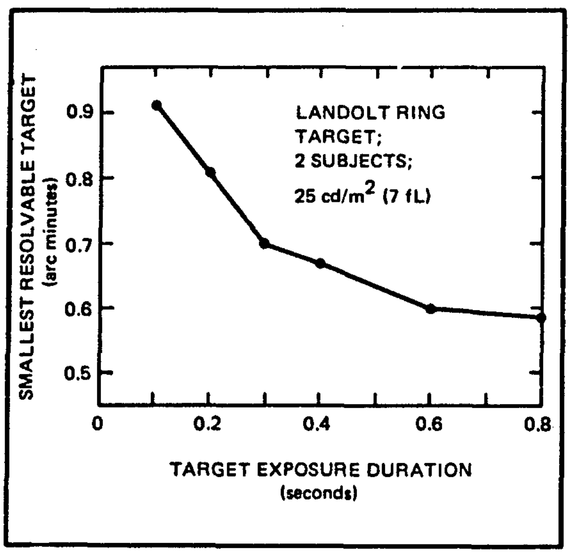

Figure 3.10-7. Exposure Time for Static Targets. The ability to see a static target increases with exposure time. In the study illustrated here, maximum performance was achieved with an exposure of 0.6 second (Ref. 11,C).

To investigate the possibility that longer exposures improved vision by allowing more light to reach the retina, there was limited testing at higher luminances. Values up to 500 cd/m^2 (150 fL) yielded a similar relationship, indicating that increased light level cannot be substituted directly for target exposure time (Ref. 12).

In visual search, eye fixation time is necessarily a compromise between the duration required to resolve the image completely and the time that is available. The most frequently used eye fixation time during some kinds of visual search is 0.2 to 0.3 second (Ref. 3). Most of these fixations, of course, are on areas that do not contain targets.

3.10.3 VELOCITY REQUIREMENTS

RECOMMENDATIONS:
Provide the following image velocities:

- **Zero**
- **A range of 2 to 30 degrees, and preferably 1 to 50 degrees, per second, on a single control. This motion must be steady and free of jerks at all velocities and all magnifications.**

Provide an imagery velocity of 60 to 90 mm (2.2 to 3.6 in) per second for translating within a frame. Because the operator would not be viewing the displayed image at this velocity, smoothness is not critical.

For roll film, provide a means of moving over distances of a few meters at a velocity of at least 0.3m (1 ft) per second and of moving through an entire roll at a velocity of at least 3m (10 ft) per second.

As was discussed in Section 3.10.1, the display user experiences the motion of the image, not the imagery. When appropriate the treatment in this section is therefore in terms of image velocity, which as Figure 3.10-1 illustrates is a function of both imagery velocity and magnification.

The image velocity requirements developed in this section are highly subjective and are almost certainly influenced both by the test equipment used and by the experience of the interpreter test subjects with their present displays.

One of the more important and difficult to quantify aspects of image motion is constancy or smoothness. As the data summarized in Section 3.10.2 illustrate, so long as the eye can track the target for a sufficient length of time, image motion at velocities below 10 degrees per second and in some instances even up to 60 degrees per second has little effect on visual ability. However, any irregularity or jerkiness in the motion can disrupt eye tracking and interfere with ability to see the target. In addition, interpreter comments about present and experimental displays indicate that such variations in velocity are extremely annoying and can make an otherwise good display unacceptable.

In the absence of adequate test data, quantitative recommendations for image motion smoothness are not feasible. However, if any velocity irregularity is perceptible it is safe to assume that at least some users will complain. If the motion is produced by a stepping motor, it is likely that the individual steps will become noticeable at very low stepping rates if the magnification makes each step equal to more than 0.5 to 1.0 arc minute in the image.

In a display that provides a very wide magnification range, small velocity irregularities at high magnification can be very difficult to eliminate. So long as such a display is used primarily at lower magnification, these will probably not cause significant problems.

3.10.3 VELOCITY REQUIREMENTS (CONTINUED)

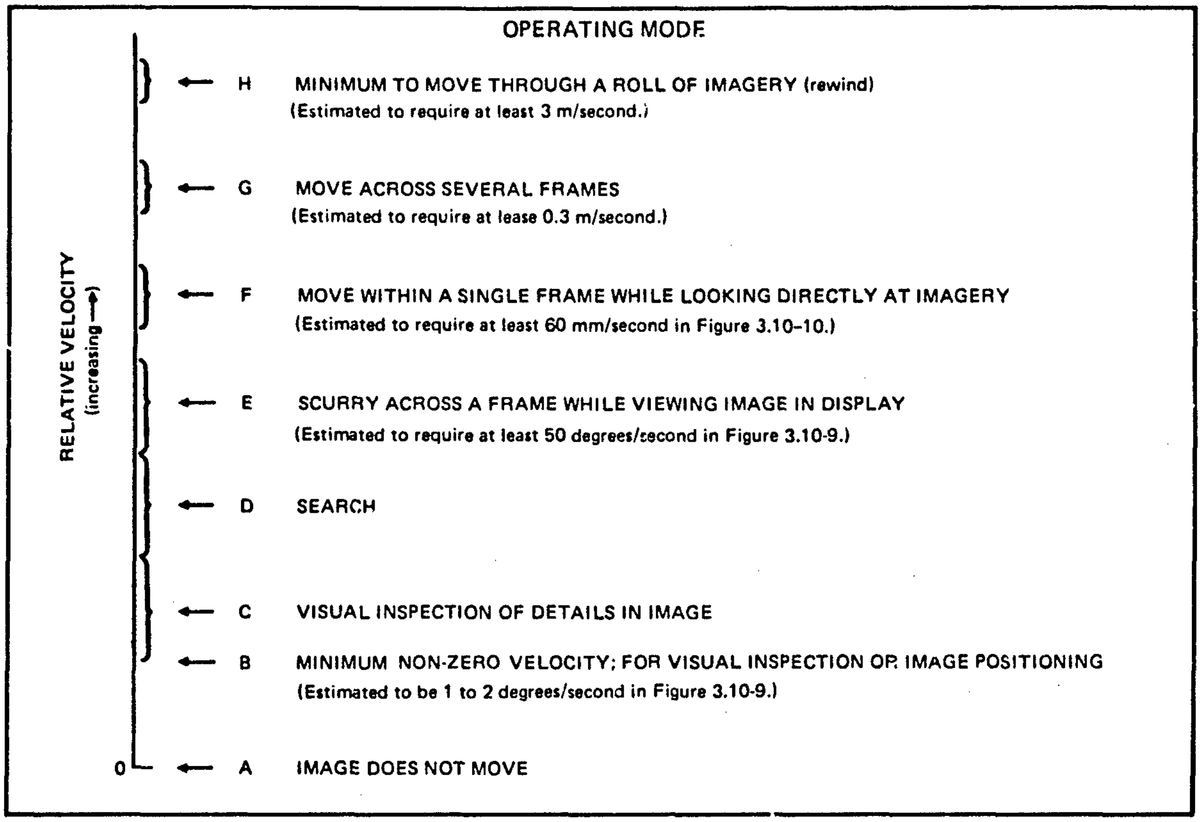

Figure 3.10-8. Transition Velocity Analysis. Display translation velocity is broken down into separate regions in this figure as an aid in deriving design recommendations. The following regions are illustrated:

A–Zero velocity is essential when the user must take a long look at the image and when he is not actively using the display. The image must not creep in this mode.

B, C–Visual inspection of an extended area on an image often takes place as the area is moved slowly through the central portion of the display field. The minimum velocity available to perform this activity, B, should be sufficiently slow that this activity can be performed with continuous motion rather than by a series of starts and stops. If required, velocity B must also be adequate for positioning the image relative to a reticle (Section 3.10.5).

D–Because of the need to cover more territory, search for targets involves higher velocities than the close inspection activity included under C. The exact values depend on many factors and, because velocities C, D, and E will normally be available on a single control, are not too important.

E–Maximum velocity while looking at the display image, rather than the imagery occurs when the user moves rapidly from one point to another in the frame; vision at this velocity is limited to looking for the gross cues that indicate the desired area on the frame has been reached.

F–To move between two widely separated points within a frame, the user will generally look directly at the imagery, or use minimum magnification if direct viewing is not possible. He will not be looking at details in the imagery. Maximum velocity must be adequate to complete the transit in an acceptable amount of time, and the minimum must allow positioning the desired object within the display field.

G–Translation from one frame to another nearby frame should occur rapidly since this is essentially wasted time for the display user. No good data are available, so design limits depend on an estimate of how long the user will tolerate waiting.

H–Moving through an entire roll of imagery should also occur rapidly, and, because of the lack of good data, design limits must be based on estimates of how long the user will tolerate waiting.

The number of controls used to achieve these velocities must be minimized. A single control should include A through E, and preferably F also. Velocity G should be available on the same control as either F or H. (See Section 3.10.4.)

3.10.3 VELOCITY REQUIREMENTS (CONTINUED)

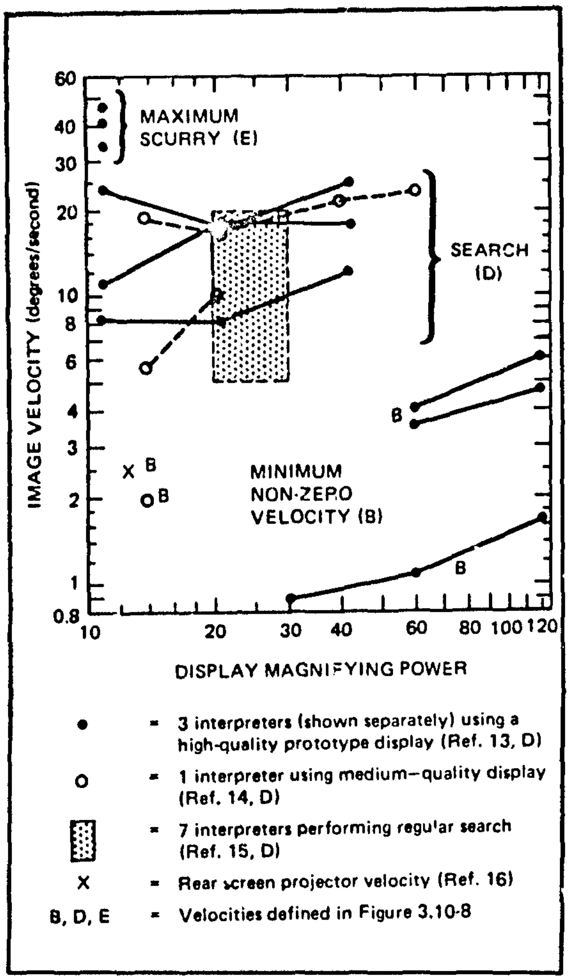

Figure 3.10-9. Image Velocity Preferences. The small amount of data available on image velocity preferences of interpreters is summarized here. These data are all based on experienced interpreters working with high-quality aerial photography.

The data plotted as dots (• and o) were obtained in simulated work situations described to the interpreters in terms of the operating modes in Figure 3.10-8. For example, they were asked to demonstrate the lowest velocity they would ever require in a display. The results, with data points for individual interpreters connected, are labeled B at the bottom of the graph.

The minimum image velocity of a prototype rear screen projector, nominally 2.5 degrees per second (shown as X), can be compared with these values (Ref. 16). On one occasion, this velocity was judged to be sufficiently slow and on another occasion it was judged to be too fast.

The search velocity data (D) were obtained in much the same way but represent nominal rather than minimal values. In the case of the single subject identified with an open dot (o), both fast and normal search was simulated. The filled region represents an average range of values for interpreters during regular work activity (Ref. 15).

To determine maximum scurry velocity (E), the interpreters were instructed to view the image in their display while moving along two paths at the maximum velocity they expected from a very good display. The paths were:

- 60 mm (2.4 in) along a relatively straight road, stopping where the road made a sharp turn
- 120 mm (5.8 in) in a straight line, stopping at a large, easily seen airfield

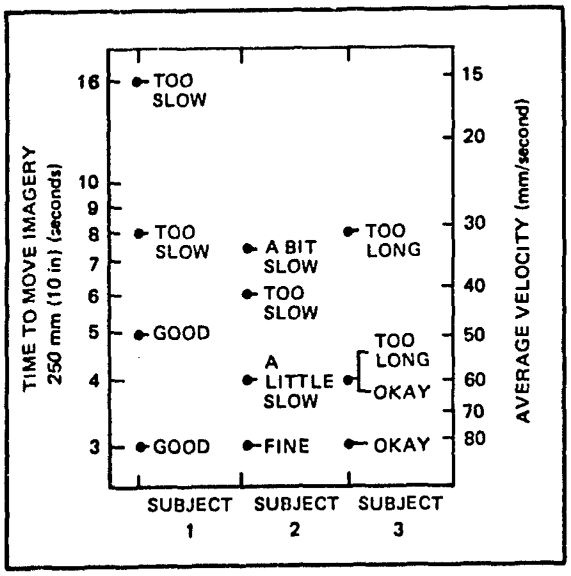

Figure 3.10-10. Imagery Velocity Preferences. In order to obtain an estimate of velocity F (Figure 3.10-8), the three interpreters in Figure 3.10-9 also indicated their satisfaction with various times required to translate imagery 250 mm (10 in) on the light table surface of their display. As this figure illustrates, the maximum duration that satisfied most of the subjects was approximately 4 seconds, which corresponds to an average velocity of approximately 60 mm (2.4 in) per second.

The noise level produced by the drive mechanism became significant when the velocity exceeded approximately 60 mm (2.4 in) per second, and this may have had some effect on judgments. At approximately 100 mm (4 in) per second, the noise level was very high and made some subjects fear for the safety of the display.

3.10.4 CONTROL OF IMAGE TRANSLATION

RECOMMENDATIONS:

For a display limited to small imagery chips or moderate sized chips and a small magnification range, provide manual image translation, preferably with a rotary knob.

For other displays, the preferred translation velocity control is a 2-axis, position-type joystick, spring loaded to the center-off position.

Make image velocity at a given control setting constant regardless of display magnification.

To obtain a wide velocity range plus adequate control sensitivity at low velocities, use a nonlinear relationship between control setting and image velocity, or provide a 5X speedup pushbutton in the end of the joystick.

For moving imagery only short distances, a well designed manually operated system is superior to a motor-driven system in both ease of use and cost. A good example is the stage translation mechanism used on laboratory microscopes. The best control for such a device is generally a knob or handwheel. Resistance should be light so that the control can be operated at a wide range of rates.

The best available single device for controlling image velocity in two axes is a joystick configured so that image velocity is a function of joystick position. Joystick design parameters are treated in Section 6.2 and operator ability to adjust a joystick is compared with image velocity control requirements in Figure 3.10-13 below.

A simple on/off joystick with a separate knob or thumbwheel to set velocity is a functional alternative to an ordinary joystick. However, because it is so much more difficult to use, it should be avoided except perhaps when modifying an existing display or when it is the only kind of control that will fit in the available space.

A force, or isometric, joystick can be adjusted by an operator with the same precision as a position-type joystick (Ref. 17,B). However, a force joystick provides less indication of control setting than a position-type one, and this can cause problems, particularly if the display user wants a higher image velocity than is available. If he has no indication that he is at maximum velocity, he may keep pushing harder on the joystick, increasing both his fatigue and his frustration with the display (Ref. 18).

Force joysticks are available that incorporate a small amount of movement and thereby provide the operator an indication that he is making a maximum input (Ref. 17). These work well for tasks such as positioning a cursor on a CRT. However, in the absence of experience with this type of control for imagery displays it should be used with caution.

In some situations, primarily when using a back-and-forth pattern in order to ensure thorough search of an entire frame of imagery, the display user must move an extended distance along one axis of the imagery with no motion along the other. Therefore, the detent that indicates the off position of a two-axis control such as a joystick should be sufficiently noticeable to minimize motion along the second axis. A special control which when activated would limit motion to whichever axis was receiving the largest input command might also be a good solution. A control that must be switched to whichever axis is in use would also eliminate the problem, but only at a considerable increase in operating complexity.

If the display magnification range is large, the very wide imagery velocity range required will exceed the user's ability to adjust a simple joystick-type control. The best solution is to couple the velocity control to the display magnification, so that the image velocity for a particular control setting remains constant as magnification changes. Less desirable is an easily operated velocity range control.

Some operators will occasionally change the control input very rapidly. If the translation mechanism makes an extremely fast response to a change in control input, an undesirably high acceleration may occur. Such

3.10.4 CONTROL OF IMAGE TRANSLATION (CONTINUED)

mechanisms should be protected by the addition of circuitry to limit the rate of velocity change to a safe level.

Whatever style of device is used to control image velocity, it will be used constantly for long periods of time and it should therefore offer light resistance to motion. This in turn makes it more susceptible to inadvertent operation, making it important to locate the control where it is unlikely to be bumped.

Design limits on the two highest velocities in Figure 3.10-8, moving across several frames (G) and rewinding an entire roll of imagery (H), depend on how long the display operator should reasonably be expected to wait for the completion of these actions. This depends on many poorly defined factors, including how much time pressure the operator is under. In the absence of any useful test data, design recommendations in this area are necessarily based on an educated guess.

The following figures include an analysis of the relationship that should exist between the position of a joystick control and image velocity. A similar analysis can be conducted for other types of controls if the precision with which an operator can adjust them is known.

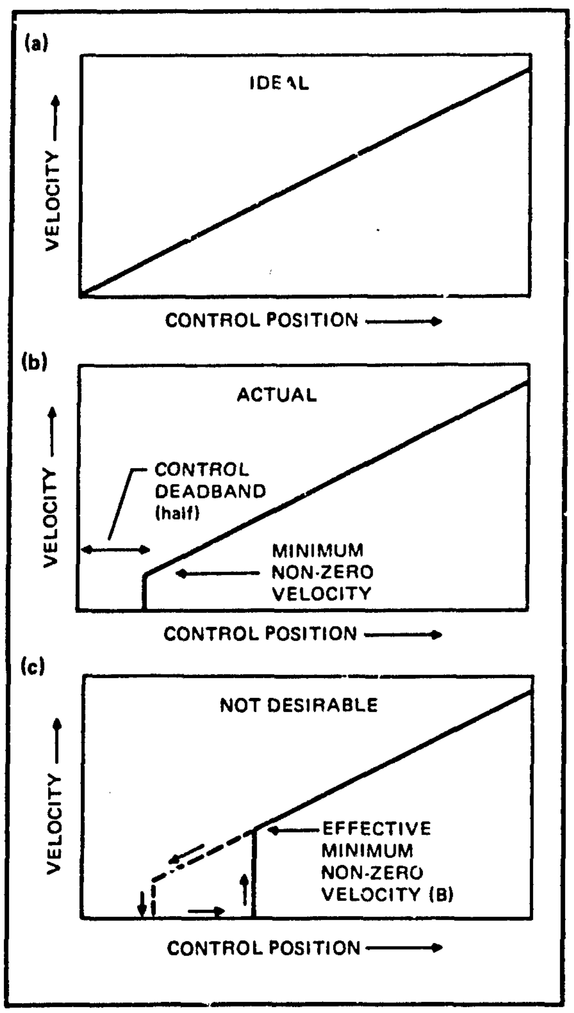

Figure 3.10-11. Control of Low End of Velocity Range. In theory, image velocity might match control position, as is illustrated in (a). However, exactly centering the control in order to obtain zero image velocity will be nearly impossible, especially when the operator is attempting to move the image along the other axis.

Therefore, the control mechanism is usually designed so that the image velocity remains zero as the control is moved through a small deadband at the off position. In addition, because the resistance to motion due to friction decreases when motion starts, most devices for translating imagery accelerate very rapidly from zero to some small but finite velocity (Ref. 19). The result of these two effects is a typical image-velocity to control-position relationship like that shown in (b).

With some imagery translation mechanisms, the velocity obtained when the control reaches the position where motion starts is excessive, but the velocity can then be reduced to a more reasonable value by moving the control back toward zero, following the broken portion of the curve in the figure. The effective minimum non-zero velocity in this case (B in Figure 3.10-8) is that obtained at the control setting where motion starts, rather than the minimum that can be achieved. This kind of display response can cause the operator to feel that the image is running away, and it should be avoided.

3.10.4 CONTROL OF IMAGE TRANSLATION (CONTINUED)

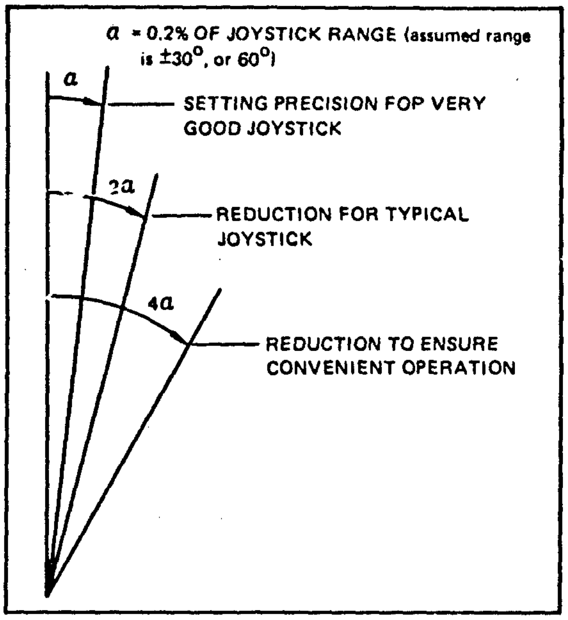

Figure 3.10-12. Joystick Positioning Ability. Testing has demonstrated that with an adequate display, a high-quality joystick can be positioned to within 0.2 percent of its total range (Ref. 17,B). For an average quality joystick that has seen many hours of use, this value should be increased; a factor of 2 is used here. It should also be increased because the operator should not have to be concerned about positioning the control precisely; this introduces a second factor of 2. On this basis, the display operator can reasonably be expected to position a joystick control to within 0.8 percent of its full range, or to any one of 125 positions.

This means that in order to obtain a desired minimum non-zero velocity (B in Figure 3.10-8), the operator will be able to use a joystick displacement from the center, or null position, of about 1/60th of the full deflection.

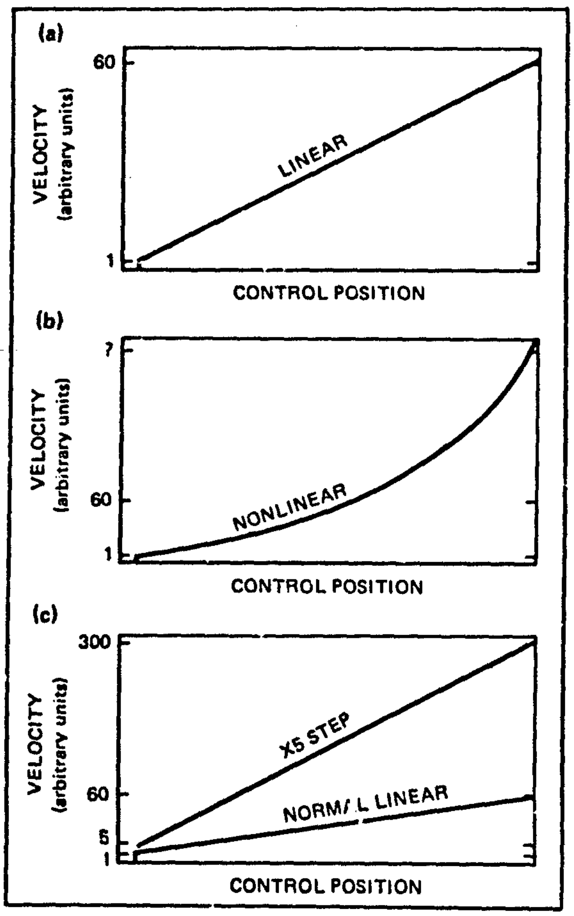

Figure 3.10-13. Control of Entire Velocity Range. Assuming that the simple analysis in Figure 3.10-12 is valid and that the deadband will not take up much of the control range, the operator should be able to conveniently set the joystick to approximately 60 positions either side of center. If the relationship between joystick position and velocity is linear, as in (a), then the maximum velocity is 60 times the minimum that the operator must be able to maintain. Assuming that the minimum non-zero velocity of the display approximately matches the minimum required by the user (B in Figure 3.10-8) and that the control circuitry automatically compensates for changes in magnification, then this 60 to 1 velocity range would accommodate velocities B to E of Figure 3.10-8, but would leave little room for F or G.

The best way to increase the available velocity range while maintaining adequate control sensitivity at low velocities is by making the relationship between control position and velocity nonlinear, as is illustrated in (b). The exact shape of the nonlinear function can not be determined from available data, but an adequate design should be easy to develop.

An alternative method for increasing the range of velocities available is to provide a velocity range control. For convenience, this should be a pushbutton mounted in the end of the joystick that increases the velocity by a factor of at least 5 when depressed. This option is illustrated in (c). It will not be as convenient to use as the nonlinear control. Depressing the pushbutton should increase the velocity, rather than reduce it, because it will reduce the operator's ability to position the stick precisely.

3.10.5 PRECISE IMAGE POSITIONING (COMPARATORS)

Controls used to position an image very precisely relative to a reticle present different problems than were treated in the previous section. The principal application is in comparators (Section 5.3).

The standard dimensional unit for comparators is micrometers (μm) ($1\ \mu m = 10^{-6}$ m) on the imagery, rather than a visual angle in the image as was used in the previous section. Using an imagery dimension in the analysis that follows eliminates the need to consider display magnification.

At one extreme, the translation system must not reduce the precision with which the operator can align the reticle with an edge in the imagery. For several skilled operators using three different comparators to make pointings on edges in good quality imagery, the average standard deviation for individual operators was 2.5 μm (Ref. 20,B). Expressing this another way, 67 percent of the pointings made by a single operator on a single edge would fall within a region 5.0 μm wide. In order that the stage translation system not significantly increase this value, it should allow the operator to easily position the reticle within a much smaller region, preferably no greater than 1.0 μm.

At the other extreme, the operator must be able to move across an entire imagery chip in a reasonable period of time. Chip size is limited by the size of the stage, which for a typical high-precision comparator might be 250,000 μm (10 in). There is no way to determine exactly how long a wait the user will tolerate for the completion of this excursion, but 30 seconds is a reasonable upper limit. This implies a need for a maximum velocity of at least 8300 μm per second.

Figure 3.10-14 below contains an analysis of the three most promising types of controls:

- A manually operated crank/handwheel. This control would be used as a crank for high velocities and as a handwheel for precise positioning.
- A trackball operated in the position mode.
- A joystick operated in the velocity mode, so that joystick position determines image velocity.

The implication of this analysis is that none of the three control devices is particularly good by itself. Both a crank/handwheel and a trackball take too long to cross the stage and will require a second control, probably operating in the velocity mode, to perform this function. A velocity mode joystick will probably require both a nonlinear relationship between control setting and velocity and a separate velocity range control in order to obtain the necessary velocity range.

Some types of controls, such as joysticks and trackballs, are inherently suitable for controlling motion along both X and Y axes simultaneously. Others such as handwheels are basically single-axis devices. The impact of these differences depends on the application. Nonstereo mensuration involves reticle movement along both axes and so two-axis controls are much more convenient. On the other hand, much of floating dot stereo height mensuration involves moving a single stage in the X direction in order to measure lateral disparity. In this application a two-axis control such as a trackball is likely to result in movement in the Y direction when it is not desired. The same is true of a joystick unless a noticeable *detent* indicates when the stick is moved out of the null position along each axis.

3.10.5 PRECISE IMAGE POSITIONING (COMPARATORS) (CONTINUED)

CONTROL DEVICE	ASSUMPTIONS	STAGE/CONTROL MOVEMENT RATIO TO ACHIEVE 1-μm POSITIONING	IMPLICATION FOR CROSSING 250,000-μm STAGE
CRANK/ HANDWHEEL	SETTING PRECISION OF HANDWHEEL IS 1° (Fig. 6.2-11)	1 μm DEGREE, OR 360 μm/ REVOLUTION	250,000/360 = 700 REVOLUTIONS TO CROSS STAGE; AT 250 RPM REQUIRES 2.8 MINUTES
POSITION MODE TRACKBALL	SETTING PRECISION IS 1/400 REVOLUTION Fig. 6.2-4)	400 μm/ REVOLUTION	250,000/400 = 625 REVOLUTIONS TO CROSS STAGE; WILL TAKE A LONG TIME
VELOCITY MODE JOYSTICK	MINIMUM OPERATOR INPUT TIME IS ESTIMATED TO BE 0.5 SECOND, AND MOTOR DOES NOT DRIFT (Ref. 21)	A MINIMUM EFFECTIVE NON-ZERO VELOCITY OF 1/0.5 = 2 μm/ SECOND	VELOCITY OF 8,300 μm/ SECOND TO CROSS STAGE IN 30 SECONDS; VELOCITY RANGE IS 4150:1

Figure 3.10-14. Analysis of Comparator Control Devices. An analysis of three kinds of devices that might be used to control the translation of a comparator stage is illustrated here. If the stage to control movement ratio of the first two devices is set to ensure adequate precision when positioning the stage, too much time is required to cross the stage. The third device requires a velocity range that will be very difficult to achieve in a single control.

3.10.6 IMAGE ROTATION AND INTERCHANGE BETWEEN THE EYES

RECOMMENDATIONS:

Provide a means of rotating the image through 360 degrees. Preferably allow both physical and optical rotation.

Provide a convenient means of adjusting optical rotation exactly to zero, and of locking it in that position.

Provide a scale to indicate the optical rotation setting. Ideally, include an indication of the rotation in the display field.

In order to eliminate inadvertent rotational misregistration between the image to each eye in a binocular monoscopic display utilizing a separate optical path to each eye, place the image rotator between the beamsplitter and the imagery.

With a stereoscopic display, provide a means by which either eye can view either member of the stereo pair, preferably without moving the imagery or repositioning the equipment.

The preferred orientation for viewing an image of a ground scene depends on the following:

- Shadow direction
- Obliquity direction
- Orientation of reference material, such as another photo or a map
- Camera flightpath if the image is in stereo(Figure5.1-5)

The image should be oriented so that shadows fall toward the observer. If they fall away, interpretation of relief is more difficult and some features may be seen reversed. This is a particular problem with hills and depressions on the ground, which do not provide such strong cues to their shape as do buildings and other cultural features.

The image should also be oriented so that the obliquity direction is normal. That is, raised objects such as buildings and trees should fall away, rather than toward the observer. If the obliquity is reversed, ground features will be difficult to interpret and the observer may have a sensation of viewing the world while standing on his head.

A conflict can occur between obliquity and shadow directions. For most observers obliquity is the most important, particularly if there is a significant amount present.

As the following two figures illustrate, the right and left eye members of a stereo pair do not always fall in the same relative locations on a roll of imagery. Therefore, in addition to rotating the images, a stereo display must allow the observer to view either member of the pair with either eye. Usually an optical switch in the display is the most convenient way of achieving this goal, but its advantages must be weighed against the cost and possible reduction in image quality.

To view imagery in stereo, it is essential that the camera flightpath be approximately parallel to a line connecting the entrance pupils of the observer's eyes. (See Section 5.1.1.) For many display/imagery combinations, image rotation of 90 degrees or 180 degrees is necessary to achieve this situation. In addition, if significant obliquity is present, objects will be rotated a few degrees in the opposite direction in the two members of the stereo pair and the best stereo can be obtained only if these small rotations are removed in the display.

Image rotation can be achieved by physically turning the imagery or by optically rotating the displayed image with mirrors or a prism. Physical rotation of the imagery, if feasible, is superior to optical rotation of the image for the following reasons:

- If the imagery can be viewed directly, without optical aids, then if no optical rotation is in use it will have the same orientation as the displayed image.

- With a manual image translation system, the image can be positioned more easily with no optical image rotation in use because the direction of image motion and hand motion will match.

3.10.6 IMAGE ROTATION AND INTERCHANGE BETWEEN THE EYES (CONTINUED)

- With a motorized image translation system, optical rotation of the image requires compensation within the display so that the direction of image motion will always match the direction of control motion.

- When viewing in stereo, the two images must be rotated as described in Figure 5.1-5. If this is achieved by optically rotating one image relative to the other, then translation will cause the two images to appear to move in different directions, destroying the stereo alignment. With only physical rotation of the two pieces of imagery, translation over a considerable distance while viewing stereo will be possible.

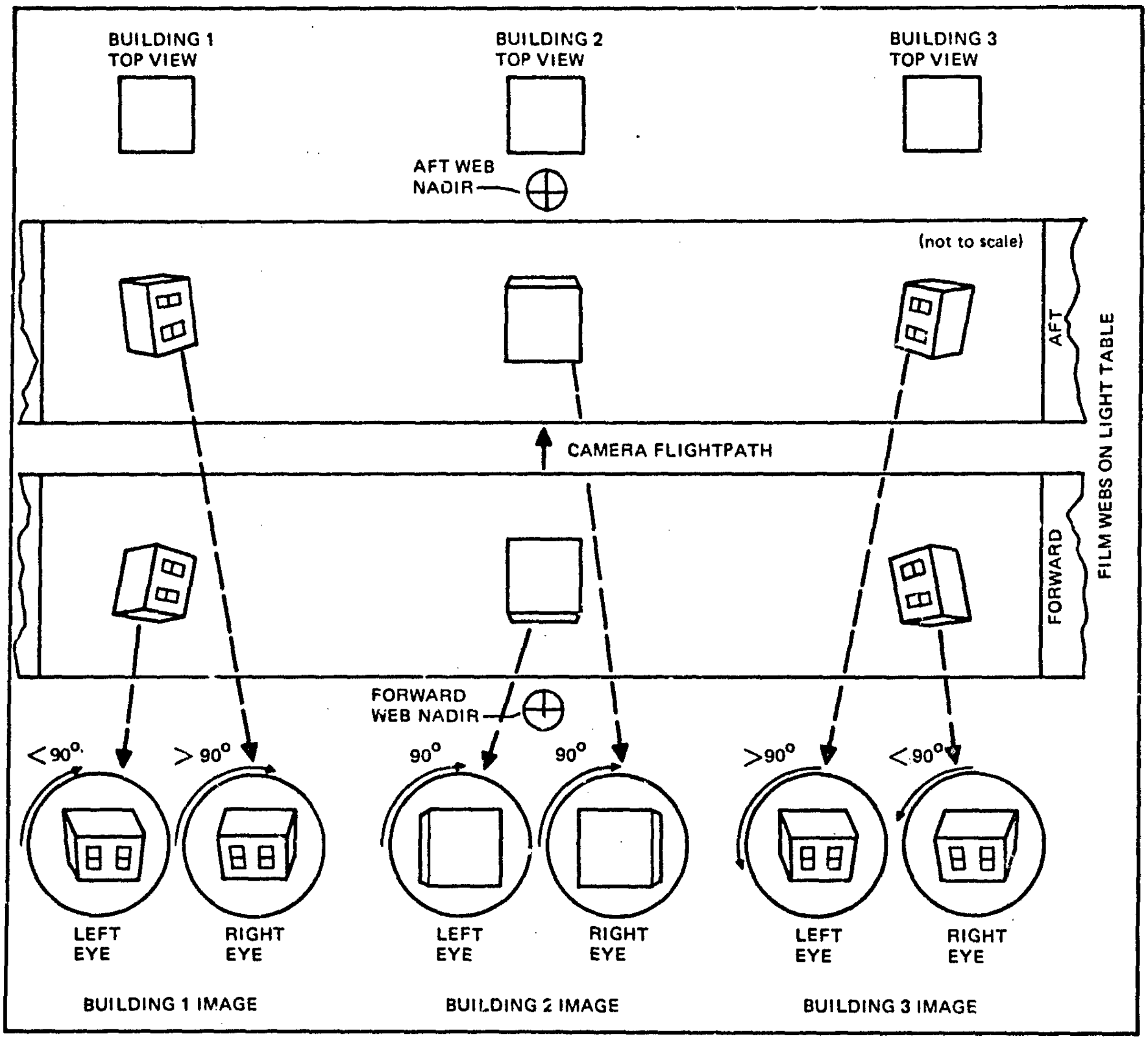

Figure 3.10-15. Panoramic Stereo Imagery. The shapes of three identical buildings as they are imaged by a pair of panoramic slit cameras are illustrated (Ref. 22). The two rolls of film obtained from such a collection system are typically mounted on a light table at a right angle to the observer's line of sight.

In order to obtain a stereo image, both images must be rotated approximately 90 degrees. Close to nadir, the best rotation is exactly 90 degrees, and at an obliquity angle of 45 degrees, it differs from 90 degrees by approximately 10 degrees in the directions illustrated in the figure.

Close to nadir, the choice of which eye sees which image is arbitrary, but in other regions the choice is dictated by the obliquity. Design of the display is complicated by the fact that the correct choice is different on either side of the nadir point.

3.10.7 CONTROL OF THE DIRECTION OF IMAGE MOTION

RECOMMENDATIONS:

Make the direction of motion in the displayed image match, at least to within 10 or 20 degrees, the direction of displacement of a two-axis image translation control.

The control rotation need not be infinitely adjustable. Rotation in 90-degree increments is essential.

Manual, rather than automatic, rotation of the control following image rotation is adequate.

The direction in which the displayed image moves should have a consistent relationship with the direction in which a two-axis image translation control is displaced, regardless of what image rotation setting is in use. In Section 3.10.6, a requirement for the capability to rotate the image through a full 360 degrees is developed. However, as Figure 3.10-15 illustrates, the image rotation in use will almost always be within a few degrees of 0, 90, or 180 degrees. Therefore, although full rotation is preferred, it is reasonable to reduce the complexity of the control system by limiting rotation of the control to increments of 90 degrees.

Any convenient technique for rotating the control output so that it and the image match is acceptable. For example, a four-position switch can be used to interchange the signals from the control. Alternatively, the translation control can be manually rotated.

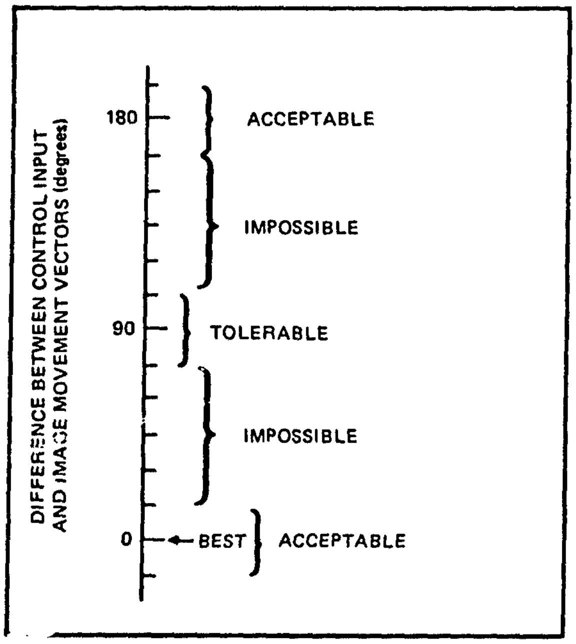

Figure 3.10-16. Control/Image Direction Relationships. The control system can be designed so that the direction of control movement matches either the movement of the image or the movement of the display. That is, the user can either think of the display as being fixed and use the control to move the image, or he can think of the image as being fixed and he can fly the display across it. There is no test data on which to base a choice between these two options, and experience indicates that it is fairly easy to adapt to either.

However, if the display is fixed physically so that it is actually the imagery that moves, and if the imagery can be viewed directly, then the first choice is best. With this choice, the motion of both the image and the imagery will match the motion of the control, at least when no image rotation is in use.

Adaptation to a shift of 90 degrees between image and control direction is possible but will be disturbing to some users and should be avoided.

A situation in which the direction of image and control motion differ by more than 10 or 20 degrees from a difference of 0, 90, or 180 degrees is extremely disturbing and will make it impossible for some individuals to use the display effectively. With common types of imagery there is little reason for this kind of situation to occur, even if control rotation is limited to increments of 90 degrees.

SECTION 3.10 REFERENCES

1. The imagery velocity in millimeters per second is (250/MP) tan θ, where MP is magnifying power and θ is image velocity in degrees per second.

2. Westheimer, G. Eye movement responses to a horizontally moving visual stimulus. *AMA Arch. Ophthal.*, Vol. 52, 1954, pp. 932-941.

3. White, C. T. and Ford, A. Eye movements during simulated radar search. *J. Opt. Soc. Am.*, Vol. 50, 1960, pp. 909-913

   Ford, A., White, C. T., and Lichtenstein, M. Analysis of eye movements during free search. *J. Opt. Soc. Am.*, Vol. 49, 1959, pp. 287-292.

   Both of these studies and additional data are summarized in Figure 1 of Gould, J. D., *Eye Movements during Visual Search.* IBM, Thomas J. Watson Research Center, Yorktown Heights, New York, August 1969.

4. Enoch, J. M. *The Effect of the Size of the Display on Visual Search.* Report RADC-TN-59-64, Rome Air Development Center, January 1958. The sequence of eye movements illustrated is typical of many included in this article.

5. Brown, B. Resolution thresholds for moving targets at the fovea and in the peripheral retina. *Vision Research*, Vol. 12, 1972, pp. 293-304. Two complementary articles by this author appear in the same volume of this journal, one on pp. 305-321 and another on pp. 1213-1224.

6. Westheimer, G. and McKee, S. P. Visual acuity in the presence of retinal-image motion. *J. Opt. Soc. Am.*, Vol. 65, 1975, pp. 847-850.

7. Ludvigh, E. and Miller, J. W. Study of visual acuity during the ocular pursuit of moving test objects. I. Introduction. *J. Opt. Soc. Am.*, Vol. 48, 1958, pp. 799-802.

   A survey of the several studies conducted by these authors appears in Miller, J. W., Ludvigh, E. The effect of relative motion on visual acuity. *Survey of Ophthal.*, Vol. 7, 1962, pp. 83-116.

8. Ludvigh, E. Visual acuity during ocular pursuit. In Horne, E. P. and Whitcomb, M. A. (Ed.), *Vision Research Reports.* Publication 835, National Academy of Sciences/National Research Council, Washington, D.C., 1960, pp. 70-74.

9. Elkin, E. H. Target velocity, exposure time and anticipatory tracking time as determinants of dynamic visual acuity, *J. Engr. Psychol.*, Vol. 1, 1962, pp. 26-33. Test subject training was not mentioned in this report. It can have a very large impact on performance.

10. Erickson, R. A. *Visual Search for Targets: Laboratory Experiments.* NAVWEPS Report 8406, U.S. Naval Ordnance Test Station, China Lake, California, 1964. (Also available as AD 005650.)

    Erickson, R. A. Visual search performance in a moving structured field. *J. Opt. Soc. Am.*, Vol. 54, 1964, pp. 399-405. This is a summary article.

11. Baron, W. S. and Westheimer, G. Visual acuity as a function of exposure duration. *J. Opt. Soc. Am.*, Vol. 63, No. 2, 1973, pp. 212-219.

12. When the sensation of brightness, or probability of detection of a point source, is measured, it appears that for short exposure durations the eye tends to integrate the luminous energy over time. For a wide range of target luminance levels, the ratio of performance to exposure time was nearly constant in Ref. 11, indicating that exposure time was the dominant variable.

13. Based on an unpublished pilot study conducted by the senior author in 1974.

14. Based on an unpublished pilot study conducted by military personnel in 1974.

15. These data are based on an unpublished portion of a study by J. Leachtenauer of The Boeing Company in which seven interpreters kept records of the time they spent actively searching regularly assigned imagery. A total of 141 man-days of such data were collected. To obtain the data plotted in Figure 3.10-9, average magnifications were used to convert average imagery translation to average image translation rates. (This conversion was made by the author of the present document, not Leachtenauer.) Such a procedure obviously yields only very approximate values.

16. Unpublished evaluation of a prototype rear screen projector display by the senior author. The magnifying power plotted in Figure 3.10-9 is less than the magnification on the screen because the viewing distance was more than 250 mm (10 in).

17. Mehr, M. H. and Mehr, M. Manual digital positioning in 2 axes: A comparison of joystick and track ball controls. *Sixteenth Meeting of Human Factors Society*, 1972, pp. 110-116.

Also, personal communication from the first author.

18. This problem became so serious with a recently built stereo comparator that the force joystick originally installed on it was replaced with a position joystick.

19. Several factors contribute to the velocity at the control setting that first causes motion. The reduction in friction after motion has begun is one. Another is the reduction in current through the drive motor when it starts to turn; if the power source is not properly designed, this will cause the voltage to the motor to increase. Both of these effects can be seen clearly in very simple devices such as slot cars and model trains. In general, feedback of drive motor velocity into the power source is necessary to eliminate this problem.

20. Dean, R. D. and Fallis, R. F. *Relative Accuracy of Mensuration.* Document D2-114252-1, The Boeing Company, Seattle, Washington, 1968.

21. Frost, G. Man machine dynamics. Chapter 6 in Van Cott, H. P. and Kinkade, R. G. *Human Engineering Guide to Equipment Design.* U.S. Govt. Printing Office, Washington, D.C., 1972.

This analysis is necessarily sensitive to the value of 0.5 second assumed as a minimum control input duration. There are no good data from which to establish this value, but Frost, on page 299-305, notes that the absolute minimum response time for an operator using a control to track a signal is 0.06 to 0.09 second, and that values up to 0.6 second, or even longer, may occur under adverse conditions. The time required to react to a discrete event that is obvious and expected is 0.1 to 0.2 second, but if the signal is weak or the operator must choose among several responses, reaction time increases sharply. Therefore, a design allowance of 0.5 second is the minimum to ensure that the comparator operator need not concentrate on the image translation mechanism when he should be concentrating on the relative alignment of the reticle and the target.

22. Thompson, M. M. (Ed.) *Manual of Photogrammetry* (3rd ed.). Amer. Soc. Photogrammetry, Falls Church, Virginia, 1966. See page 150+.

3.11 IMAGE VIBRATION

SECTION 3.11 IMAGE VIBRATION

RECOMMENDATION:

Reduce image vibration to the point where it does not reduce the quality of the displayed image. For vibration in the plane of the image, this is probably a maximum peak-to-peak vibration amplitude no more than one-fourth the resolution limit for a high contrast grating (Figure 3.11-2).

In situations where vibration cannot be eliminated, reduce the vibration amplitude by increasing the vibration frequency (Figure 3.11-7).

The impact of vibration of the image in an imagery display is treated in this section. If vibration of the observer along with the display is anticipated, additional sources should be consulted (Ref. 1).

The quality of the image in an imagery display should not be reduced by vibration. The limited test data available make it impossible to set good quantitative limits, and in any case, measuring vibration amplitude at high display magnification is so difficult that such limits are not very useful. As a result, in most situations the best way to determine if vibration is a problem is to compare display image quality measured under normal operating conditions and again with all possible sources of image vibration eliminated.

Oscillatory variation in the axis running from the imagery to the objective lens of the display will blur the image if the displacement exceeds the display depth of field calculated with no allowance for variation in eye accommodation (Section 3.8.2). Although this is certainly a common problem for microscope type displays on lightweight mounts, there is no known test data. In general, the same solution discussed in Figure 3.11-7 applies. That is, if the variation in distance is small enough there will be no loss of image quality, and one way of making the variation small is to increase the vibration frequency.

The first step in eliminating vibration is to redesign the source of the vibrational energy. For example, it may be possible to improve the balance of a cooling fan, or perhaps to reduce its velocity. Second, a change in the mount that connects the vibration source to the display may result in more of the vibrational energy being converted to heat instead of being transmitted into the rest of the display. Finally, it may be necessary to change the structure of the display so that the vibration occurs at a more desirable frequency. The data in Figures 3.11-1 and -2 below provide very limited evidence that vibration reduces vision less at low than at high frequencies. However, vibration amplitude varies inversely with the square of the vibration frequency (Figure 3.11-7). Therefore, it will usually be best to redesign the display structure to increase the vibration frequency to the point where vibration amplitude is negligible.

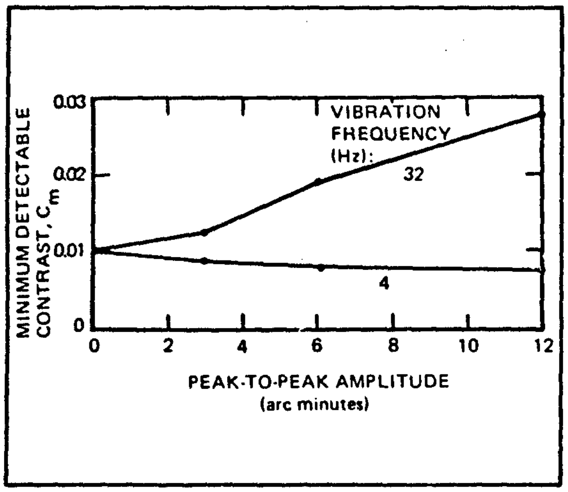

Figure 3.11-1. Change in Visibility of a Single Low Contrast Bar. Detection of a single 7 by 160 arc minute positive contrast bar required a greater contrast when it was vibrated at 32 Hz than when it was stationary (Ref. 2,C). When the vibration frequency was 4 Hz, there was actually a slight enhancement of visibility. The available data are not adequate to predict whether this enhancement would also occur for the more complex image normally seen in an imagery display.

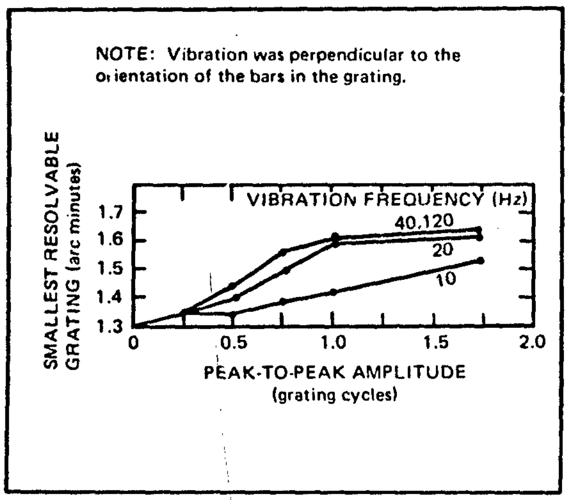

Figure 3.11-2. Reduction in Visibility of a High Contrast Grating. The increase in size required for 3 observers to detect the orientation of a grating when it was vibrating at different frequencies is illustrated here (Ref. 3,C). The impact of vibration was greatest at frequencies of 20 Hz or higher, and as the peak-to-peak vibration amplitude exceeded 0.25 cycle. Note that 0.25 cycle corresponds to approximately 0.25 of the resolution limit for the grating under the particular viewing conditions in use. A theoretical analysis in this reference implied that the loss would be more dramatic for a lower contrast grating.

The small loss as the amplitude increased from 1.0 to 1.75 cycles is probably a result of the periodic nature of the target. The loss for more common materials, such as imagery, would likely be much greater.

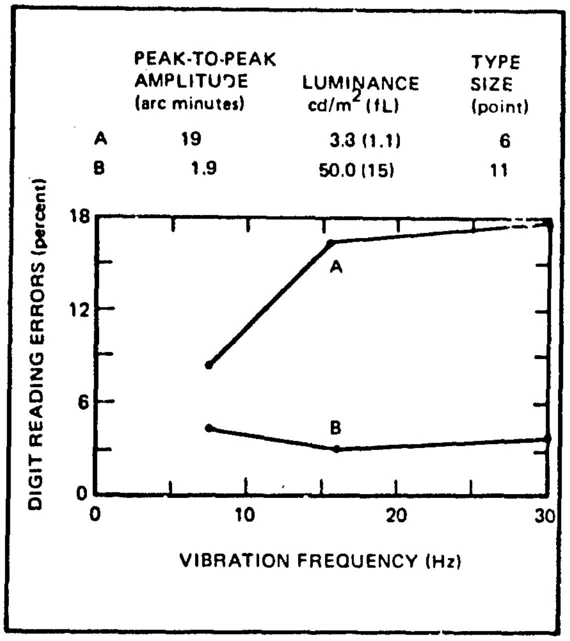

Figure 3.11-3. Loss in Digit Reading Ability With Vibration. When the amplitude of the motion was large enough, the luminance low enough, and the type small enough, vibration reduced the ability of subjects to indicate whether the two digits in a pair were identical (Ref. 4,C). This loss was greater at 15.5 and 30.5 Hz than at 7.5 Hz. Since the test targets were high contrast, it is difficult to apply these results directly to imagery displays. The time required to complete the task increased in the same fashion as errors and is not illustrated here.

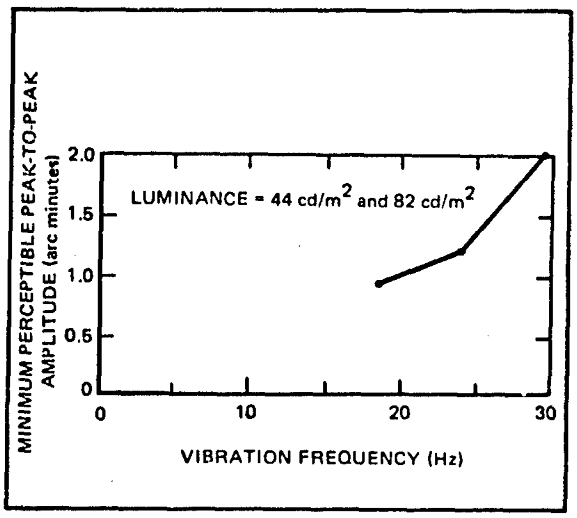

Figure 3.11-4. Threshold for Perception of Vibration. The study summarized in the previous figure was preceded by an experiment to measure the minimum motion at which subjects could detect vibration (Ref. 5,C). Unfortunately, performance was not measured with no vibration and it is not possible to be certain that a vibration amplitude of 1.9 arc minutes did not reduce performance. However, the data in Figure 3.11-3 suggest that this is the case, leading to the conclusion that, at least for large high contrast objects, vibration can be detected at levels that will not hurt performance. Performance was not different at the two levels of luminance tested, 44 cd/m^2 and 82 cd/m^2 (13 and 24 fL).

In attempting to apply this result to a display, it is important to note that the test subjects were allowed to view the digits both with and without vibration present.

Increasing the frequency of vibration made it more difficult to detect. This is the opposite of the impact of frequency on visual performance.

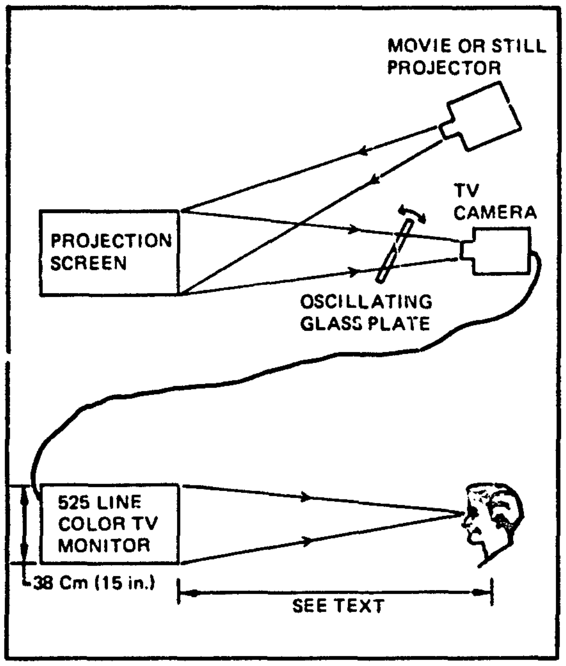

Figure 3.11-5. Test Setup for Evaluating Vertical Vibration in Television Displays. Subjects responded to vertical vibration in an image viewed on a closed circuit color television (Ref. 6,C).

Scene content was representative of commercial television. Several subjects were tested at once, so distance to the display ranged from 2.0 to 3.8m (80 to 150 in), with a mean value of 2.9m (115 in).

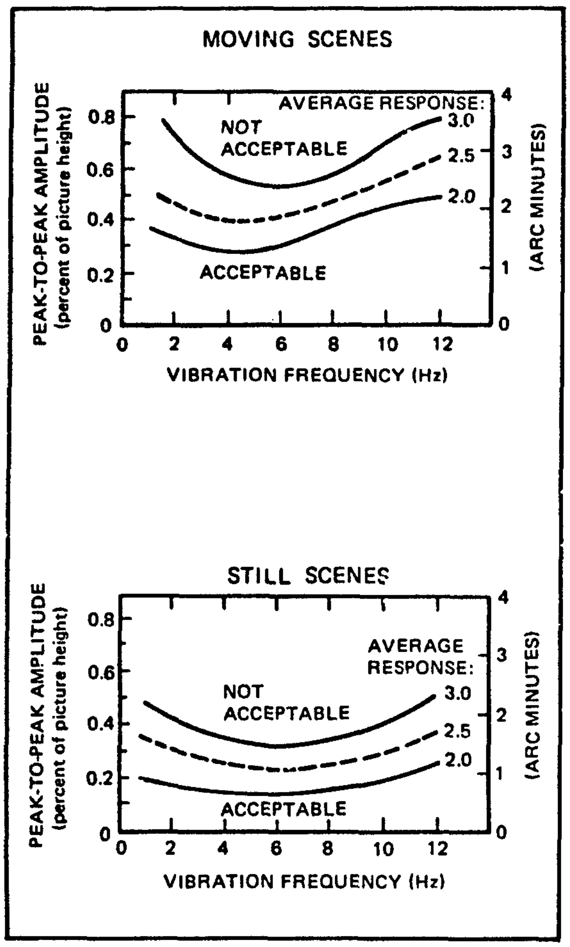

Figure 3.11-6. Subjective Response to Vertical Vibration in a TV Display. The subjects judged each display condition according to how disturbing the vibration was and whether the quality was acceptable for home viewing. The four categories were:

1 – Vibration not perceptible; acceptable quality

2 – Vibration perceptible; acceptable quality

3 – Vibration slightly disturbing; not acceptable

4 – Vibration very disturbing; not acceptable

In contrast to the studies discussed earlier in this section, image quality was reduced most by vibration frequencies of 3 to 6 Hz. Moving scenes were less sensitive to vibration, perhaps because of some type of temporal integration or perhaps simply because the image quality of the moving scenes was poorer before the introduction of vibration.

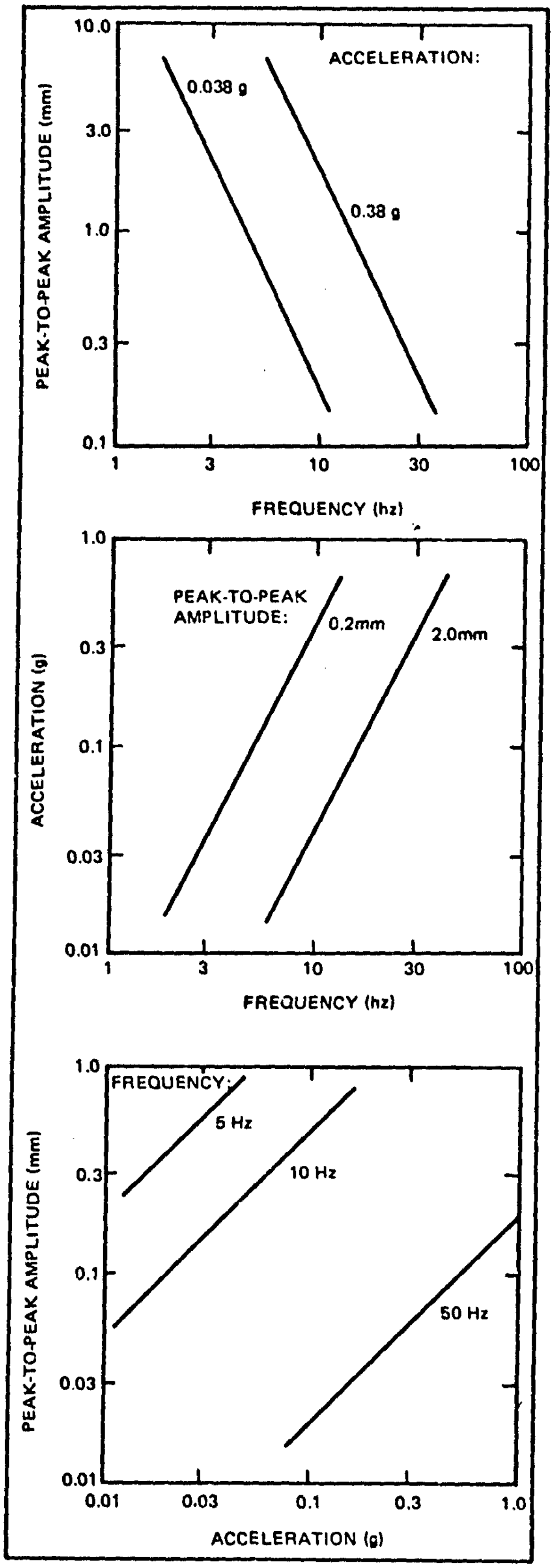

Figure 3.11-7. Interaction of Vibration Parameters. The relationship among vibration energy, amplitude and frequency, is (Ref. 7):

$$E = \frac{A f^2}{497.2} \quad \text{, where}$$

E = the vibration energy in acceleration, or g, units,

A = the double amplitude of the motion in mm, and

f = the frequency in Hz

This relationship is illustrated in the three figures, once with each of the three terms held constant.

Referring to the first figure, where vibration energy is a constant, redesign of the display to increase vibration frequency will drastically reduce vibration amplitude.

SECTION 3.11 REFERENCES

1. Taylor, J. H. Vision. Chapter 13 in Parker, J. F. Jr. and West, V. R. *Bioastronautics Data Book*, NASA SP-3006, National Aeronautics and Space Administration, 1973. Available from U.S. Government Printing Office, Washington D.C.

2. Krauskopf, J. Effect of target oscillation on contrast resolution. *J. Opt. Soc. Am.*, Vol. 52, 1962, p. 1306. Two subjects were tested 12 times at each condition. Exposure time was 1 second. Two different psychophysical techniques were used, the method of constant stimuli at 4 Hz and an "up-and-down" method at 32 Hz.

3. Ercoles, Anna M., Fiorentini, A., and diFrancia, G. T. Visual experiments with a vibrating test object. *Optica Acta*. Vol. 3, March 1956, pp. 40-46. The grating contained opaque bars (10 cd/m^2) 3 times the width of the clear (420 cd/m^2) spaces. This figure is a summary of three figures, each for a different test subject, appearing in the reference. The results for a vertical grating were similar to those shown in Figure 3.11-2 for a horizontal grating.

4. Crook, M. N., Hoffman, A. C., Wessell, M. Y., Wulfeck, J. W., and Kennedy, J. L. *Effect of Vibration on Legibility of Tabular Numerical Material–Experiments 5 to 7*. USAF Air Material Command Report No. TSEAA-694-1K, 1947.

5. Crook, M. N., Harker, G. S., Hoffman, A. C., Wulfeck, J. W., and Kennedy, J. L. *Amplitude Thresholds for Visual Perception of Vibration*. USAF Air Material Command Report No. MCREXD-694-1R, 1949. Test subjects were three college students. Stimulus material was 6, 8, and 10 point type viewed at 0.36m (14 in).

6. Gilbert, R. G., Norris, J. C., and Wood, H. D. Perceptibility of vertical unsteadiness in television display of motion-picture films. *J. Soc. Motion Picture and Television Engr.*, Vol. 82, 1973, pp. 654-657. (Additional information obtained by direct communication with the first author, December 1974). A total of 42 subjects viewed the moving scenes and 51 viewed the still scenes. Visual angles (in Figures 3.11-6) are based on the average viewing distance. The display was a Conrac studio monitor with a 0.38m (15 in) high image.

7. Maten, S. Velocity criteria for machine vibration. Chapter 9 in Blake, M. P. and Mitchell, W. S. (Ed.), *Vibration and Acoustic Measurement Handbook*. Spartan Books, New York, 1972, p. 276. This reference gives peak-to-peak vibration amplitude as $\frac{a}{2\pi^2 f^2}$, where a is the gravity constant, 32.2 feet/sec^2 or 9810 mm/sec^2, and f is the frequency in hertz.

SECTION 4.0
ELECTRO-OPTICAL IMAGERY DISPLAYS

4.1 BASIC ELECTRO-OPTICAL SYSTEM OPERATING PRINCIPLES

4.2 CATHODE RAY TUBE FLICKER, LINE CRAWL AND SCINTILLATION

4.3 DATA FROM LABORATORY STUDIES ON SAMPLED IMAGERY

4.4 ELECTRO-OPTICAL DISPLAY CHARACTERISTICS

SECTION 4.0 ELECTRO-OPTICAL IMAGERY DISPLAYS

This section is concerned with the interaction between the characteristics of *electro-optical* imaging systems and the ability of the interpreter to extract information of intelligence value from the images they produce. Section 4.1 provides a brief introduction to the basic concepts and vocabulary of electro-optical systems for those readers not familiar with the area. Section 4.2 contains data on *interlace* techniques and their effect on the appearance of *flicker, line crawl*, and *scintillation* of the image produced on *cathode ray tubes*.

Data from laboratory studies on interpreter performance and visual performance as a function of electro-optical system characteristics are presented in Section 4.3 along with data on image quality judgments where performance data was lacking. The influence of specific system characteristics on the nature of the visual stimulus is discussed in Section 4.4.

The primary emphasis is on the use of the CRT as the image-producing device. In instances where performance or quality judgment data were available for imagery generated by *optical line-scan printers*, it has been included.

All electro-optical image-forming systems are *sampling* systems; that is, they do not produce a continuous two-dimensional image, but rather they reproduce such images as a series of samples in either one or two dimensions. This sampling process creates artifacts of several kinds, most of which the designer can do little to control. However, one type, *aliasing* can be controlled to some extent by the designer. Aliasing occurs when a signal is sampled at a rate less than twice its frequency (Ref. 1). If the optics of the imaging system are designed to prevent the presence of images on the photosensor that have a greater than twice the spatial frequency of the sampling system (*electron beam* or sensing element size), then aliasing will be avoided. A complete discussion of this problem is outside the scope of the present handbook.

Developing design recommendations for the display of electro-optical imagery is a hazardous undertaking. In many instances the data upon which recommendations are based are fragmentary, or have been collected under conditions which make generalization to broader applications a questionable practice. Most of the recommendations which follow in this section therefore include cautions concerning their application. In some instances, recommendations are included for which substantiating data is lacking. These are based on present design practice or estimates of performance effects and are followed by a warning.

RECOMMENDATION:

The peak luminance produced by a CRT used to display imagery should be at least 85 cd/m^2 (25 (fL), but probably no greater than 350 cd/m^2 (~ 100 fL), unless special provisions are provided to prevent light reflections and scattering in the faceplate.

Warning: No data relating CRT luminance to interpreter performance is available. The recommendation is based on the need to provide adequate luminance for the visual system as discussed in Section 3.2 while at the same time recognizing that the contrast of the image, particularly in low luminance areas will be degraded by light which is scattered within the faceplate (Figures 4.4-24 and 4.4-25).

RECOMMENDATION:

For black and white systems, *bandwidth* should be partitioned equally between *quantizing* levels and *spatial frequency* until a 3-bit quantizing level has been reached. After this level, bandwidth should be partitioned between spatial frequency and quantizing levels at the ratio of 2:1.

Caution: Data on this subject is contradictory. Figure 4.3-42 shows that for judged image quality for home entertainment purposes, spatial frequency appears to almost universally take precedence over quantizing levels. Figure 4.3-44 shows performance improving up to the 7-bit quantizing level. Figure 4.3-45 shows that, in terms of total information needed and therefore bandwidth requirements, lower spatial resolutions are better up to about an 80-percent performance level on dot-scanned transparencies generated by an optical line scan image generator.

RECOMMENDATION:

The *signal-to-noise ratio* (SNR) for the signal delivered to the *electron gun* of a CRT display system should exceed 35 dB for the peak luminance signal.

Caution: Performance will improve somewhat above this level. A higher SNR is desirable, if it can be provided.

RECOMMENDATION:
Line pairing should not exceed ±5 percent (Figure 4.4-18).
Warning: No performance data are available to substantiate this recommendation. As the referenced figure shows, banding which will lead to errors in *modulation transfer* will occur if line pairing exists. The recommendation is based on current good design practice (Ref. 2).
RECOMMENDATION: CRT Line Spacing
The scan lines on a CRT display should overlap at the 50-percent intensity level.
Warning: No performance data are available to substantiate this recommendation. A compromise must be made between the visibility of the scan line structure which may be undesirable and image modulation and resolution perpendicular to the scan lines, which should be preserved to the extent possible.
RECOMMENDATION:
The difference in *flat field luminance* between the center and edges of the CRT display (*shading*) should not be greater than 20 percent.
Warning: No performance data exist to substantiate this recommendation. CRT's with small *deflection angles* should exhibit less shading than CRT's with large deflection angles. If the criteria cannot be met without extensive development engineering expense, then the value of such expenditures should be determined through performance testing on simulated systems before engineering is begun.
Use of high-order interlace in tasks where image motion is minimum, *high-order line-dot interlace* display systems using long-persistence phosphors should be considered.
Caution: The data which show that image quality can be maintained, or even improved, for static scenes by use of high-order line-dot interlace techniques were developed from judgments of image acceptability, not interpretation performance. Before such a system is adopted for any major installation, prototype equipment directed at the intended application must be built and evaluated (Figures 4.2-8 through 4.2-13).
RECOMMENDATION:
For static images used in tasks not requiring the maximum target area coverage, a square image format on the CRT display should be used.
Caution: No data exist dealing specifically with this problem for other than real-time reconnaissance, where displays having their long dimension in the direction of the flightpath yielded better interpreter performance for some conditions than the square format. The recommendation is based on the improvements in horizontal resolution that can be achieved by the reduced electron beam deflection angles and the distance through which a beam must travel to cover a square format as opposed to one with a 4:3 *aspect ratio*.
RECOMMENDATION:
CRT size should be selected so that the scan line structure will be marginally visible for a flat field of maximum intensity at the intended viewing distance, and should subtend a visual angle of at least 20 degrees.
Warning: No performance data exist to substantiate this recommendation. One study on display size showed that the visual angle needed to identify a target increased with display size, suggesting that the number of *scan lines* per target was the determining factor (Figure 4.3-55). If such is the case, the smallest display compatible with maintaining a 20-degree field of view (Figure 4.3-54) should be provided.
RECOMMENDATION:
Given equal quality in other characteristics, cathode ray tubes should be chosen that can cover the required image format with the smallest electron beam deflection angles in order to reduce resolution and contrast loss at the edges of the image.
Caution: No performance data are available on this subject. The loss of performance, if any, as a function of off-axis resolution and contrast loss has not been studied in CRT's.
RECOMMENDATION:
If color imagery is to be used and the imaging system is operating near the acceptable limits of resolution, the use of a four-tube color camera is desirable (Figure 4.1-11).

Caution: Four-tube color cameras generally require more illumination than three-tube cameras. The illumination range of the material to be used must be known and related to camera performance specifications.

RECOMMENDATION:

Provide separate black and white and color CRT's to interpreters who must work with both, and require the maximum resolution which can be provided from the black and white image (Figure 4.4-17).

Caution: Color CRT's contain *aperture masks* and discontinuous phosphors, which have the effect of reducing resolution; no data is available to quantify the loss in terms of interpreter performance.

RECOMMENDATION:

The face of a CRT display should be shielded to prevent ambient illumination from reaching it (Figures 4.4-26 and 4.4-27).

There are no data relating a loss of interpreter performance to contrast losses in the CRT image caused by either the diffuse reflection of ambient light from the surface of the *phosphor* or specular reflections from the glass elements of the *faceplate*. However, calculations clearly show the contrast losses involved, and they should be prevented by considering the lighting environment in which the tube will operate so that appropriate shields can be provided.

RECOMMENDATION:

A spot shape providing either linear or quadratic interpolation of transmittance values in two dimension should be selected for optical line-scan image generators (Figures 4.3-56 and 4.3-57).

Caution: The data from the studies in the referenced figures are from judgments of the intelligenc content of the images tested and not on interpretation performance.

SECTION 4.0 REFERENCES

1. A large volume of literature exists dealing with the effects of the discontinuous nature of the scanning process on the imagery produced by electro-optical systems. Several are referenced below. Articles dealing with topics other than aliasing, as strictly defined, have been included.

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Shade, O.H., Sr. Image gradation, graininess and sharpness in television and motion picture systems. Part III: The grain structure of television images. *J. Soc. Motion Picture Television Engr.* (SMPTE). Vol. 61, 1963, pp. 97-164.

Shade, O. H., Sr. Image reproduction by a line raster process. In Berberman, L. M. (Ed.), *Perception of Displayed Information*. Plenum, New York, 1973, pp. 233-278.

Legault, R. The aliasing problems in two-dimensional sampled imagery. In Berberman, L. M. (Ed.), *Perception of Displayed Information*. Plenum, New York, 1973, pp. 279-312.

A basic reference to the mathematical basis of aliasing can be found in:

Kohlenberg, Exact interpolation of band-limited functions. *J. Apl. Phys.* Vol. 24, 1959, pp. 1432-1436.

2. Personal communication. David Gilblom, Sierra Scientific Corporation, Mountain View, California.

4.1 BASIC ELECTRO-OPTICAL SYSTEM OPERATING PRINCIPLES

SECTION 4.1 BASIC ELECTRO-OPTICAL SYSTEM OPERATING PRINCIPLES

This section is included for those readers who lack familiarity with the operating principles of electro-optical imaging systems.

It is designed to assist the reader in understanding the material that appears later in this section by providing him with additional knowledge of the operating characteristics of these systems and the terminology used to describe them.

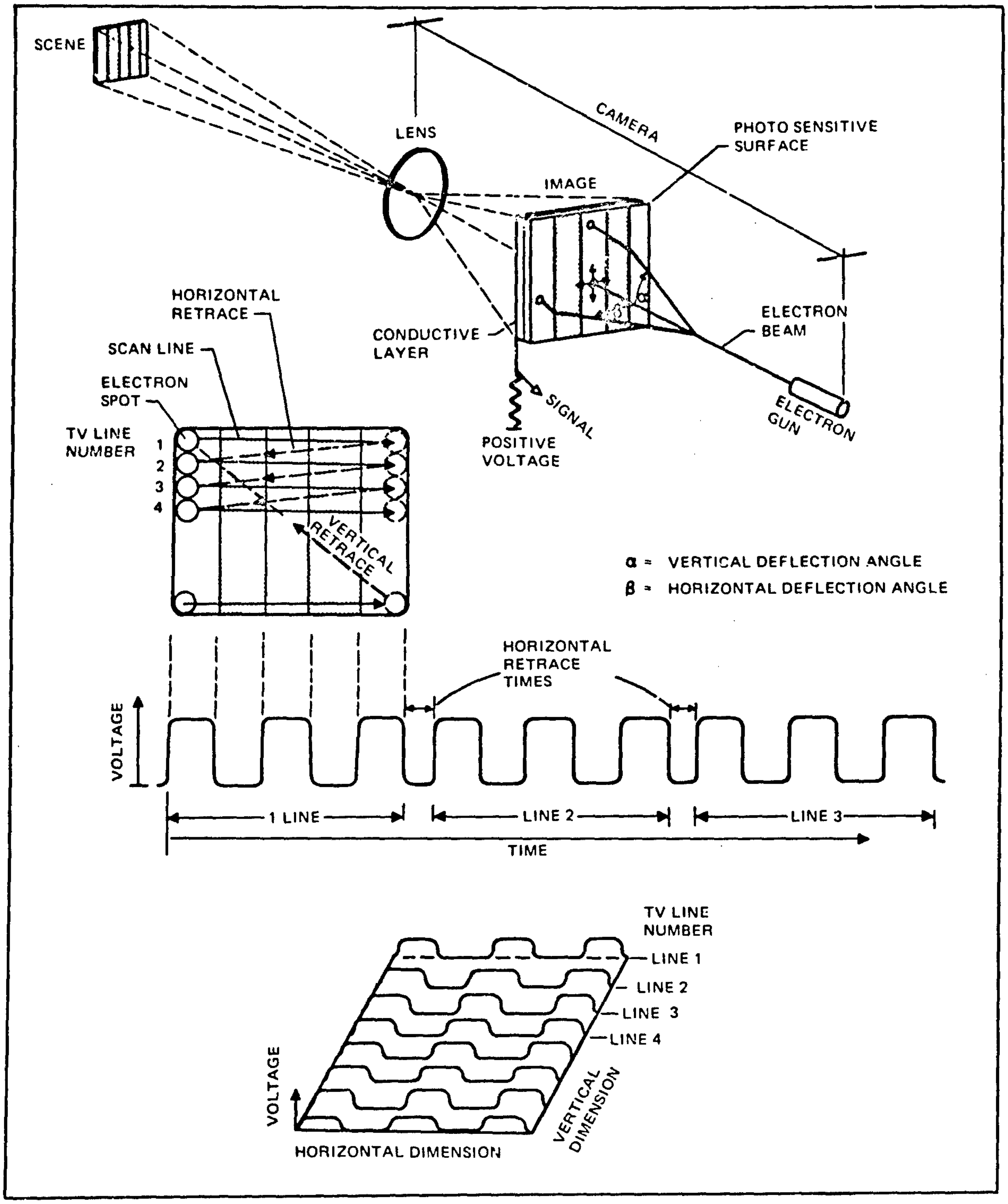


Figure 4.1-1. Line-Scan Image Signal Generation

Figure 4.1-1. Line-Scan Image Signal Generation. Television systems using cameras in which the image is scanned by an electron beam are representative of *line raster*, or line-scan systems; they are also referred to as *one-dimensional sampling systems* (Ref. 1). A simplified sketch of a camera for such a system is shown here to illustrate the way in which a scene is converted into an electric signal.

The lens of the camera focuses the scene on a light-sensitive (photosensitive) surface whose electrical characteristics change in proportion to the amount of light it receives. A *photoconductive* (Ref. 2) sensor has been chosen for the illustration. When a scene is focused on a very thin layer of photoconductive material, the electrical *conductance* through the material changes in proportion to the amount of light striking it. In dark areas, it remains a very poor conductor; in light areas, its conductance increases as the intensity of the light striking it increases. Thus the pattern of illumination in the scene is changed to a similar pattern of conductance on the sensor. This spatial pattern of conductance is changed into a temporal (time-varying) pattern of voltages by systematically scanning it with a small *spot* generated by an electron beam. The beam, generated by an *electron gun*, is made to follow a predetermined scan pattern, called a *raster*, by having its path from the gun to the sensor deflected electrically or magnetically through the action of a *sweep circuit*. The face of the photoconductive film opposite that scanned by the spot is in contact with a transparent conducting surface carrying a small positive voltage.

When the spot passes over a dark area on the photosensor, the electrons are prevented from flowing to the positively charged surface because of the low conductivity of the sensor in that area. When the spot passes over a light area, the electrons can flow in proportion to the amount of light striking the sensor. This varying electron flow (electrical current) is used to create voltage differences by the camera's electronic circuits. These voltages constitute signals from the sensor.

In usual practice, the signal is generated with the spot scanning in horizontal lines across the image, creating a raster of lines from top to bottom of the image. It is also usual practice to have the signal generated in only one direction of the scan. The return of the beam at the end of one scan line to the start of the next is called the *horizontal retrace*. When the bottom line has been scanned, the beam is returned to the top of the image again by means of a *vertical retrace*. The nature of the signal output is illustrated at the bottom of the figure, with the higher signal level associated with the light area of the scan and the lower level with the dark area. In order to prevent the retrace lines from appearing when the signal is displayed on a *cathode ray tube* (CRT) or printed on film, the electron beam is cut off during retrace. This process is called *blanking*.

The sketch at the bottom of the figure illustrates the voltage as it is generated line by line for the image shown at the top of the illustration.

The device illustrated here belongs to a family of electro-optical imaging devices called *vidicons*. Descriptions of other devices such as the *image orthicon* can be found in Reference 2.

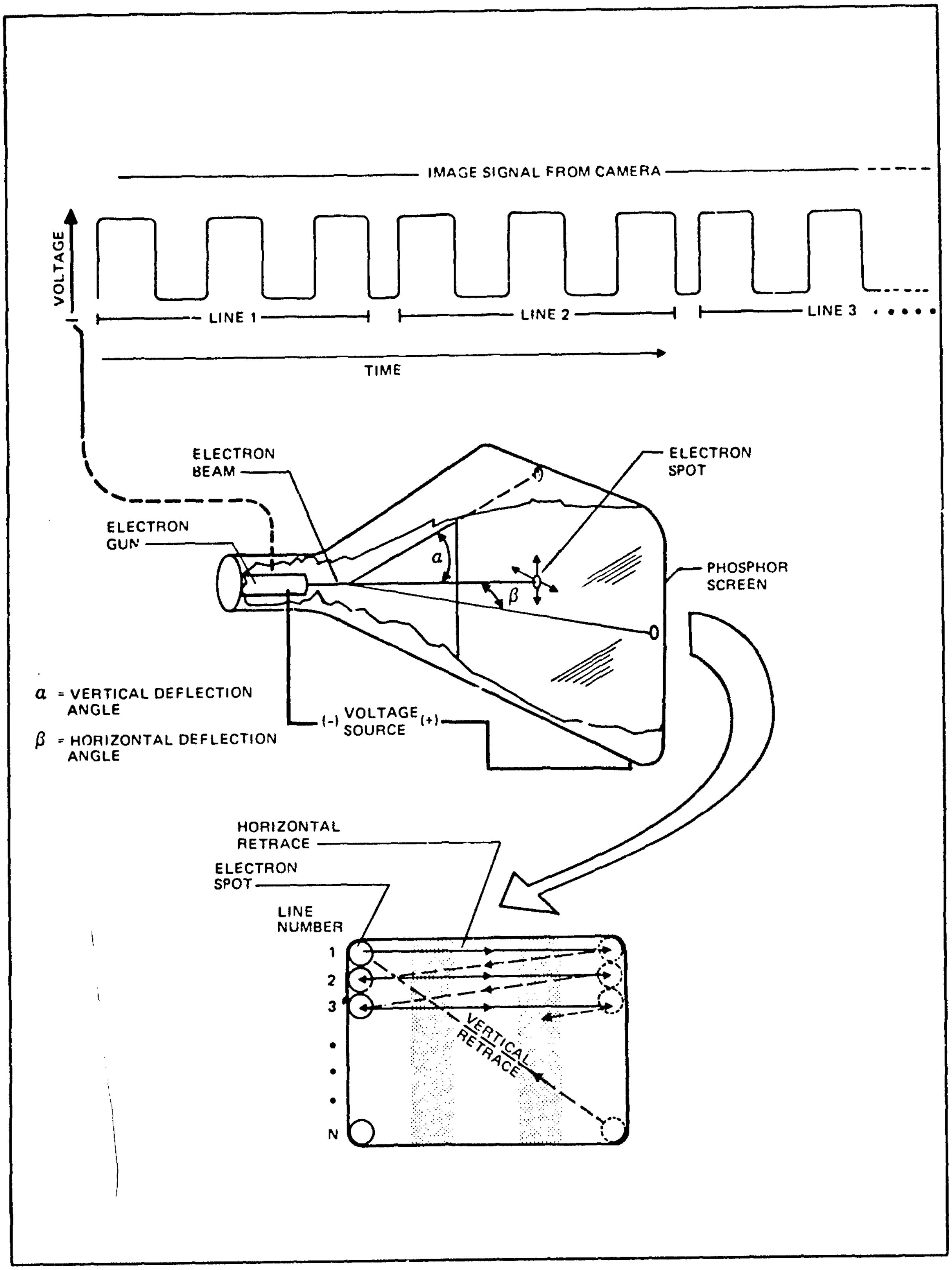


Figure 4.1-2. Line Scan Image Reconstruction by Cathode Ray Tube

Figure 4.1-2. Image Reconstruction by Cathode Ray Tube. Signals such as those generated by a TV camera can be displayed as imagery on a cathode ray tube (CRT). CRT's operate on the principle that certain chemical elements and compounds, called *phosphors*, emit light when struck by electrons. In the CRT, as in the TV camera, a beam of electrons is generated by an electron gun. The amount of light emitted is proportional to the number and the energy of the electrons striking the phosphor (Ref. 3). The number of electrons determines the strength of the current that flows, and the energy of the beam is determined by the anode potential, which is the voltage applied between the electron gun and the screen. If a constant-energy beam of electrons is scanned across a phosphor screen, a pattern of light can be formed by varying the beam current.

A simplified sketch of a CRT is given here to help illustrate the image-forming process. The voltage signal from the camera is used to control the current in a beam generated by the electron gun. The energy of the beam is established by the *anode potential*. The beam is focused to form a spot on the phosphor screen, and its horizontal and vertical deflections are synchronized with those of the camera, thus forming a raster on the face of the tube that is identical with the one formed on the photosensitive element in the camera. The current variations in the moving beam are converted into a pattern of luminous intensity by the phosphor, creating an image of the scene.

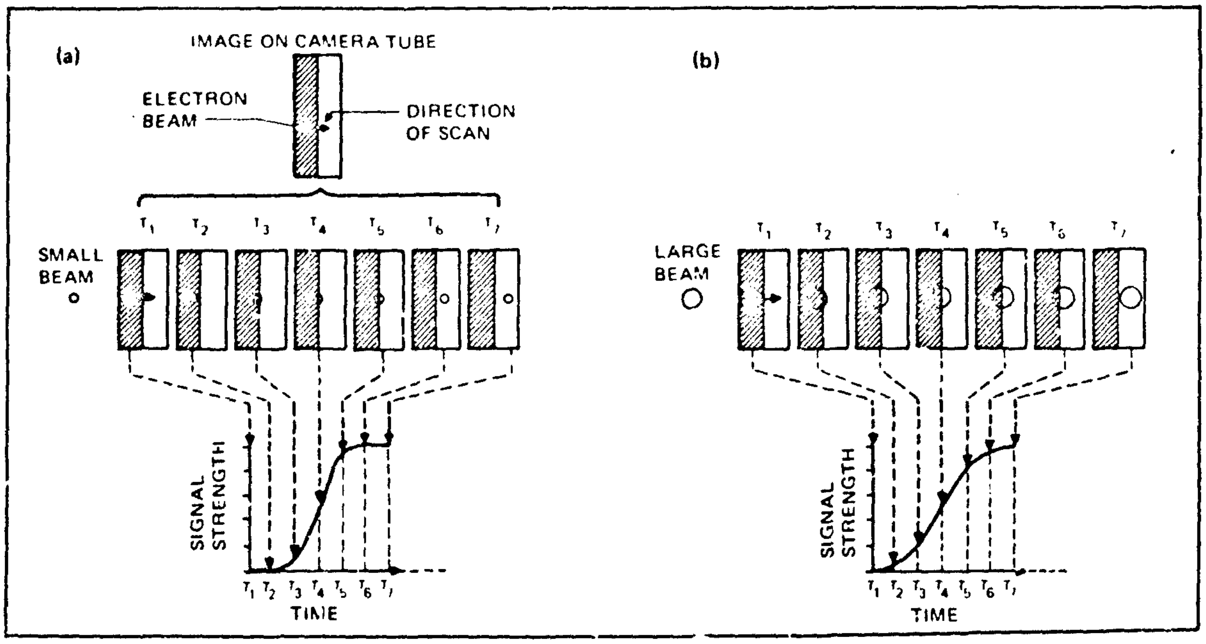


Figure 4.1-3. Influence of the Finite Size of the Scanning Beam. In the system described in Figure 4.1-1, the continuous scan in the horizontal direction produces a continuously varying signal, representing the changes in the scene luminance as imaged on the photoconductive film. The same condition does not apply to differences in the vertical direction because the spot is moved vertically in discrete steps. Because the vertical differences are discrete, the image is said to have been sampled in the vertical dimension. Thus, a horizontal scan samples the image in the vertical dimension. To illustrate this difference, the signals that result from scanning horizontal and vertical stripes are shown here.

In considering the horizontal and vertical differences, it is instructive to consider the effect of the size of the spot covered on the image by the scanning electron beam. If the spot were infinitely small (and electronic circuits infinitely responsive), the changes in signal strength as the beam passed over the image would follow exactly the changes in the conductance in the sensor. Neither condition can be met in a practical system. Parts (a) and (b) illustrate the general effect of the size of the spot on the signal generated during a horizontal scan. In the case shown, in passing from a dark to a light area an increasing portion of each spot falls in the light, or conducting, part of the image, which allows an increasing flow of electrons; this, in turn, generates signals of increasing strength. This process continues for each spot until it is entirely within the light area, at which point the signal level becomes constant. In each case the signal is continuous although it is "spread" somewhat in time, the spread being greater for the large spot.

In the case of the signal for the horizontal scanning of horizontal stripes, the result is altogether different. Part (c) at the top of the following page illustrates the case where the spot is *in phase* with the image. The signal strength is constant for the entire length of any one scan line but is discontinuous in the vertical direction (from line to line). The pattern of the signal strength in the vertical direction is, however, the same as the pattern of light and dark on the image.

Part (d) illustrates the case where the spot is *out of phase* with the image. The scanning spot is equally divided between the light and dark areas of the image, and the signal levels for all of the scan lines are identical. The pattern of the image has been lost completely. Because the phase relationships between the scanning spot and the objects in a natural scene cannot be controlled, some loss of resolution results. A commonly used figure is 30 percent. Thus the number of lines for effectively calculating resolution is 70 percent of the total. This value is known as the *Kell factor* (Ref. 4).

In part (e), the spot size is larger than the individual light and dark stripes in the image; as a result, part of the spot is in the light area and part in the dark area for each scan line, with the proportion changing from line to line. This changing proportion causes the signal level for each scan line to be different from the others, and the pattern of these levels does not accurately represent the pattern of illumination in the image.

The term *sampling* has been applied to the process that occurs in generating the signal of the horizontal stripes, and line raster systems are described as *one-dimensional sampling systems* because the signal is a continuous representation of the scene in the horizontal dimension and a sampled representation in the vertical dimension (Ref. 5).

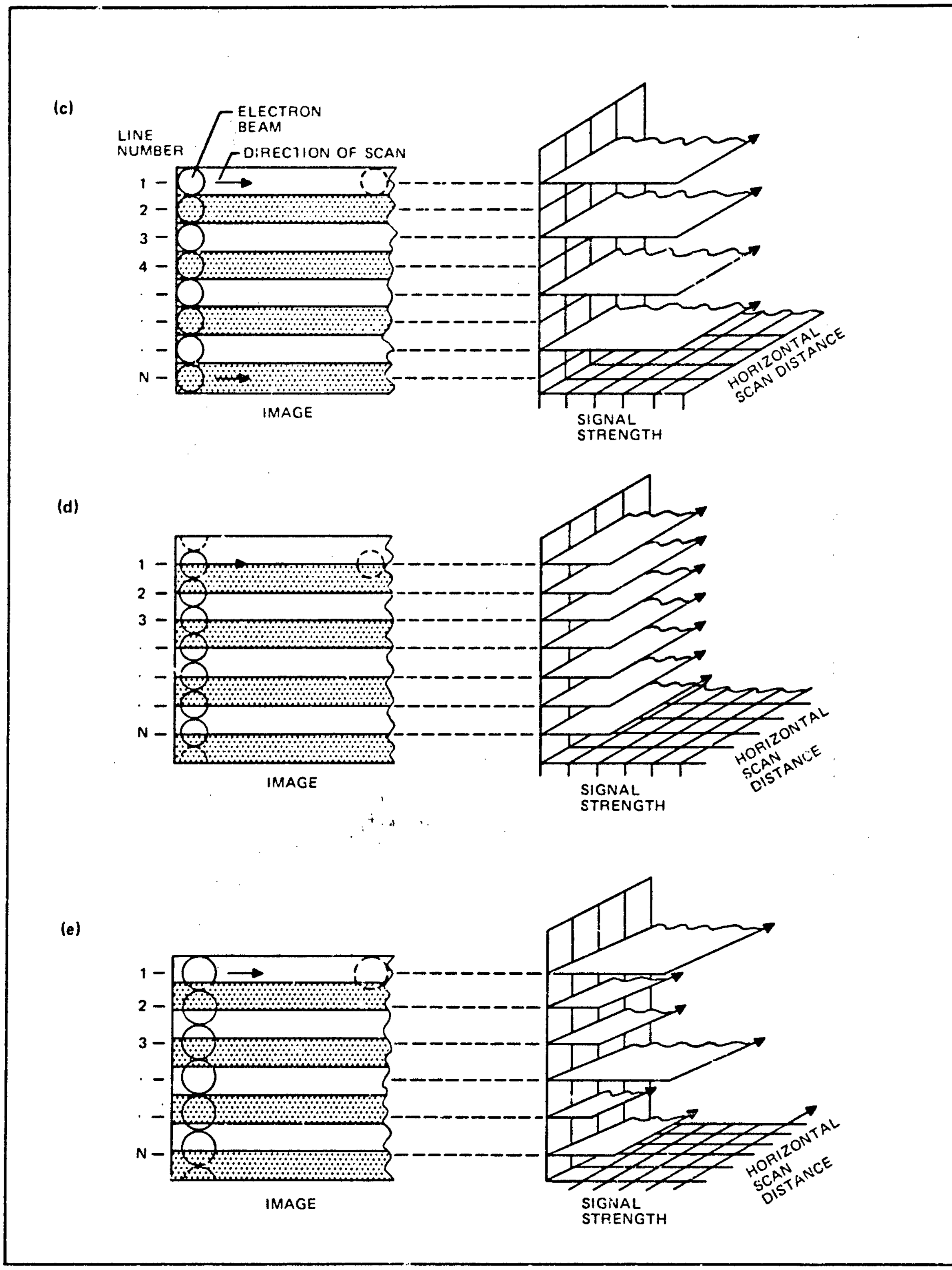


Figure 4.1-3. Influence of the Finite Size of the Scanning Beam (continued)

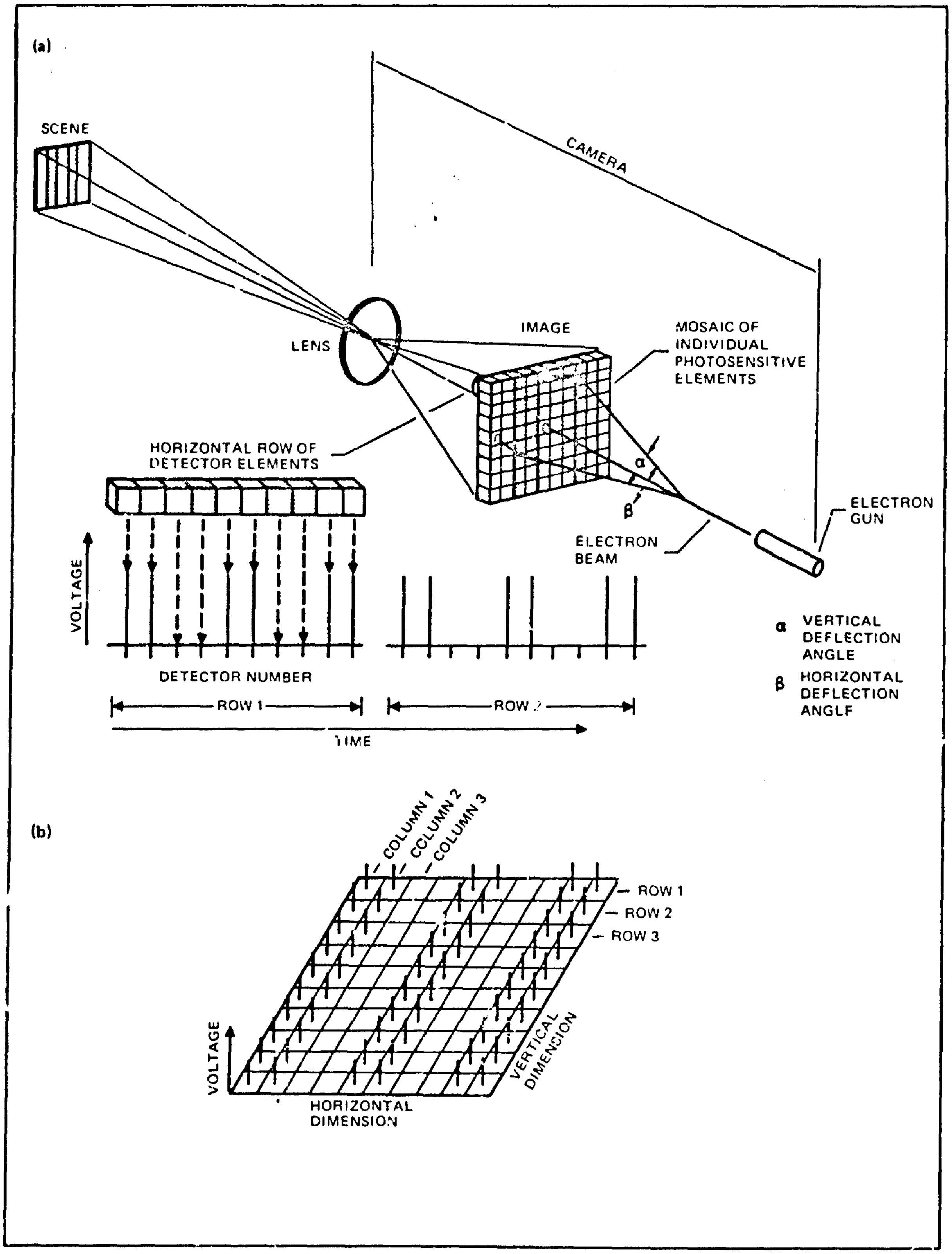


Figure 4.1-4. Two-Dimensional Sampling

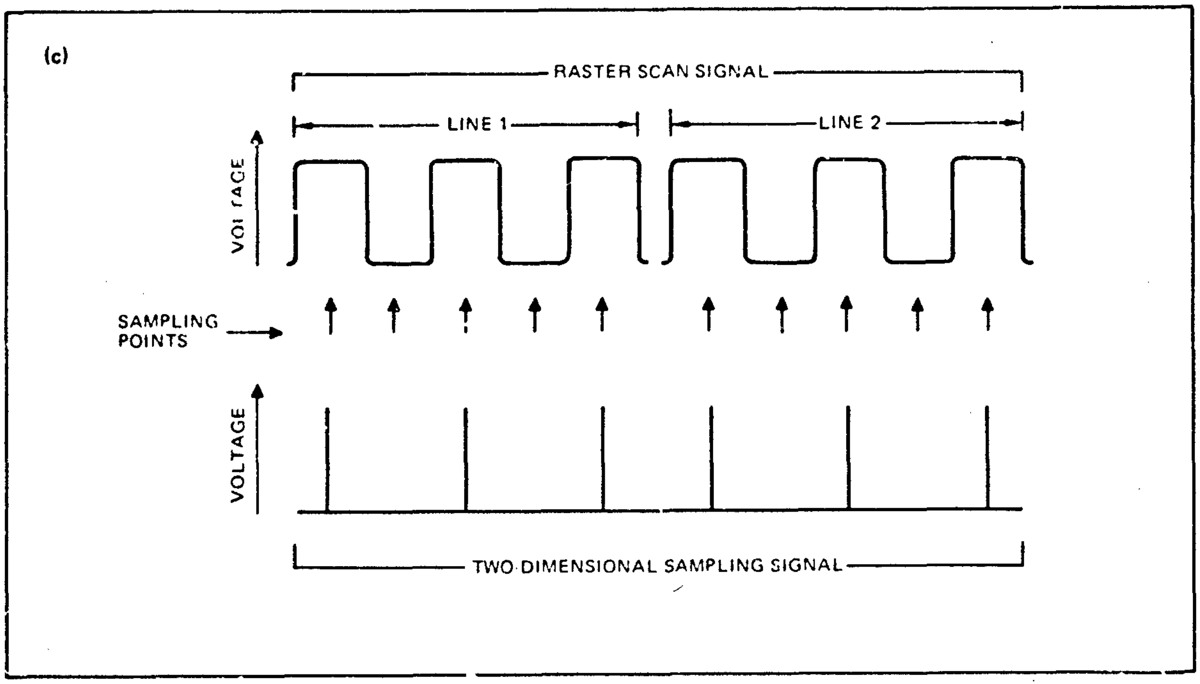


Figure 4.1-4. Two-Dimensional Sampling (continued)

Figure 4.1-4. Two-Dimensional Sampling. Digital transmission, processing, storage, and display systems require that images be broken down into some number of discrete subsections. The usual practice is to divide the image into a matrix of subsections equally spaced in both the horizontal and vertical dimensions. These subsections are commonly called picture elements or *pixels*. The pixel size determines the smallest area in the scene that can produce an independent signal, and therefore the smallest area that can be resolved. Each element is given a luminance value, which is an area weighted average of the values in the portion of the image it covers. This means that the image luminance is sampled in both the horizontal and vertical directions.

Some electro-optical sensors operate as sampling systems in both the horizontal and vertical dimensions. These are known as *two-dimensional sampling* or *point raster* systems (Ref. 6). Part (a) of this figure illustrates a sensor made of a two-dimensional array of individual photosensitive elements, each element providing a discrete signal proportional to the light falling on it. A signal may be produced by a scanning electron beam crossing the element or, in solid state systems, by direct readout through permanent electrical connections that are switched on and off in the proper sequence. This latter process is known as *self scanning*. The illustration shows a signal pattern for a single horizontal line of such elements. When the elements are scanned, or switched on, those receiving light produce a signal proportional to the amount of the light received, and those not receiving light produce no signal.

The lower part of the figure (b) portrays the signal developed for each element, or pixel, of the sensor in the top of the illustration.

The figure at the top of this page (c) illustrates how a continuous signal, such as that produced by the raster scan system of Figure 4.1-1, can be converted into a series of discrete signals by sampling the signal level at fixed intervals. Since the raster scan system already samples in the vertical direction, the result of sampling in the horizontal direction will be to produce a point raster or two-dimensionally sampled signal suitable for use in digital systems.

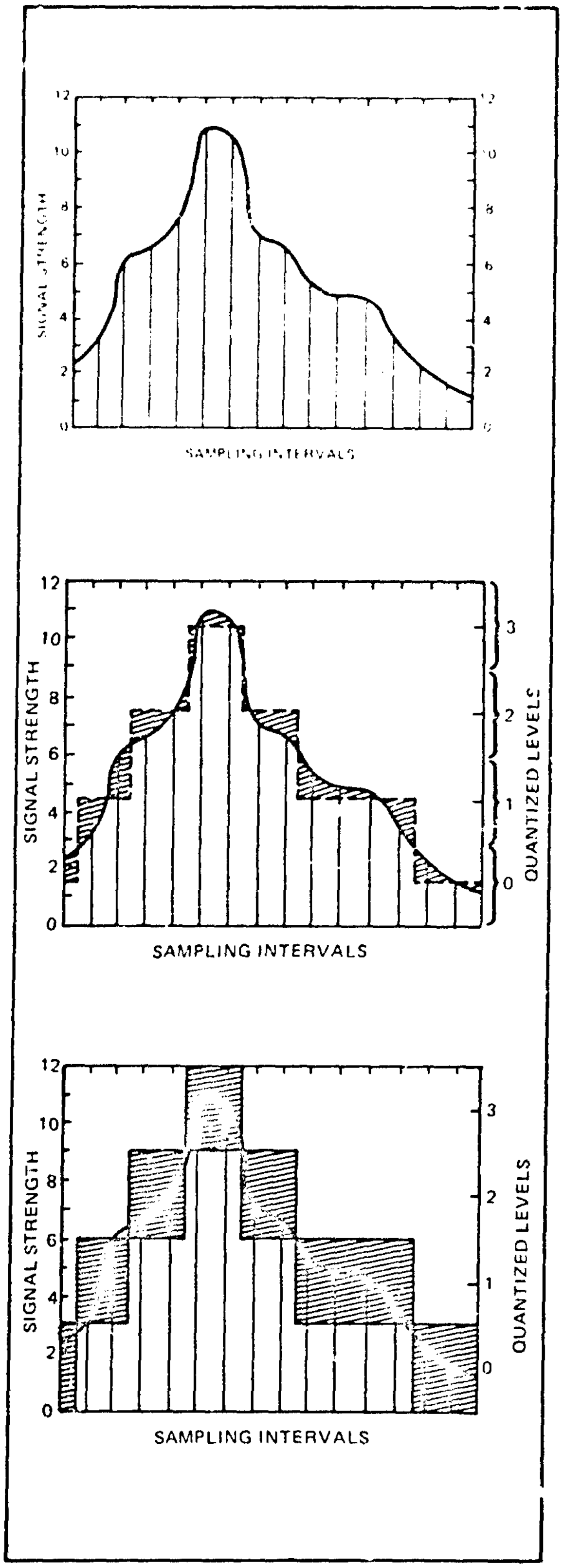


Figure 4.1-5. Quantization

Figure 4.1-5. Quantization. If the signal strength from the sensor is continuously variable and can assume any value within its operating range, it is called an *analog* signal. For use in digital systems, the range of signal strength must be broken into discrete, single valued steps. This process is known as quantization. The number of steps is commonly some power of 2 (such as 2^8, that is, 256) so as to be compatible with *binary* data handling systems. The 2^8 level of quantizing is referred to as 8 *bit* quantizing. To simplify the presentation here, a four step scale (2^2, or 2-bit) with values of 0, 1, 2, and 3 has been used.

The solid line in the top graph is a si[illegible]ed representation of the signal from a one dimensional sampling system. The bars represent the signal for the same line from a two dimensional system. The strength of both has the property of being continuously variable, and they therefore represent an analog system.

The scale to the right of the middle graph indicates how the signal strength values will be partitioned into the four quantizing levels. Zero through 2.99^+ are assigned a quantized value of 0; 3 through 5.99^+ a value of 1; 6 through 8.99^+ a value of 2; and 9 through 12 a value of 3. The dashed line in the center graph shows the result of applying this conversion to the original signal. The shaded area indicates the difference between the quantized and original signal strengths. This difference is called the *quantizing error* and has a maximum value of 1/2 a quantizing step. As the number of steps is increased, producing smaller and smaller intervals, the amount of the error becomes less and less, being reduced by half for each bit added to the quantizing levels (Ref. 7).

The shaded area in the bottom graph shows the envelope within which a signal from an analog system could fall to produce the quantized signal shown in the middle graph. The range from the top or bottom of a shaded area to its middle represents the range of possible errors in the quantized signal. There are schemes for minimizing these errors whose full description is outside the scope of this book. Reference 8 cites examples of work which has been done on this subject, and it is discussed further in Figure 4.4-13.

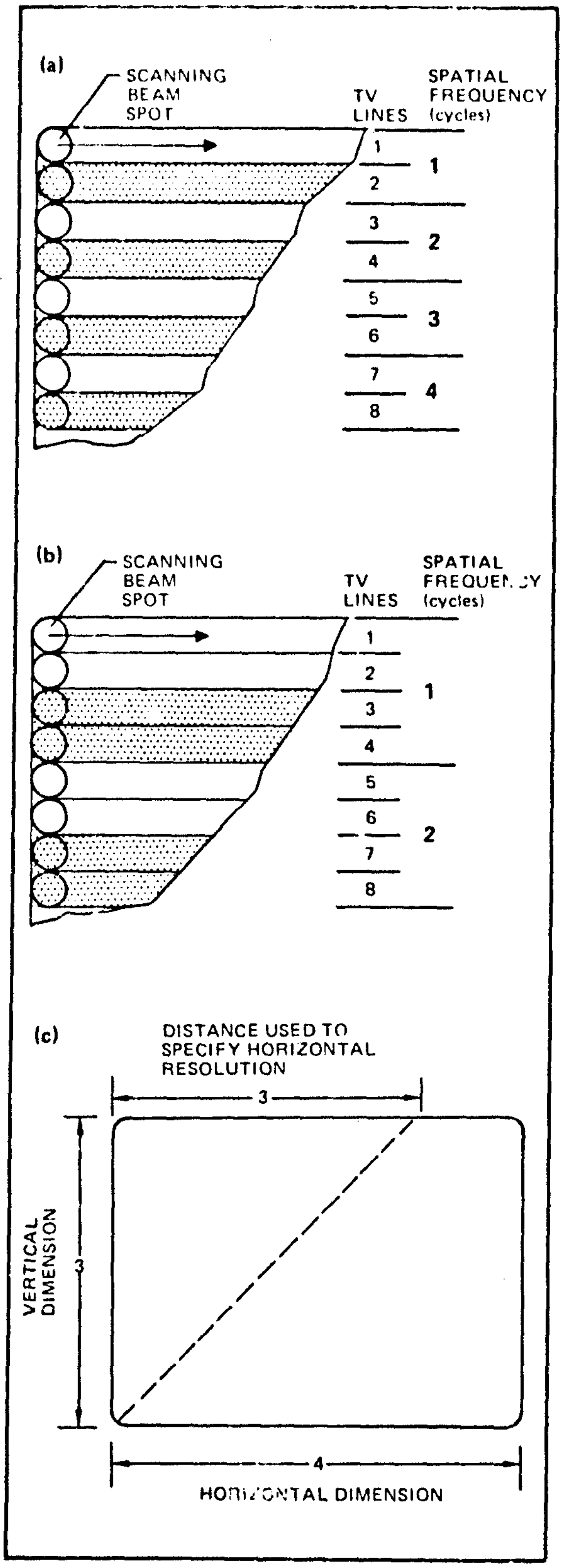


Figure 4.1-6. Spatial Frequency and TV Lines

Figure 4.1-6. Spatial Frequency and TV Lines. For a periodic target; i.e., one which is divided into regularly spaced light and dark areas, an adjacent pair of bars (one light and one dark) taken together constitute a cycle. The number of such cycles over a specified distance determines the target's spatial frequency. Spatial frequency is usually specified in cycles per millimeter (c/mm) or cycles per inch (c/in); an equivalent nomenclature that is frequently used is line pairs per millimeter (l/mm) or line pairs per inch (l/in). It is common, however, even in technical articles, to shorten this latter terminology to lines per millimeter or lines per inch.

In television terminology, a line refers either to an actual scan line, as suggested by the top two illustrations in this figure, or to the time period allocated for a scan line. By this last definition, commercial broadcast TV in the U.S. is a 525-line system. This means that the time taken to complete one scan of the image is equal to 525 individual line-scan periods. However, fewer than 525 actual scans are possible because approximately 35 of the periods are used for the vertical retrace. The actual number used for vertical retrace varies from 35 to 42, depending upon the design of the transmitter. Thus the number of actual, or *active TV lines*, is between 483 and 490, with 490 being the most common figure. Applying a Kell factor of 0.7 to this figure gives the equivalent of 343 active lines for use in considering resolution capabilities. In this book, the term "TV lines" will be used to refer to the number of scan periods per complete image scan and the phrase "active TV lines" will be used to refer to the actual number of scans across the vertical dimension of the tube.

Since an active TV line can represent, at most, one-half of a cycle of a periodic target (a light or a dark bar), at least two are required to represent one cycle of a periodic target. It is important to keep this ratio of 2 active TV lines per cycle of spatial frequency in mind when dealing with line-scan systems.

With less than two active lines per cycle, the effect shown in part (e) of Figure 4.1-3 results. The spatial frequency displayed on the CRT may vary as shown in part (b) of this figure, but for a given TV system the number of active TV lines will be constant.

Part (c) of this figure illustrates the relationship between the vertical and horizontal dimensions used in specifying horizontal resolution for television systems. Standard practice is to speak of horizontal resolution in active TV lines as though the raster were rotated 90 degrees and the resolution expressed as equivalent TV lines measured over a distance equal to the vertical dimension of the tube (Ref. 9).

The relationship between the horizontal and vertical dimensions of the picture area is called the *aspect ratio*; for CRT's used to display pictorial information, it is commonly 4:3, as shown in the sketch. For such a display a resolution of 343 active TV lines would mean that 343/2, or 171 cycles, could be displayed a distance equal to three-fourths of the horizontal dimension of the picture area, or approximately 457 lines (229 cycles) across the entire horizontal dimension.

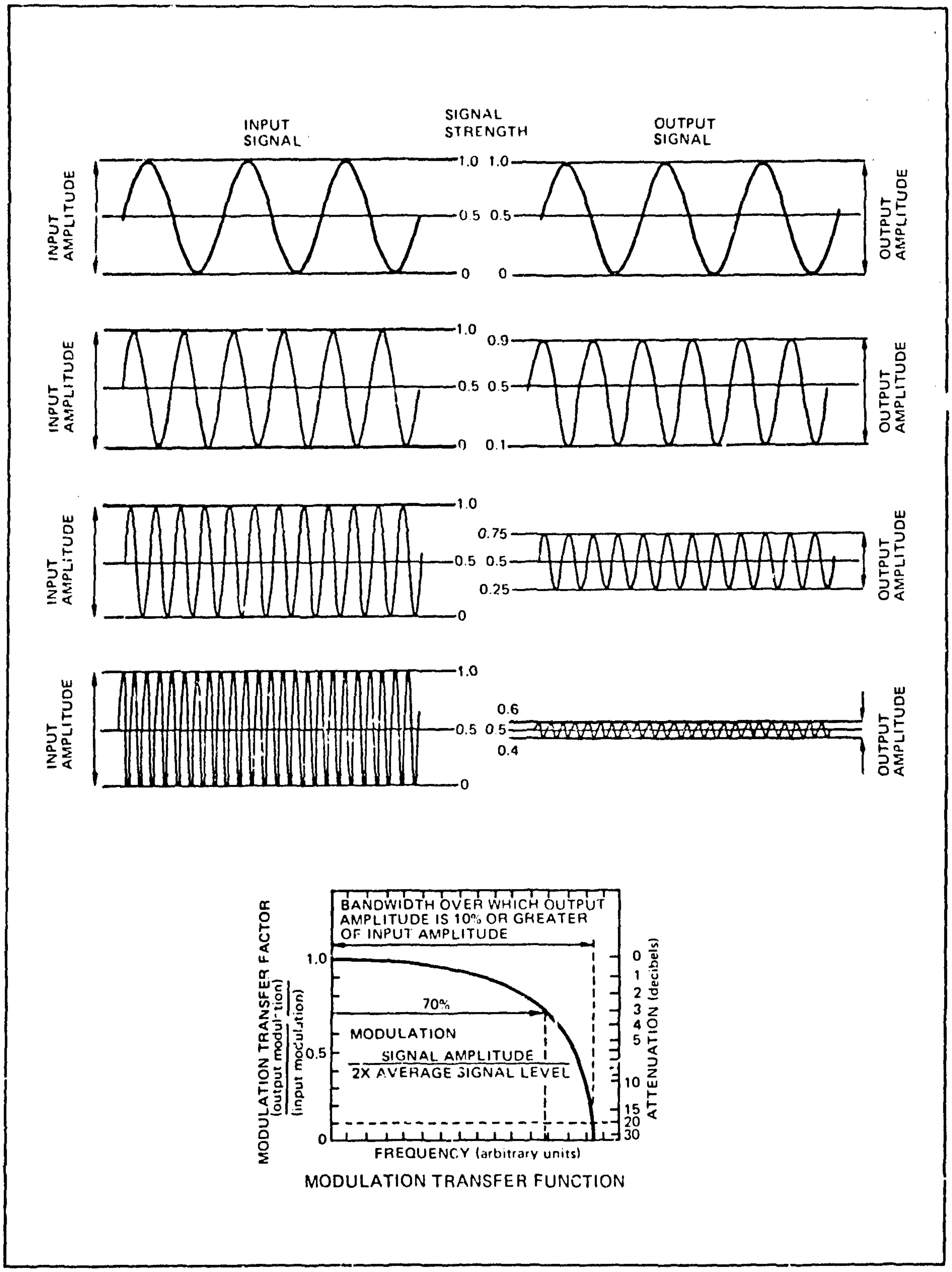


Figure 4.1-7. Modulation Response and Bandwidth

Figure 4.1-7. Modulation Response and Bandwidth. Electronic circuits do not respond equally well to all frequencies. In general the amplitudes of higher frequencies are attenuated as they are processed by the circuit. The four pairs of curves at the top of the figure illustrate this phenomenon. The left-hand curve of each pair represents a signal that is being fed into the circuit, and the right-hand curve represents the output of the circuit. For the top pair, the input and output *modulations* are equal, and for this frequency the *modulation transfer factor* is said to be one, and is defined as:

$$\text{Modulation Transfer Factor} = \frac{\text{output modulation}}{\text{input modulation}} \qquad \text{(Ref. 10)}$$

If the MTF is measured, or calculated, for a number of points, a curve describing the system's frequency response characteristics can be drawn, as illustrated in the bottom graph. Such a curve is called the modulation transfer function (MTF) of the system.

The attenuation is also frequently specified as decibels below some reference level. Attenuation is specified in decibels (dB) (see Section 6.6.2) using the definition:

$$\text{dB} = -20 \log \frac{\text{modulation of output signal}}{\text{modulation of input signal}}$$

$$= -20 \log \text{(modulation transfer factor)}$$

This gives a value, for instance, of 20 dB for a modulation transfer factor of 0.1.

For the second, third, and fourth curves at the top of the figure, modulation transfer factor is 0.80, 0.50, and 0.2, and they are attenuated by 1.9,6, and 14db respectively. At some point the attenuation of the output signal becomes so great that even for very strong input signals the output cannot be effectively used. The point at which this happens depends upon the circuit design and the intended use of the output. When a minimum acceptable value is chosen, it sets the *bandwidth* of the system; i.e., the band of frequencies over which its performance is within acceptable levels (Ref. 11). In some systems, circuits are included which ensure that signals above a specified frequency will be strongly attenuated, thus establishing the bandwidth. For instance, for standard U.S. broadcast television, the video, or picture-carrying portion of the signal, is limited to slightly less than 5 MHz.

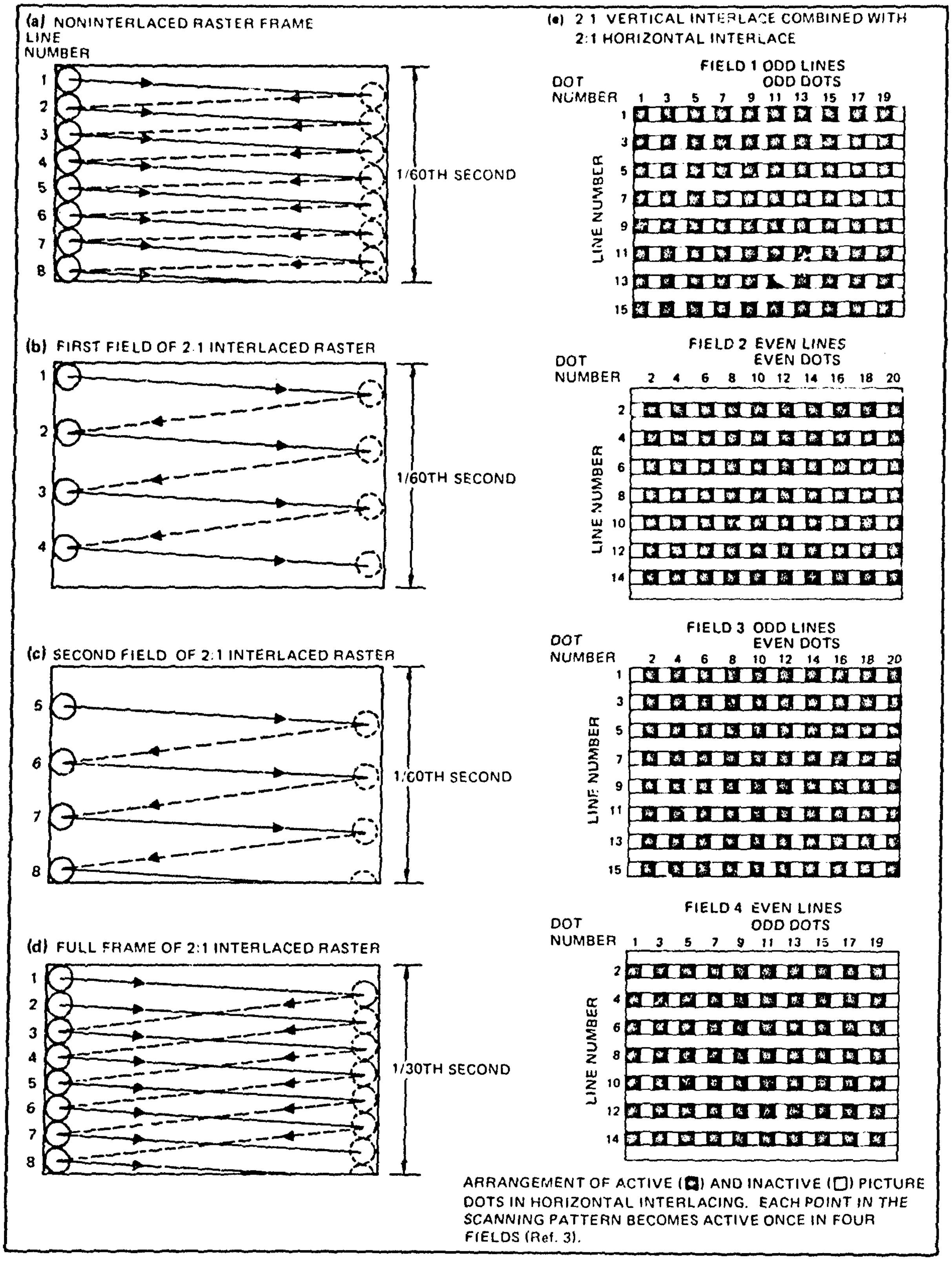


Figure 4.1-8. Interlace Techniques

Figure 4.1-8. Interlace Techniques. In order to conserve bandwidth while meeting the requirement to eliminate visual flicker (see Section 4.2), the National Television System Committee (NTSC) adopted a 60-Hz, 2:1 interlace system (Ref. 12).

The top illustration (a) represents the noninterlaced condition. The raster forms the entire frame in a single series of horizontal scans. The middle two illustrations (b) and (c) represent the way the image is divided into fields by the interlace process. The lower drawing (d) shows how the fields combine to form a frame. Each field is completed in one-sixtieth of a second, and both fields (the full frame) are completed in twice that time, or one-thirtieth of a second.

The importance of such an interlacing technique is the effect it has on bandwidth requirements; the following calculations illustrate this point. Standard NTSC broadcast television has the time for each frame divided into 525 equal periods. Even though all 525 are not used to generate active TV lines, each active line that is generated must be completed within one of the 525 periods. Without interlace, the total number of time periods per second will be the number of periods per frame times the number of frames per second, or 525 x 60 = 31,500. Each line then must be completed in $\frac{1}{31,500}$ sec = 31.7 μsec. Of this time, approximately 17 percent is used for horizontal retrace, which leaves 83 percent of the 31.7 microseconds, or 26.3 microseconds for the scan itself. A resolution of 177 cycles across three-fourths of the length of the line (approximately the resolution of the NTSC system) requires that 177 x 4/3 or 236 cycles be resolved per line. Since each line is completed in 26.3 microseconds, the time per cycle is 26.3/236 or 0.11 microsecond (Ref. 2).

To find the frequency required to transmit a cycle every 0.11 microsecond, this value is divided into one or,

$$\text{Frequency} = \frac{1}{0.11\ \mu\text{sec}}$$

In scientific notation this is

$$\text{Frequency} = \frac{1}{1.1 \times 10^{-7}\ \text{sec}} \simeq 9 \times 10^{6}\ \text{Hz} \quad \text{or,}$$

approximately 9 MHz.

If a 2:1 interlace is used, the time per frame drops to one-thirtieth of a second, and the calculations become

For the number of periods per second,

$$525 \times 30 = 15{,}750,$$

for the time per period,

$$1/15{,}750 = 63.5\ \mu\text{sec},$$

for the time per scan,

$$63.5 \times .83 = 52.7\ \mu\text{sec},$$

for each cycle displayed,

$$52.7/236 - 0.22\ \mu\text{sec, and}$$

for the bandwidth required,

$$\frac{1}{0.22\ \mu\text{sec}} \simeq 4.5\ \text{MHz}$$

In experiments where subjective quality ratings were giver to low-resolution (225-TV-line) systems, it was found tha for pictures judged to be of equal quality, only 6 to 37 percent actual savings in bandwidth were realized by 2:1 interlace (Figure 4.3-19 and Ref. 13).

For special applications, systems that have both vertical and horizontal interlace have been devised (Part (e) of this figure). They constitute two-dimensional sampling systems. In these systems, a field consists of a combination of one vertical and one horizontal sequence, and four such frames are required to complete a picture (Ref. 14). *High-order* combined vertical and horizontal interlace systems have been explored to improve picture quality at the cost of frame rate for a given bandwidth (Ref. 15, and Figure 4.2-8).

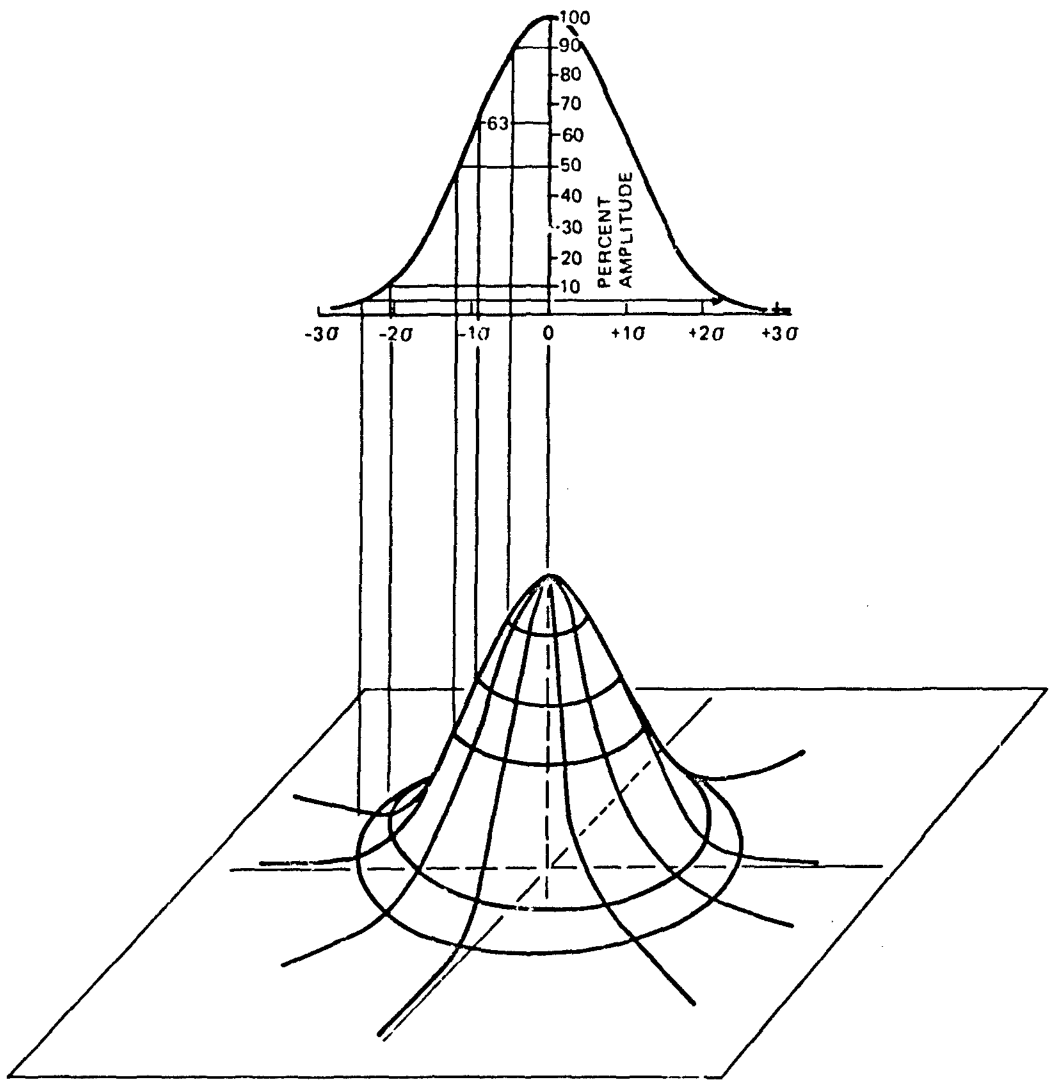


Figure 4.1-9. Spot Size

VALUES FOR VARIOUS AMPLITUDE PROPORTIONS		AMPLITUDE PROPORTIONS FOR VARIOUS VALUES OF X/σ	
PROPORTION OF MAXIMUM AMPLITUDE	$\frac{x}{\sigma}$	$\frac{x}{\sigma}$	PROPORTION OF MAXIMUM AMPLITUDE
1.00	0.0000	0.00	1.0000
0.99	0.1418	0.25	0.9692
0.95	0.3203	0.50	0.8825
0.90	0.4590	0.75	0.7548
0.80	0.6680	1.00	0.6065
0.70	0.8446	1.25	0.4578
0.60	1.012	1.50	0.3246
0.50	1.177	1.75	0.2162
0.40	1.354	2.00	0.1352
0.30	1.552	2.25	0.0796
0.20	1.794	2.50	0.0439
0.10	2.146	2.75	0.0227
0.05	2.448	3.00	0.0111
0.01	3.035	3.25	0.0051
0.005	3.255	3.50	0.0022
0.001	3.717	3.75	0.0009

Figure 4.1-9. Spot Size. The size of the spot created by an electron beam is defined in terms of a proportion of the maximum current level of the beam. The current is strongest in the center and decreases away from the center following a *Gaussian* curve, as is shown at the top of this figure (Ref. 16). One characteristic of such a distribution is that it never becomes zero. This in turn implies that the spot has no definite boundary or edge. For this reason, the size of the spot is said to be its diameter at an arbitrarily chosen proportion of the maximum current value. Two commonly used values are 50 percent of the maximum and 63 percent of the maximum. Several values are shown in the top curve and are projected down onto an isometric representation of the current distribution to assist in visualizing this method of determining spot size.

Using a previously chosen level, physical spot sizes are measured in millimeters or inches and are frequently converted into *standard deviation* (σ) units of the Gaussian distribution. Due to the nature of the Gaussian distribution, this conversion facilitates comparison between spots of different size because although the 50-percent level may have a diameter of 0.5 mm (0.014 in) for one spot and 0.2 mm (0.008 in) for another, it will be at 1.177σ for both.

Some values of σ and the corresponding proportion of the maximum current for each are given in the table. Further values can be calculated by the formula:

$$y = e^{-x^2/2\sigma^2}$$

where y = the value proportion of the maximum current and

x = the distance from the center of the curve

These values can be found in tables of the normal distribution curve (Ref. 17). If such tables are used, care should be taken because the maximum value of the ordinate is usually 0.39834 in order to keep the area under the curve equal to 1 for statistical purposes; because of this, the published ordinate values must be divided by this number to derive y as a proportion of the maximum value.

Optically formed spots used in optical line-scan printers the type illustrated in Figure 4.1-16 may or may not hav Gaussian intensity distributions (see Figure 4.1-10 and Ref. 18,B).

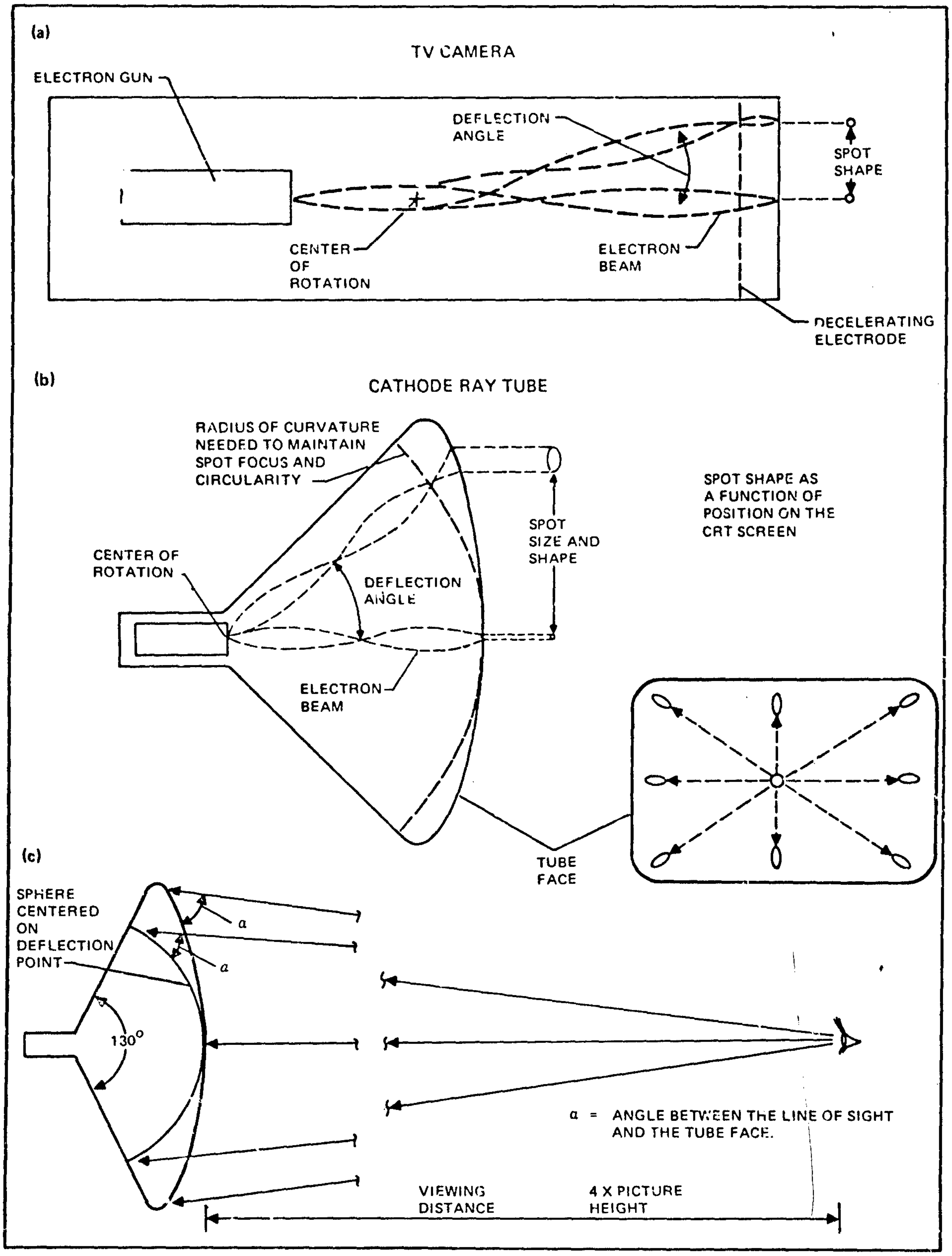


Figure 4.1-10. Spot Shape

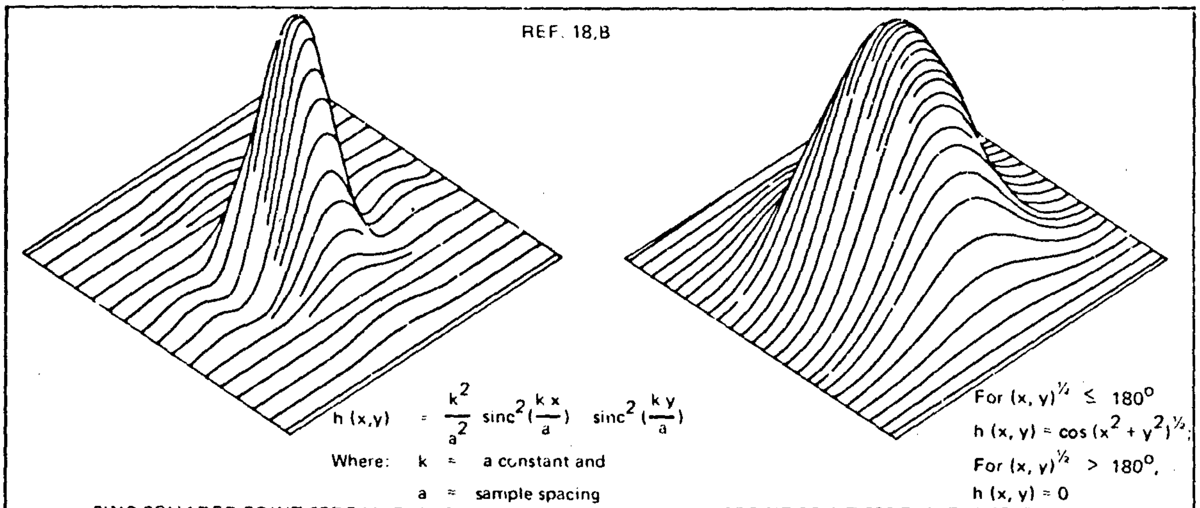


Figure 4.1-10. Spot Shape (continued)

Figure 4.1-10. Spot Shape. The term "spot shape" has two different, but related, meanings. One refers to geometric shape; for instance, circular, elliptical, or square; the second refers to the distribution of current or light within the spot. This latter is more properly referred to as the *point spread function.* The spot shown in the preceding figure (4.1-9) could be referred to either as circular or Gaussian. More properly it should be referred to as a circular spot having a Gaussian intensity distribution or Gaussian point spread function. However, this distinction is not universally made, and "spot shape" is used to refer to both characteristics.

For commercially available TV cameras and CRT's, the beam is considered to be circular in cross-section when it is projected on-axis; it therefore makes a circular spot when it lands vertically. When the beam is deflected, its shape may be changed by aberrations introduced in bending (Ref. 19); however, even if the beam remains circular, it will make an elliptical spot if it does not strike the surface at a 90-degree angle. For a given beam, an elliptical spot will have a larger area than a circular one, and the resolution which can be obtained will be reduced. Cameras, therefore, are designed so that only low-deflection angles are required. In addition, in TV cameras and CRT's, a beam that lands at a high energy will cause secondary electrons to be emitted; this interferes with the beam and reduces the output signal. Cameras contain a device known as a decelerating grid, which slows the electrons in the beam. This reduces the emission of secondary electrons because the slower arrival of electrons in the beam knocks fewer electrons from the surface upon which they land.

In CRT's, a very thin coating of aluminum is placed over the phosphor to conduct away the secondary electrons. This is done because in CRT's the beam cannot be slowed since the amount of light created by the phosphor is, in part, dependent upon the speed at which the electrons strike it. In addition, in order to make CRT's with large viewing areas, while at the same time making them shorter to fit into cabinets, very large deflection angles are employed. To make the beam land vertically on the face of such a tube would require that the surface be spherical in shape with the radius of curvature centered at the point of deflection.

For modern, high-deflection-angle CRT's, the radius of curvature required would greatly decrease the angle of view toward the edges of the picture area, resulting in considerable distortion. If the tube face is not spherical, the deflected beam will hit at an oblique angle, making the spot elliptical. The lack of sphericity will also cause the beam to be out of focus over some areas of the tube face. As part (c) shows, the problem becomes more critical with increasing deflection angles (Ref. 20).

In practical designs, it is necessary to compromise between good visual angle and good focus and landing angle. In standard practice, the tube is designed to have the beam vertical to the tube face and in focus at the center of the picture to allow the spot to be slightly elliptical and out of focus at the edges. The aberrations induced by bending the beam are tolerated in order to shorten the tube. The focusing change can be at least partially corrected with *dynamic focusing systems.* These, however, require special design.

Point spread functions other than Gaussian are found in very high resolution CRT's; for beams generated by *apertures* of 25 micrometers (1 microinch) or less, the current distribution in the beam cross-section approaches a cosine shape (Ref. 21). At high beam currents in conventional electron gun systems the beam tends to become distorted from the Gaussian shape by a spreading of the peak (Ref. 22). In optical systems, a wide variety of intensity distributions are possible (Ref. 18,B). Two such possible distributions are shown in this figure. The effect of spot spread functions on judgments of the information potential in transparencies is reported in Figures 4.3-56 and 4.3-57.

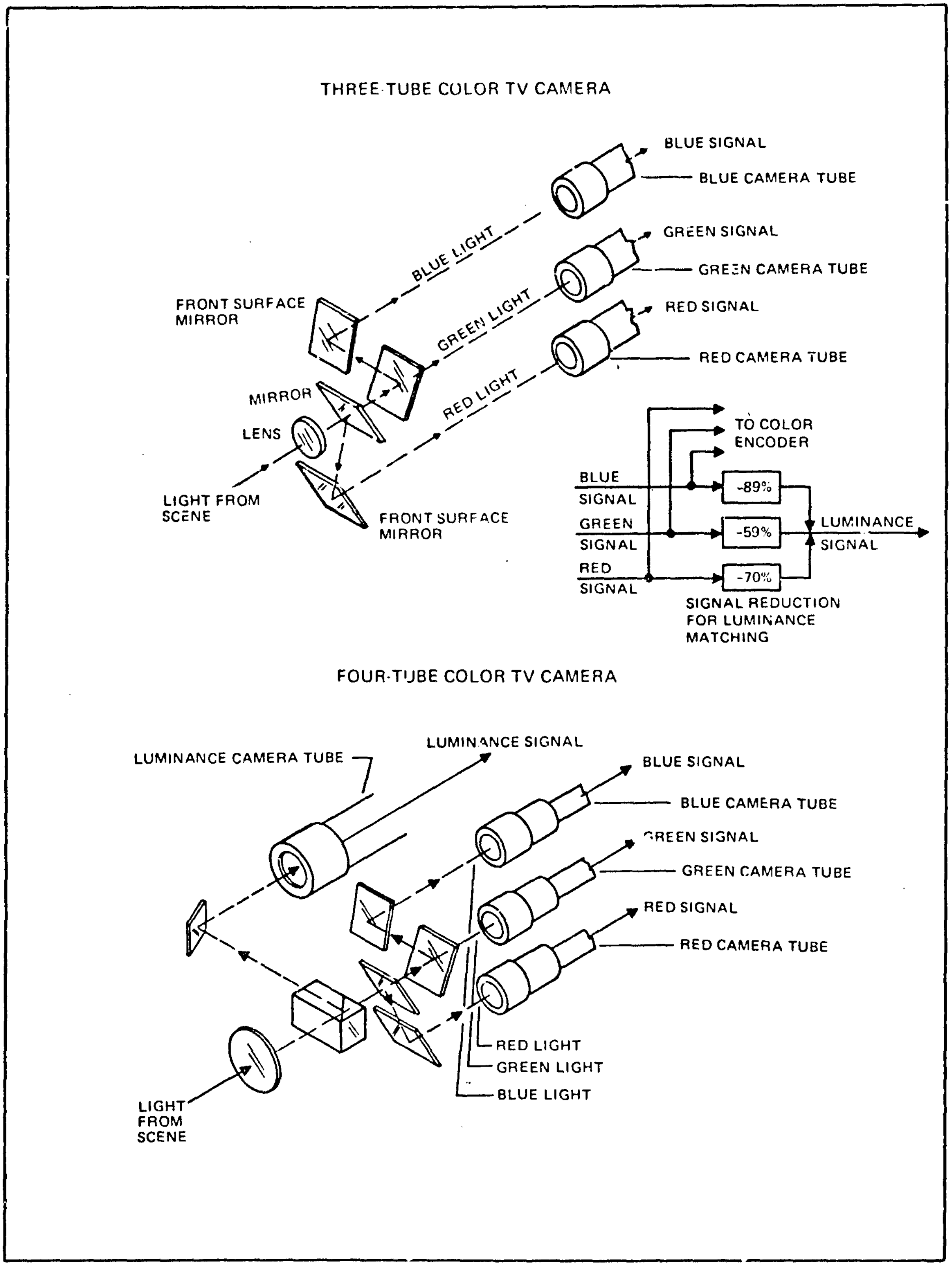


Figure 4.1-11. Color Television Signal Generation

Figure 4.1-11. Color Television Signal Generation. Color television systems that must produce pictures on black-and-white receivers or *monitors* as well as on color monitors use a system adopted by the NTSC that employs two different signals. One, called the *luminance* signal, contains the information on the variations in scene brightness and is identical to the signal generated by a black-and-white TV camera. The other, called the *chrominance* signal, carries the color information in such a way as to not interfere with the reproduction of the scene on a black-and white monitor. (Ref. 23).

There are two basic camera systems for producing color TV. They are the three-tube camera system shown at the top of this figure and the four-tube camera system shown at the bottom. They differ principally in the way the luminance signal is generated. As shown by the diagrams, the luminance signal is generated directly by one of the cameras in the four-tube camera system and by a weighted combination of the color signals in the three-tube camera system. The weighting is necessary to match the signal strength from each camera to the luminous efficiency curve of the visual system (see Figure 3.2-2). Otherwise the scene brightnesses reproduced on the black-and-white monitors would be distorted. The luminance signal in the four-camera system, although generated independently from the color signals, holds the same relationship to them as the luminance signal in the three-camera system.

Both three- and four-tube cameras generate three color signals, one for each of the primary colors, red, green, and blue. This is accomplished by having the incoming light split into the three color components by use of *dichroic* mirrors or filters. As shown in the sketches, the light of each color is focused on a separate camera tube. The colored scene imaged on each of the photodetectors is synchronously scanned, producing three separate signals of the scene—one for each color.

The chrominance signal has two components which are developed, in effect, by subtracting the luminance signal from the red and blue color signals respectively. Because the luminance signal can be expressed as a combination of known proportions of the three color signals, it, in combination with only two of the color signals, can be processed by the color monitor to reproduce the three primaries.

With regard to the two different camera systems, the four-camera system tends to produce higher resolution in the luminance signal; if an *image orthicon* is used for the luminance channel, it also produces better low light-level sensitivity. It has the disadvantage that part of the incoming light must be used for the luminance camera, reducing that available for the color cameras (Ref. 24).

Both systems present problems in balancing the luminous response functions and maintaining image registration among the individual cameras.

In installations where the color signals are to be used on color monitors only, there is no need for developing independent luminance and chrominance signals since the color signals can be used directly. The problems of balancing the luminous response of the camera tubes and the registration of the images remain, however.

For use in image interpretation, the color signals may not be generated from a natural scene or color film, but rather may be generated from black-and-white imagery as part of an image manipulation process. In such cases the generation of the color signals is carried on in a processor designed for that purpose, which may have extensive computation capability either internal or external to itself.

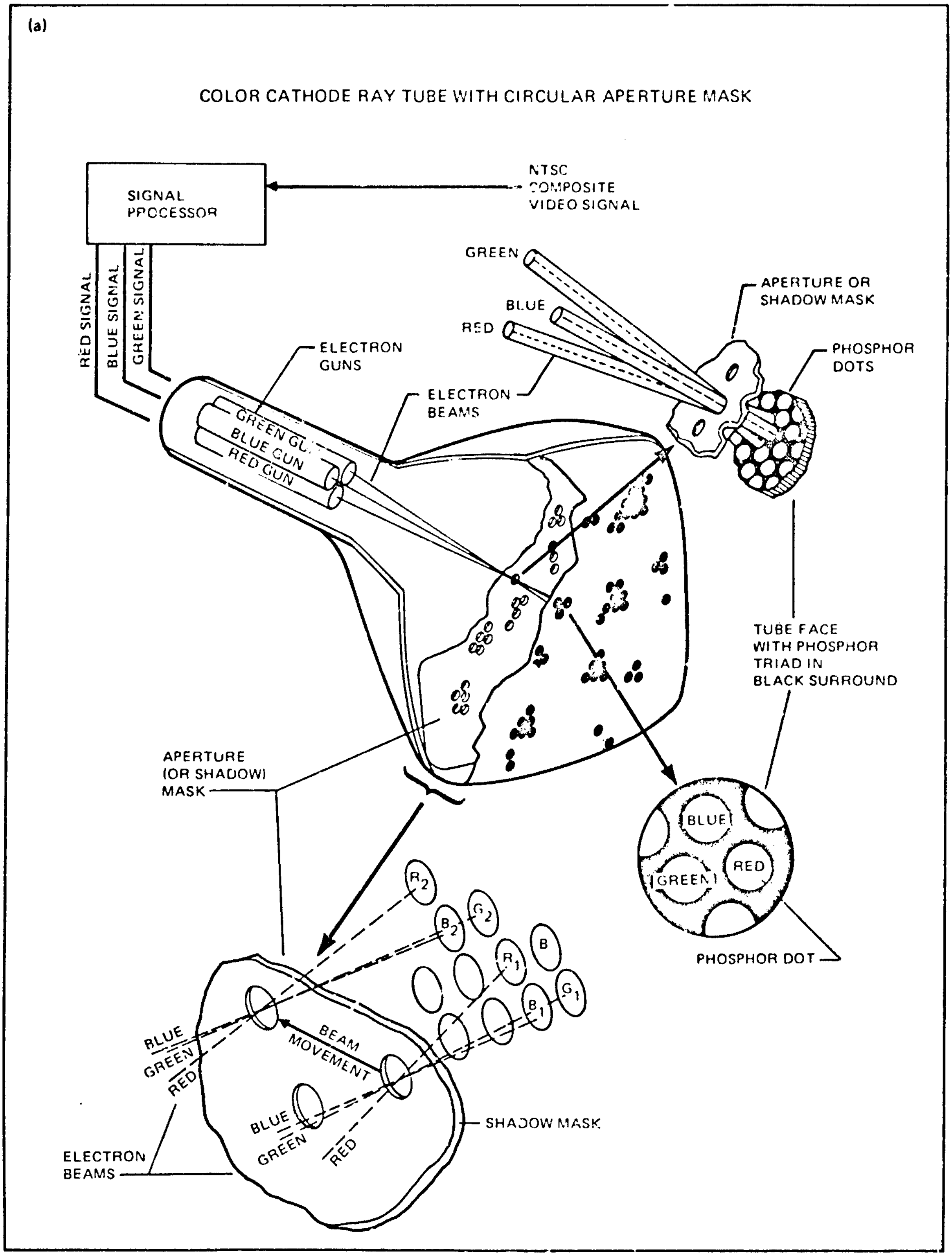
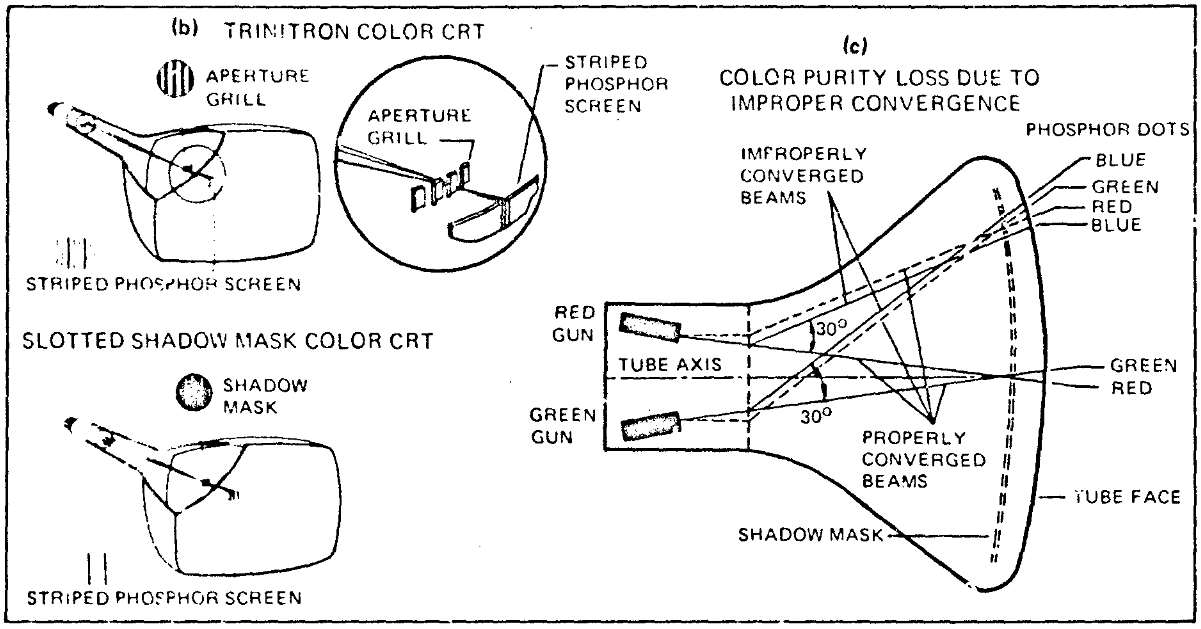


Figure 4.1-12. Color Image Regeneration by Cathode Ray Tubes



4.1-12. Color Image Regeneration by Cathode Ray Tubes. Colored images are produced on CRT's by having the face of the tube covered with tiny dots or stripes of three different kinds of phosphors that emit either red, blue, or green light when struck by an electron beam. Each separate color of phosphor is scanned by an electron gun whose current is modulated by the appropriate color signal from the camera or other input device. In the case of signals from NTSC systems, the incoming signal is processed and the luminance and chrominance signals it contains are used to recreate the red, blue, and green signals generated by the color camera.

One common type of CRT, the *shadow mask* tube, is illustrated in part (a) of this figure. In this tube the three colored phosphors are placed in groups of three called triads. The three phosphors in each triad are energized simultaneously by the three electron beams representing each of the primary color signals. The relative intensities of the light emitted by each phosphor is proportional to the relative intensity of that color in the original scene. The phosphor dots are so small that they are separately indistinguishable from normal viewing distances. The result is that the light from the three phosphor dots is integrated into a single visual sensation having a color resembling that of the same point in the original scene.

A perforated metal plate called a *shadow* or *aperture* mask is located close to the faceplate, between the electron guns and the phosphors. The plate has one hole for each phosphor triad, and the beams from the three guns must converge on a hole and pass through it to activate the phosphors. The mask ensures that a beam will strike the phosphor dot of the correct color. It also interrupts the beams as they scan the face of the tube so that no incorrect phosphors will be illuminated as they pass from triad to triad (Ref. 25).

The areas between the phosphor dots are coated with black material to reduce the reflection of ambient and internally scattered light. This results in some increase in the contrast-rendering capabilities of the tube (Ref. 26).

The combination of the shadow mask and black surround allows the use of somewhat larger beam diameters; both elements tend to cut off the edges of the beam, allowing only the central, higher intensity portion of the beam to strike the phosphor surface (Ref. 26).

Two other types of aperture masks are shown in part (b), the grill and the slotted aperture mask. For both, the phosphor is applied to the face of the tube in continuous vertical stripes whose width depends upon the light producing efficiency of the phosphor.

Part (c) illustrates the loss of color purity which will result in *dynamic convergence correction* circuits are not employed in color CRT's.

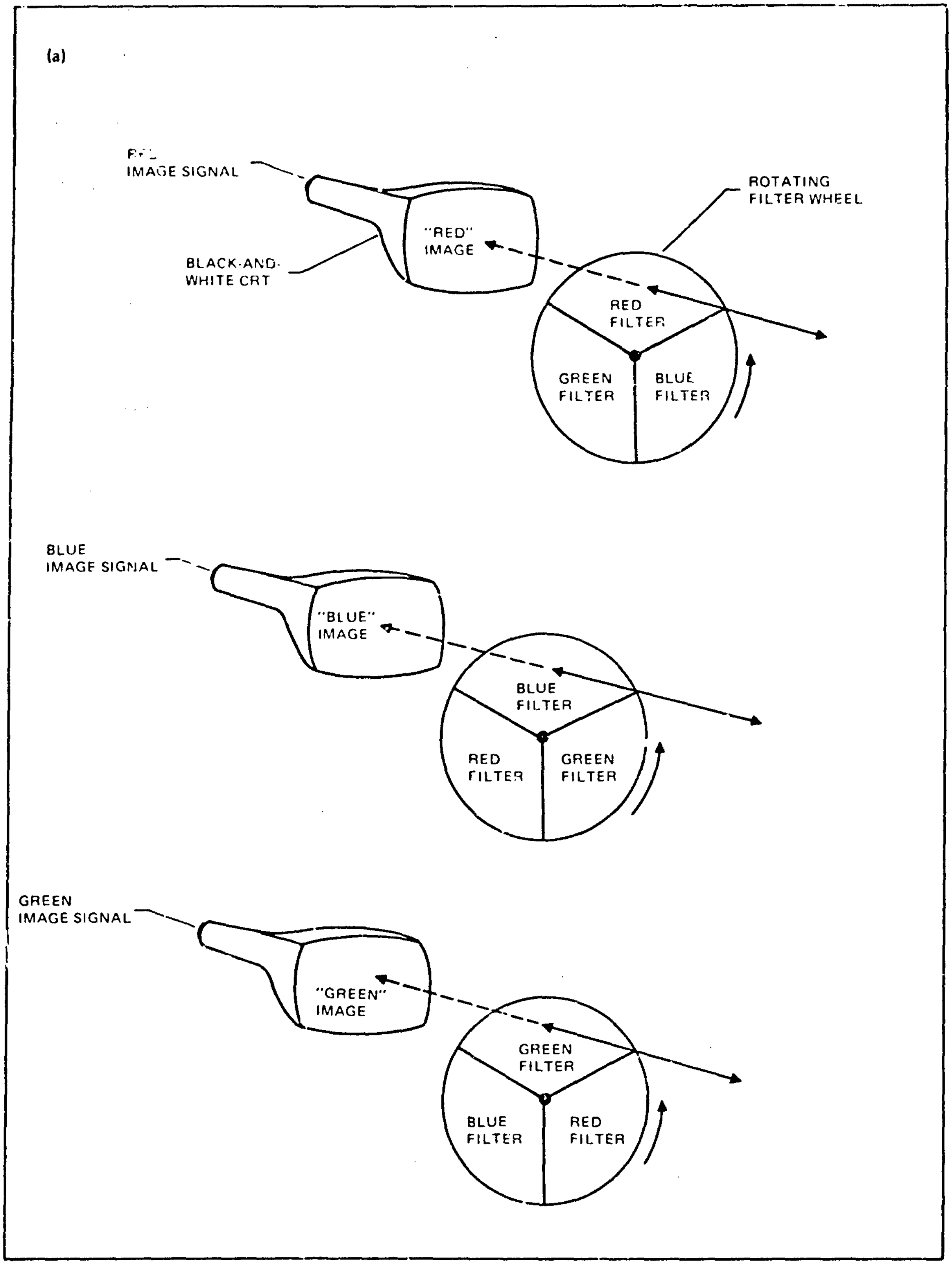


Figure 4.1-13. Sequential Color TV Systems

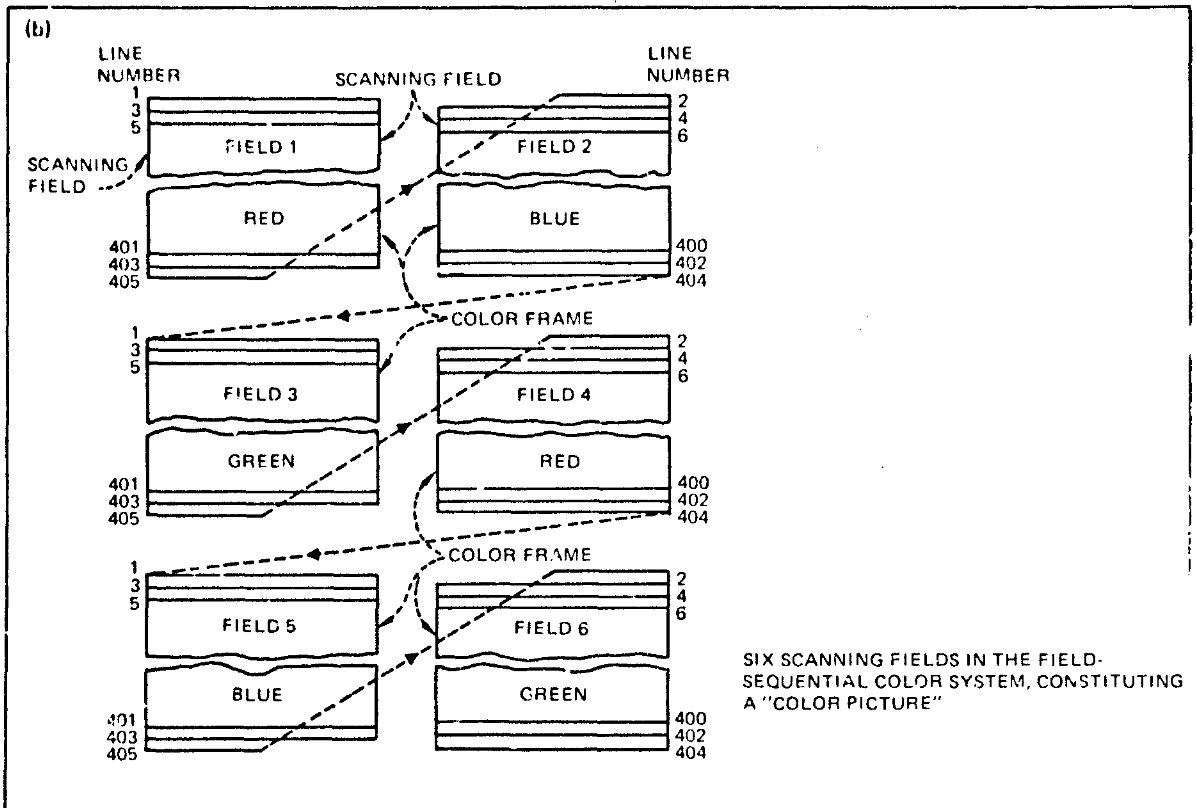


Figure 4.1-13. Sequential Color TV Systems (continued)

Figure 4.1-13. Sequential Color TV Systems. Methods other than the NTSC system for producing color TV are used in some special applications. The most common of these are the sequential systems in which the colors are interlaced by a field or a dot at a time. The signals are displayed on a black-and-white CRT monitor that is mounted behind a wheel containing the three color filters. The rotation of the filters is synchronized with the presentation of the image on the CRT so that when the red signal is being presented, the red filter wheel is between the viewer and the CRT. The blue and green filters are imposed between the viewer and the CRT when these signals are being presented (Figure 4.1-13a).

The sequence of presentation of the signals in the field sequential system is illustrated in Figure 4.1-13b. In this system, the red image is transmitted in the first *scanning field*, the blue in the second scanning field, and the green in the third scanning field. This process is repeated for the fourth, fifth, and sixth scanning fields. Examination of the diagram will show that in order to get all three primaries to the lines in two interlacing line sequencer (lines 1, 3, 5 . . . in the sequence on the left and lines 2, 4, 6 . . . in the sequence on the right), six frame periods are required.

The odd-numbered lines, for instance, receive the signal of red in field 1, green in field 3, and blue in field 5. The even-numbered lines receive the blue signal in field 2, the red in field 4, and the green in field 6.

The use of the terms "field," "frame," and "picture" are different in field sequential systems than in the NTSC systems. The application of one color to one of the two interlaced line sequences is termed a scanning field; the completion of one cycle through the three primaries is called a *color frame* and consists of three scanning fields. Two color frames (six scanning fields) constitute a *color picture*.

In such a system, the scanning field frequency must be very high to avoid both flicker and image smear for moving objects. The smear would occur if an object moved a perceptable distance between scanning frames 1 and 6; the red signal for a point on line 1 would not match in space the green for the adjacent point in line 6. Experiments have shown a scanning field rate of 144 per second is required to prevent flicker. This higher frame rate requires that either the bandwidth be increased or that the number of scan lines and horizontal resolution be decreased (Ref. 27).

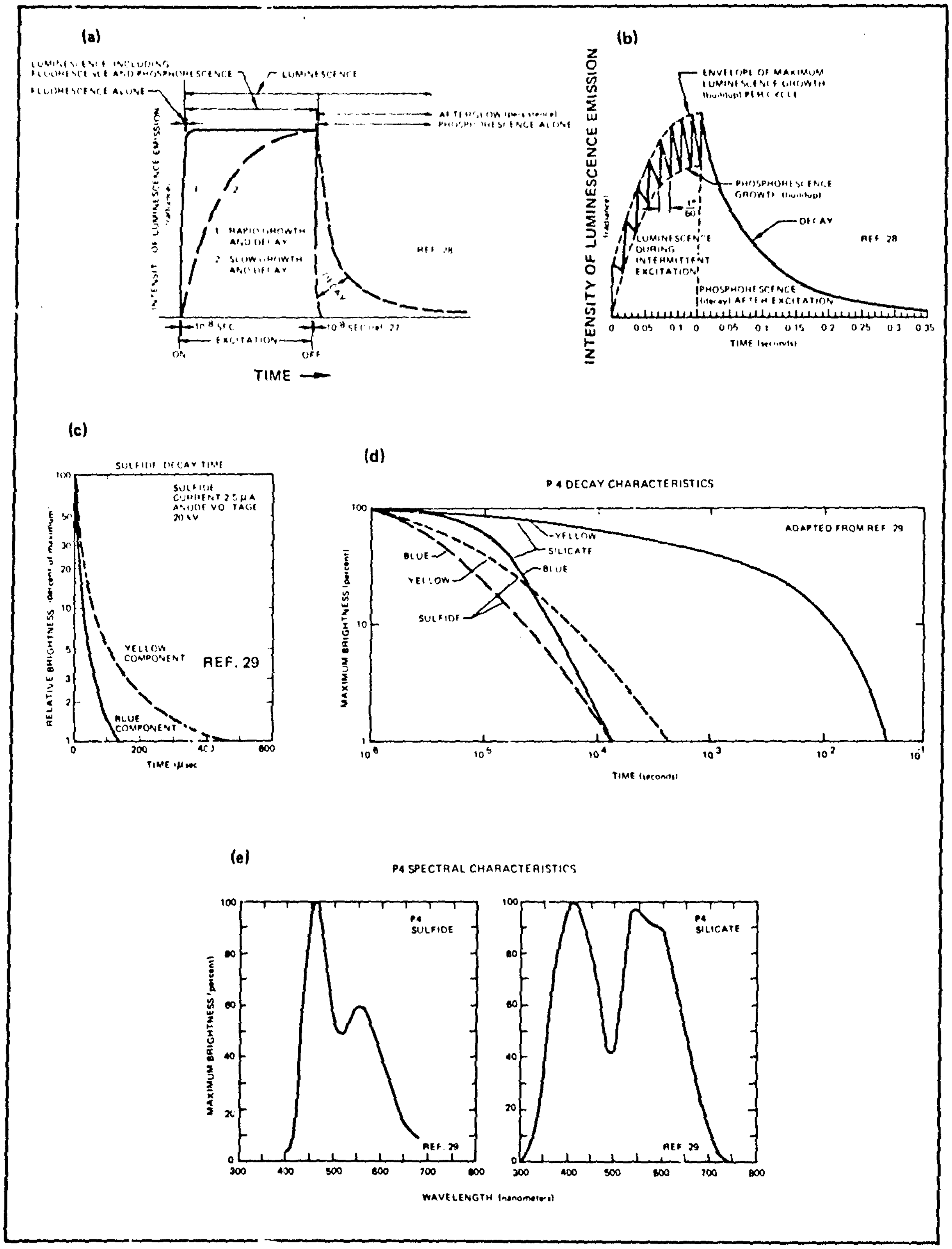


Figure 4.1-14. Phosphor Characteristics

Figure 4.1-14. Phosphor Characteristics. The word "phosphor" is generally used in CRT terminology to designate a substance that emits light when bombarded by electrons (Ref. 28). The correct term for this property is *cathodoluminescence*, which is universally shortened to "luminescence" in CRT literature.

Cathodoluminescence occurs in two phases called *fluorescence* and *phosphorescence*. Fluorescence occurs only while the electrons are energizing the phosphor and ends in about 0.01 microsecond (10^{-8} seconds) after the end of the electron bombardment. Phosphorescence, on the other hand, may last for various periods from several nanoseconds (10^{-9} seconds) to many minutes or hours.

Figure 4.1-14(a) shows the general nature of the growth and decay of light intensity when a cathodoluminescent phosphor is bombarded by electrons. The initial growth is due to fluorescence alone and takes place in about 10^{-8} seconds after excitation starts. If the excitation remains constant for some period after this, the level of intensity is a combination of the fluorescence and luminescence. After cessation of the excitation, the fluorescence decays again in approximately 10^{-8} seconds, and the phosphorescence begins a decay cycle that falls very rapidly at first, then more slowly as time progresses. The shape of the decay curve differs from one type of phosphor to another and, in some phosphors at least, it depends upon the intensity of the excitation. Figure 4.1-14(c) shows the published decay curves for sulfide P4, the phosphor commonly used in black-and-white home television receivers (Ref. 29).

The P4 designation is used for two different chemical mixtures, one of sulfides and one of silicates. P4 is also used to designate a phosphor composed of a combination of these two mixtures. Each mixture contains one compound that emits a bluish light, called the blue component, and another that emits a yellowish light, called the yellow component. The combination of these produces a white-appearing light. Figure 4.1-14(d) shows a log-log plot of the decay curves for the separate components of each of the mixtures. Figure 4.1-14(e) shows the combined spectral distribution of the light emitted by these two P4 phosphors.

The term "decay time" has arbitrarily been defined as the time for the luminance to fall from its peak value to 10 percent of that value. The term "rise time" refers to the time taken to increase to 90 percent of peak luminance. Peak luminance in both of these definitions refers to the peak brightness attained under a given set of excitation conditions.

Rise times and decay times have been given verbal classifications as follows:

Time to rise to 90 percent or decay to 10 percent of peak luminance	Classification
Greater than 1 second	Very long
100 msec to 1 sec	Long
1 msec to 100 msec	Medium
10 μsec to 10 msec	Short
Less than 10 μsec	Very short

(Ref. 29)

Part (b) of this figure illustrates the type of luminescence buildup which can take place when the rate of excitation is much greater than the decay rate. The buildup reaches a maximum value when the phosphor becomes *saturated*, that is, cannot produce more light regardless of further increases in excitation.

The fluorescence is sometimes referred to as *flash*. In some multicomponent phosphors, for instance P28, it can be strong enough for one component to constitute flicker control problem (see Section 4.2).

Different phosphors produce different brightness levels for the same level of excitation, that is, they have different *luminous efficiencies*. Luminous efficiency of cathodoluminescent phosphors is commonly defined as the ratio of the energy emitted in the form of infrared, visible, and ultraviolet radiation to the energy in the exciting beam. A more restricted, but more useful definition for display design purposes, is the ratio of the energy of the visible light output, weighted for the luminosity curve, to the electron energy of the input. Luminous efficiency varies greatly among phosphors, and for a given phosphor it depends upon the conditions of its preparation and excitation (Ref. 30).

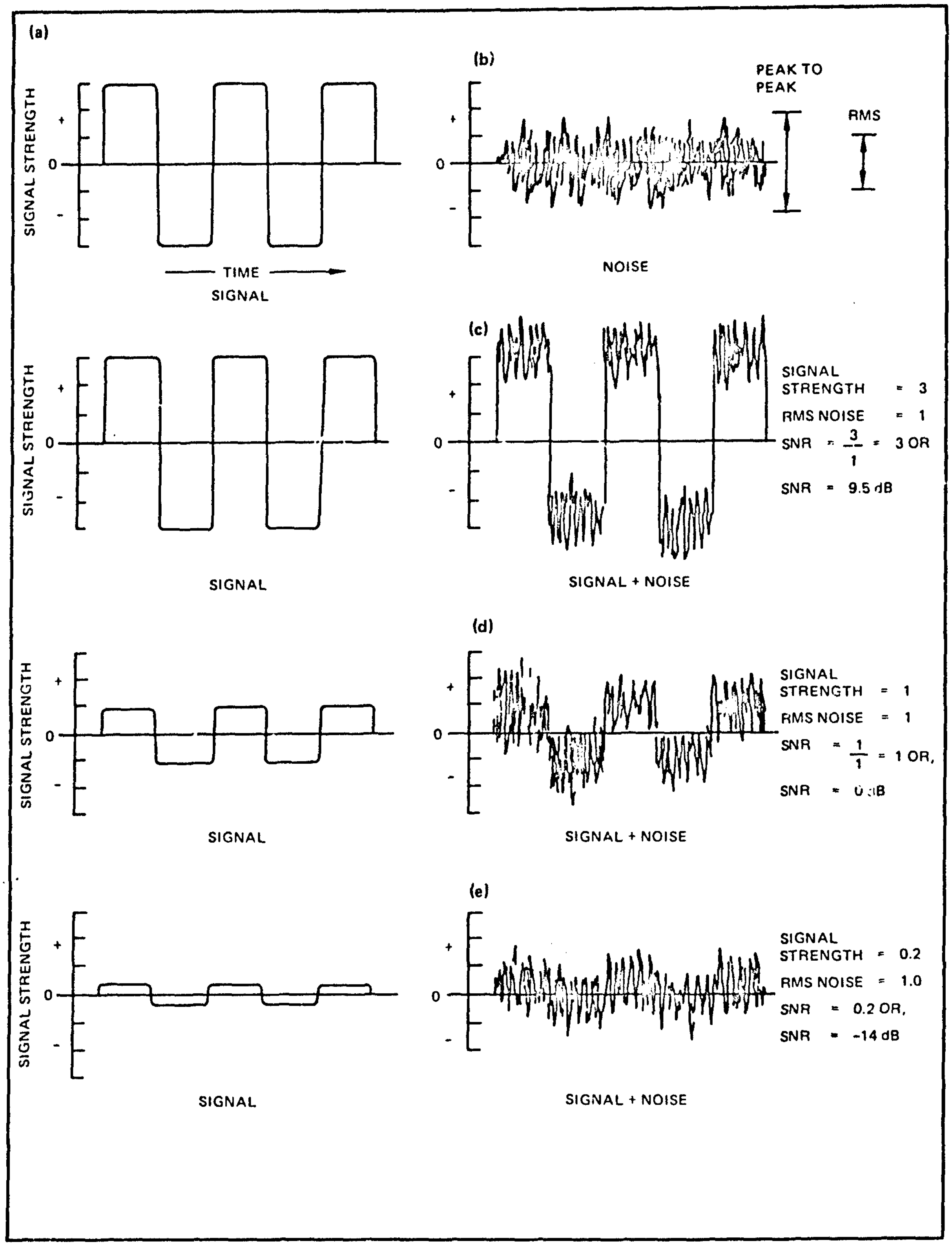


Figure 4.1-15. Signal-to-Noise Ratio

Figure 4.1-15. Signal-to-Noise Ratio. *Noise* in electronic circuits will be defined here as any extraneous voltage accompanying the signal that interferes with the detection of the signal. All electronic circuits produce noise to some degree. The strength and frequency characteristics of which depend upon such things as the circuit design, the operating conditions, and the types of components chosen to build the circuit. Additional noise is introduced from such sources as transmission lines or other transmission media, stray electromagnetic radiation generated by electrical machinery or other electronic devices, or from geophysical and astrophysical phenomenon. In addition, the errors introduced by the quantizing process are also considered noise and can be treated like any other source of noise in the analysis of the quality of electro-optical systems.

The relationship between the strength of a signal and the strength of its accompanying noise is referred to as the signal-to-noise ratio (SNR). In this book, unless otherwise stated, the IEEE definition of SNR will be adopted (Ref.11):

$$SNR = \frac{\text{Peak signal in volts}}{\text{rms noise volts}}$$

or in decibels as

$$SNR_{dB} = 20 \log \left(\frac{\text{Peak signal volts}}{\text{rms noise volts}}\right)$$

RMS refers to *root mean square* and is defined as:

$$RMS = \left(\frac{1}{N}\sum_{i=0}^{N}\left[\overline{V}-v_i\right]^2\right)^{1/2}$$

where $\overline{V}$ = average voltage

v_i = voltage at a given phase of the lowest frequency signal of interest

N = sequence length

RMS voltage is also calculated as 0.707 times the amplitude of voltage having a sine-wave form in an alternating circuit.

In part (a) of this figure, a signal and noise are separately represented as alternating currents; i.e., currents which alternate their direction of flow, represented as positive and negative values. When a signal and noise are present in the same circuit, the output is the algebraic sum of the two. In parts (b) through (e) of this figure the same noise has been added to signals of decreasing strength. As can be seen, the signal becomes obscured by the noise. In order to be detected, the strength (modulation) of a signal must be greater in the presence of noise than in its absence. This requirement of increased modulation has the effect of reducing the bandwidth of a given system. The reason for this can be seen by reference to Figure 4.1-7. As the modulation required to detect the signal is raised, the modulation produced by the frequency originally representing the top of the bandwidth will become too low. The required higher modulation is seen to be produced by a lower frequency, representing a reduction in bandwidth. Noise is characterized by its bandwidth and spectrum. The term *narrow-band noise* refers to a noise whose own bandwidth (range of frequencies) is narrow compared to the bandwidth of the circuit in which it is found. *Broad-band noise* is noise whose range of frequencies is similar to that of the circuit in which it is found. Both of these terms are simply descriptive. Precise statements which specify the frequency range of the noise, such as "0.5 MHz centered at 2.75 MHz" for narrow-band noise, or "0 to 5 MHz" for broad-band noise are required for a proper understanding of the nature of the noise being reported.

A number of descriptive words are also used to characterize the spectrum of a noise source; among the most common are terms such as "flat," "white." or "triangular." These refer to the amplitude of the noise as a function of its frequency.

Noise can also be characterized by the amount of power per unit frequency. Thus a noise source can be spoken of having 10^{-9} watts per hertz, meaning that if all of the noise except a single frequency could be eliminated, electrical power flowing in the circuit would be 10^{-9} watts (0.001 µwatts). This same noise source, if expanded to 1 MHz would deliver $(10^{-9})(10^{+6})^{1/2} = 10^{-6}$ watts (1 µwatt).

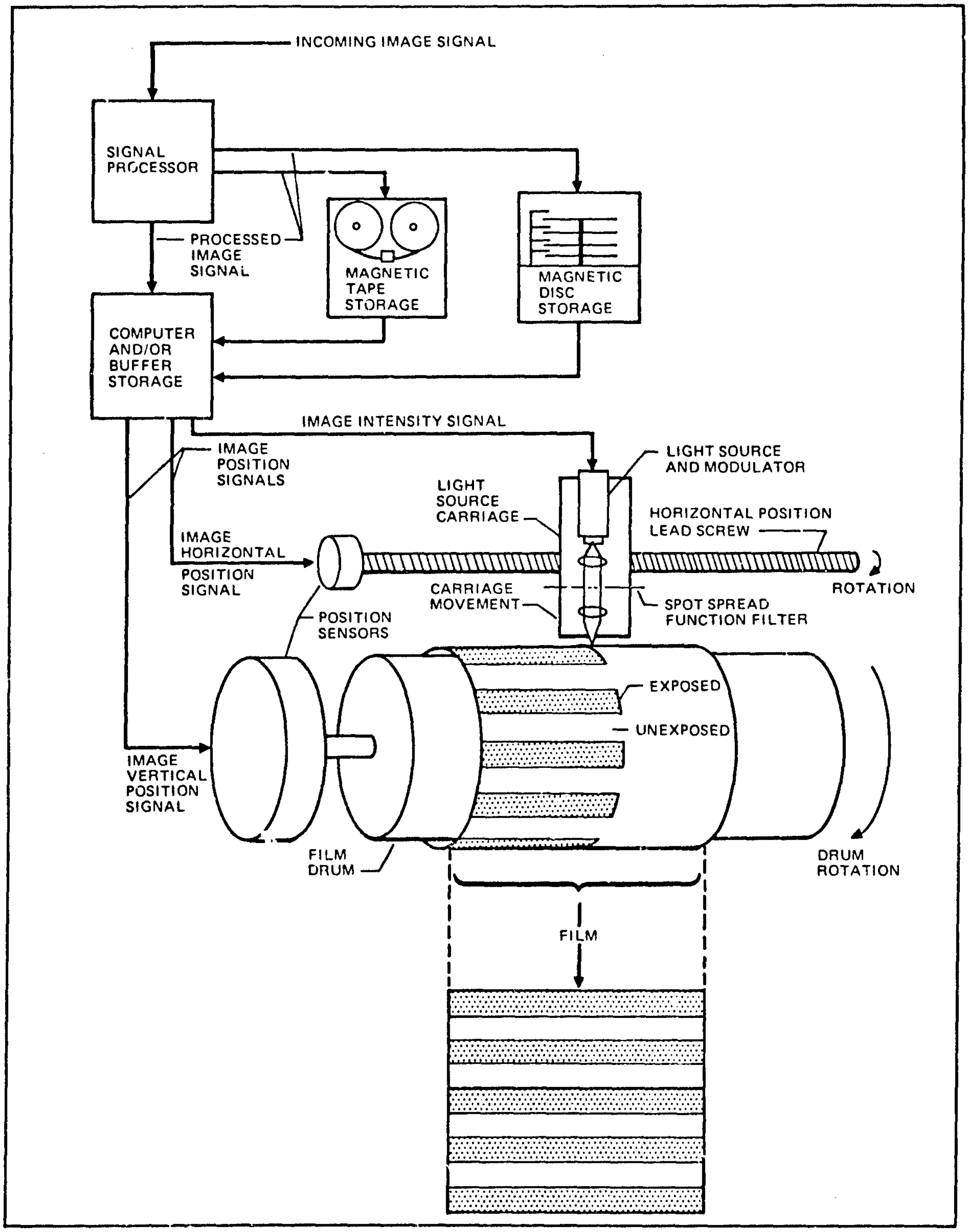


Figure 4.1-16. Optical Line-Scan Printers (continued)

Figure 4.1-16. Optical Line-Scan Printers. Both one- and two-dimensional sampled imagery is often printed on film by means of optical printers. When lasers are used as light sources, the devices are frequently called laser-beam recorders (LBR). The printers come in a variety of configurations, some with flat beds and some with rotating drums to hold the film to be exposed. A much simplified sketch of the latter type is shown here.

In such a printer, the film is exposed a spot or line at a time by means of a light shone through an optical system. The light is focused onto the emulsion of the film through a microscope objective or some similar optical system so that a small spot can be formed. Spot sizes on the order of 5 μm are not uncommon. These small spot sizes are necessary to permit high-resolution, small-scale imagery to be imaged.

The light is mounted on a carriage that is moved above the surface of the drum by a precision lead screw. The position of the light on the film is determined by the rotation of the drum and movement of the carriage. These, in turn, are controlled by position signals from the image. Typical position signals associated with the incoming signal would be the row and column number of the pixel to be exposed in the formation of a two-dimensional sampled image.

The exposure is controlled by modulating the light with the image intensity signal. By synchronizing the rotation of the drum, the position of the carriage containing the light source, and the image intensity signal, the exposure pattern formed on the film will duplicate the intensity pattern in the scene.

Since currently available printers of this type are very slow compared to the speed with which images can be generated or transmitted, some intermediate storage or *buffer* capability may be necessary. Long-term storage is usually provided by magnetic tapes or magnetic discs; short-term storage, or buffering, is usually provided by a computer that will accept the signal for a portion of the image and feed it to the printer a resolution element at a time.

The computer can be used to manipulate the image signal before it is printed. For instance, a negative or positive transparency can be generated from the same signal by programming the computer to command a high light level for a strong signal in the one case or a low light level for a strong signal in the other.

Unlike the electron beam generated by an electron gun, the point spread function of an optical beam can be changed with relative ease if appropriately shaped filters are placed at the proper position in the optical train. This capability can be used to modify the MTF of the system (Ref. 18) or to improve the cosmetic quality of the imagery.

1. Two basic references to the one-dimensional sampling process are: Mertz, P. and Gray, F. A theory of scanning and its relation to the characteristics of the transmitted signal in telephotography and television. *Bell System Technical Journal*, Vol. 13, 1934, pp. 464-515.

Schade, O., Sr. Image gradation, graininess and sharpness in television and motion-picture systems, *J. SMPTE*, Vol. 61, 1953, pp. 97-164.

2. Hansen, G. L. *Introduction to Solid-State Television Systems.* Prentice-Hall, Inc., Inglewood Cliffs, N.J., 1969, p. 73.

There are two general classes of photosensors used in electronic imaging devices, the conventional camera tubes, such as the one used as an illustration in the text, and the newer solid state array devices. For comprehensive treatment of the characteristics of the various types of sensors in each class and their relationship to photo-interpretation functions see:

Electronic Photointerpretation Equipment Study Final Report. Volume 1: Sensors and Displays Analysis. Report AED R-4044F, RCA Astro-Electronics Division, Princeton, N.J., Oct., 1975, p. II-7.

Biberman, L. M. and Nudelman, S. Eds. *Photoelectronic Imaging Devices, Volume 2, Devices and Their Evaluation.* Plenum Press, New York, 1970.

3. In Schade article in Ref. 1, see pp. 177 ff.

Buchsbaum, W. H. *Fundamentals of Television.* John F. Rider, New York, 1964, p. 5ff and p. 17ff.

There are several types of image-generating devices for electro-optical systems beside the cathode ray tube, such as *plasma displays, liquid crystal displays, light valves, electro-luminescent panels,* and *direct view storage tubes,* many of them representing recent advances in display technology. A review of the more promising of these devices for photo-interpretation can be found in: *Electronic Photointerpretation Equipment Study–Final Report, Volume 1: Sensors and Displays Analysis.* Report AED R-4044F, RCA Astro-Electronics Division, Princeton, N.J., Oct. 1975, p. III-1ff.

A basic discussion of the process of light production by *cathodoluminescent* phosphors can be found in Leverenz, H. W. *An Introduction to Luminescence in Solids.* Wiley, New York, 1950.

4. Kell, R. D., Bedford, A. V. and Trainer, M. A. An experimental television study. *Proc. IRE,* Vol. 22, November 1934, p. 1246.

5. Pages 106-110 in the Schade article in Ref. 1.

6. Legault, R. The aliasing problems in two-dimensional sampled imagery. In Biberman, L. M. (Ed.), *Perception of Displayed Information.* Plenum Press, New York, 1973, pp. 279-312.

7. Five references are provided below to give the reader access to several aspects of the quantizing process.

O'Neal, J. B., Jr. Predictive quantizing systems (differential pulse code modulation) for the transmission of television signals. *The Bell System Technical Journal,* Vol. 45, 1966, pp. 689-721.

O'Neal, J. B., Jr. A bound on signal-to-quantizing noise ratios for digital encoding systems. *Proc. IEEE,* Vol. 55, No. 3, March 1967, pp. 287-292.

O'Neal, J. B., Jr. Quantizing noise-bandwidth tradeoffs for differential PCM of television signals. Paper presented at the Picture Coding Symposium sponsored by the U.S. Air Force Office of Scientific Research, Raleigh, N.C., 1970.

O'Neal, J. B., Jr. Differential PCM entropy coding in speech and television systems. *IEEE Trans. Info. Theory,* Vol. IT-17, No. 6, Nov. 1971, pp. 758-761.

Habibi, A. Comparison of nth order DPCM encoder with linear transformations and block quantization techniques. *IEEE Trans. on Communication Technology,* Vol. COM-19, No. 6, December, 1971, pp. 948-957.

8. See Ref. 7, particularly the second, fourth, and fifth references.

9. See Ref. 2, p. 90ff.

10. The abbreviation MTF is sometimes erroneously applied to the modulation transfer factor. It should properly be reserved to refer to modulation transfer function.

11. *IEEE Standard Dictionary of Electrical and Electronics Terms.* The Institute of Electrical and Electronics Engineers, Inc. Wiley Interscience, New York, 1972.

12. Engstrom, E. W. A study of television image characteristics Part Two. Determination of frame frequency for television in terms of flicker characteristics. *Proceedings of the Institute of Radio Engineers,* Vol. 23, 1935, pp. 295-310.

13. Brown, E. F. Low-resolution T.V.: Subjective comparison of interlaced and noninterlaced pictures. *Bell System Technical Journal,* Vol. 46, 1967, pp. 199-232.

14. Fink, D. G. *Television Engineering* (2nd ed.). McGraw-Hill, New York, 1952, p. 500.

15. Cherry, E. M. High-order line interlace in television rasters. *J. SMPTE,* Vol. 83, 1974, pp. 708-710.

    Cherry, E. M. Combined line and dot interlace in television rasters. *J. SMPTE,* Vol. 83, 1974, pp. 711-718.

16. Zworykin, V. K. and Morton, G. A. Television The *Electronics of Image Transmission.* Wiley, New York, 1940, p. 183.

    Spangenberg, K. R. *Vacuum Tubes.* McGraw-Hill, New York, 1948, p. 437.

17. Hald, A. *Statistical Tables and Formulas.* Wiley, New York, 1952, p. 13, or almost any textbook on elementary statistics.

18. Arquello, R., Crockett, M., Grey, L., Hufnagel, R., Kob, E. and Sellner, H. *SIAM Program Sampled Image Reconstruction Spot Study - Volume 1, Technical Volume.* Perkin Elmer Report ER-205, Perkin Elmer, Danburry, Connecticut, 1972.

19. See Ref. 15, Zworykin, V. K. and Morton, G. A., p. 122ff.

20. See Ref. 14, p. 173.

21. Schade, O. H., Sr. Electron optics and signal readout of high-definition return-beam vidicon cameras. *RCA Rev.,* Vol. 22, 1960, p. 66.

22. Shibata, A., Ogino, M. Electron-beam spot characteristics and video circuit characteristics. *J. SMPTE,* Vol. 81, 1972, pp. 841-845.

23. Fink, D. G. (Ed.) *Color Television Standards–Selected Papers and Records of the National Television System Committee.* McGraw-Hill, New York, 1955, pp. 41-246.

    In the NTSC color television system the luminance channel is made up of accurately known proportions of the three primary colors. To transmit the color information in the chrominance signal, it is only necessary to transmit information on how the signals for two of the primaries differ from the total of all three (which is the luminance signal). With appropriate circuitry, the monitor can then add the two transmitted color signals together, and by subtracting the sum from the luminance signal, recover the third color signal. Other references on the NTSC and other color systems can be found in Ref. 2, Chapter 10; Ref. 13, Chapter 9; and Hunt, R. W. G. *The Reproduction of Color.* Wiley, New York, 1967, p. 417ff.

24. Ref. 2, p. 261.

    The improvement in resolution occurs chiefly because the problems of precisely registering the scans from the three color cameras to compose the image, which is carried by the luminance channel, are avoided. The luminance image is generated directly by a single camera.

25. Ref. 2, p. 354ff.

26. Flore, J. P. and Kaplan, S. H. A second generation color tube providing more than twice the brightness and improved contrast. *IEEE-PTR,* Vol. 15, No. 3, 1969, pp. 267-276.

27. Reference 14, p. 487ff.

28. Leverenz, H. W. *An Introduction to Luminescence in Solids.* Wiley, New York, 1950, p. 150.

29. *Optical Characteristics of Cathode Ray Tube Screens,* Joint Electronic Devices Engineering Council (JEDEC) Electron Tube Council. Electronic Industries Association, Washington, D.C., 1971.

4.2 CATHODE RAY TUBE FLICKER, LINE CRAWL, AND SCINTILLATION

4.2.1 Laboratory Studies on CRT Flicker, Line Crawl, and Scintillation

SECTION 4.2 CATHODE RAY TUBE FLICKER, LINE CRAWL, AND SCINTILLATION

The appearance of visually perceptible flicker in CRT displays depends upon the *refresh rate*, brightness, color, and size of the illuminated area, and, to some extent, the decay characteristics of the display. It also depends upon the level of ambient illumination and the position on the retina which is stimulated (see Section 3.2-10 and Ref. 1). Two general categories of flicker are spoken of in the CRT literature: *small field* flicker and *large field* flicker. Small field flicker usually refers to flicker of elements in single lines or small groups of lines having a visual angle that does not exceed that of *foveal* vision (a solid angle of about 3 degrees). Small field flicker, restricted to two or three lines, is sometimes referred to as *interline flicker*. Large field flicker refers to flicker appearing over all, or substantially all portions of the face of the tube.

In CRT terminology, *refresh rate* means the frequency with which the electron beam returns to a given spot on the phosphor. This is nominally assumed to be equal to the frame rate for National Television Systems Committee (NTSC) systems.

The requirement to prevent perceptible flicker (or at a minimum reduce it to a tolerable level) has a direct effect on the bandwidth requirements of a system. This is because the perception of flicker is strongly tied to the rate at which the intensity of a light varies. In a CRT, this rate depends upon the frame rate, which in turn sets the bandwidth requirement for a system of a given spatial resolution and, for *pulse code modulated* digital systems, signal-level quantization.

At the frame rate of 30 Hz used in NTSC systems, it is 0.0333 second (3.33×10^{-2} sec) between passages of the beam over a given spot on a scan line. For the P4 sulfide phosphor used in black-and-white pictorial displays, the blue component decays to 1 percent of its peak luminance in about 150 μsec (150×10^{-6} sec) and the yellow component in about 470 μsec (470×10^{-6} sec; Ref. 2). Thus the light from a given spot on a line pulsates at the 30-Hz rate. Because of the spot spread function, part of the energy from one line overlaps into the adjoining lines. To the extent that this energy creates luminance, the combined effect for *interlaced* scans is a 60-Hz pulsation with one strong component and one weak, individually varying at 30 Hz for a given line.

For the luminance levels found in both black-and-white and color *monitors*, a 30-Hz rate for the strong signal alone would produce unacceptable flicker. Such a situation would occur if the frame were scanned without interlace. By interlacing two fields, each of which has half the total number of TV lines of the frame, and presenting the alternate fields at a 60-Hz rate, visual flicker is eliminated or reduced to a tolerable level for home entertainment systems (Ref. 3,C). There appears to be no information on the effect of CRT flicker on the performance of image interpretation tasks.

Line crawl (also referred to as *raster crawl*) is a term used to describe the appearance of brightness differences extending across the face of the CRT parallel to the scan lines; they appear to move perpendicularly to the scan lines. In the most common systems with horizontal scanning, the areas of brightness difference may appear to move up, down, or both simultaneously (Ref. 4,C). A descriptive term which is sometimes used for this phenomenon is the "window shade effect." Another type of motion may occur which is limited to small fields. Short segments of an individual line may appear to move back and forth between an adjacent line in an oscillatory motion. Both of these phenomena are examples of what is referred to in the literature on vision as apparent motion, stroboscopic motion, or phi phenomenon (Ref. 5). The appearance of the effect is strongly influenced by interlace techniques (see Figures 4.2-9 through 4.2-13).

Scintillation refers to a "twinkling" appearance over substantial portions of the tube face. It is associated with dot interlace patterns and is generally considered less annoying visually than either small area or a large area flicker (Ref. 6).

The larger "snowflake" areas that flicker and appear to move randomly in the display are created by some line-dot interlace patterns and are considered very objectionable but appear to be greatly reduced by the use of long-*persistence* phosphors (Ref. 7,C and Figures 4.2-8 to 4.2-12).

Figure 4.2-1. Relationship Between Interlace and Flicker Line Crawl, Scintillation, and Snow. The sketch at the top of this figure (Figure 4.2-1(a)) illustrates the time sequence for the illumination of contiguous areas on adjacent lines of a 2:1 interlaced raster at a 30-Hz frame rate (see Figure 4.1-8). Lines (1,1) and (1,2) belong to one of the two fields and lines (2,1) and (2,2) to the other. (The first number in parentheses refers to the field and the second to the line within that field.) An activated area in any one of the lines is refreshed at the frame rate (30 Hz). Within a single frame, however, it is only 1/60 second between the activation of the area in (1,1) or (1,2) and the activation of the area in (2,1). At normal TV viewing distances of 4 to 8 times the picture height (Ref. 8,D), the spatial and temporal integration characteristics of the eye combine to eliminate, or greatly reduce, the appearance of flicker for *foveal* vision. Early work on TV flicker elimination (Ref. 3,C) led to the adoption of this system by the NTSC. When viewed from a short distance, or under optical magnification, the angular subtence of each line becomes greater, reducing the visual integration between lines, and small field, or interline, flicker may be observed. Small field flicker may also appear in areas of high luminance even at "normal" viewing distances (see Section 3.2.10).

The perception of flicker occurs at a higher frequency in the periphery of the visual field than in the fovea (see Section 3.2.10). As a result, large field flicker may be visible at the edges of a 2:1 interlaced 30-Hz frame rate system under conditions of high ambient illumination or high display luminance. Both small area and large area flicker will be introduced by higher order *sequential interlace* patterns if the field rate is held constant (Ref. 4,C and Figure 4.2-4). This is because the refresh time for areas in the individual lines is increased in direct proportion to the increase in the interlace order. Figure 4.2-1(b) illustrates this point for 3:1 and 4:1 *sequential interlace*. *Line crawl*, which is described in the introduction to this section, is particularly pronounced in *sequentially scanned* high-order interlace systems. (A sequentially scanned or interlaced system is one in which the lines from succeeding fields are written adjacent to each other as is illustrated in Figure 4.2-1(b).) In these systems, light and dark bands appear to move in a direction perpendicular to the direction of scan. For horizontally scanned systems, the bands move vertically. This effect is seen in motion picture recordings of CRT's when the camera frame rate has not been synchronizing with the CRT frame rate.

In high-order interlace systems, line crawl may be made less objectionable by using *staggered interlace* techniques. In these techniques, the lines from succeeding fields are intermixed rather than being contiguous as in the sequential interlace systems. Two types of staggered interlace have been considered—periodic and aperiodic (Ref. 4,C). In *periodic staggered interlace*, the time allotted for each field is the same; in this respect, the technique is like the sequential systems. Figures 4.2-1(c) and 4.2-1(d) give examples of periodic staggered line interlaces for a 4:1 and 5:1 interlace order. Other sequences are possible for both orders. The discussion of this interlace technique is expanded in Figure 4.2-3.

In *aperiodic interlace* systems, the fields are also staggered, but different times are alloted each field. As a result, there are considerable differences in the times between adjacent lines. Figure 4.2-1(e) illustrates the case of a 4:1 in[illegible] where the field times would stand in the ratios 1[illegible], 1:1.006, 1:1.002 and 1:1 to each other for a system with 492 active TV lines. The large differences this slight aperiodicity in the field times makes, in the times between adjacent lines while eliminating line crawl, results in uneven signal readout from the camera, which creates a very disturbing pattern of bright and dim lines in the display (Ref. 4,C).

Scintillation and *snow* are defects produced in *point scan* systems. In these systems, aside from the basic differences between the *two-dimensional sampling* system of the point scan technique and the *one-dimensional sampling* system of the line scan technique (see Figures 4.1-3 and 4.1-4), there is a significant difference in the visual appearance of the flicker each produces. The small field flicker of the line scan system is most analogous to the scintillation that is produced by point scan systems. Scintillation, however, appears as a "twinkling" over the entire surface of the tube. It is considered much less annoying than large field flicker (Ref. 6). Snow, on the other hand, is a random variation of brightness over larger areas, as when a TV set is turned to a channel having no broadcast; it is very disruptive. There is no known quantitative distinction between the two effects.

Dot scan systems, like line scan systems, can be interlaced or noninterlaced; they can also be interlaced sequentially or staggered. In addition they are sometimes random; that is, the refresh sequence of the dots comprising the scene is not a clearly identifiable pattern of rows or dots, but is some fixed pattern with successive spots located at widely different locations.

An example of scanning patterns for an interlaced dot scan system is shown in Figure 4.2-1(f) (Ref. 7,C). The definitions of the terms "field," "frame," and "picture" are different for this system than for line scan systems and are similar to those for the dot interlaced color system described in Figure 4.1-13. A field consists of one complete traverse of the scanning beam from top to bottom of the picture area. If the writing scheme includes interlace of the dots on any particular scan line, rather than writing them all on one pass, only part of each "line" will be activated during each field. In the example shown, only 1/5 of the dots are activated on each line for each field. A frame consists of one complete set of fields. In the example shown, (part (b)), this number is seven. At the completion of one frame, 1/5 of the dots in the picture have been written. It follows then that five frames complete a picture. In such a system, the picture may be considered to consist of a number of similar cells as shown in the illustration. The cells themselves may also be staggered, as shown.

Evaluations of such systems are given in Figures 4.2-8 through 4.2-13.

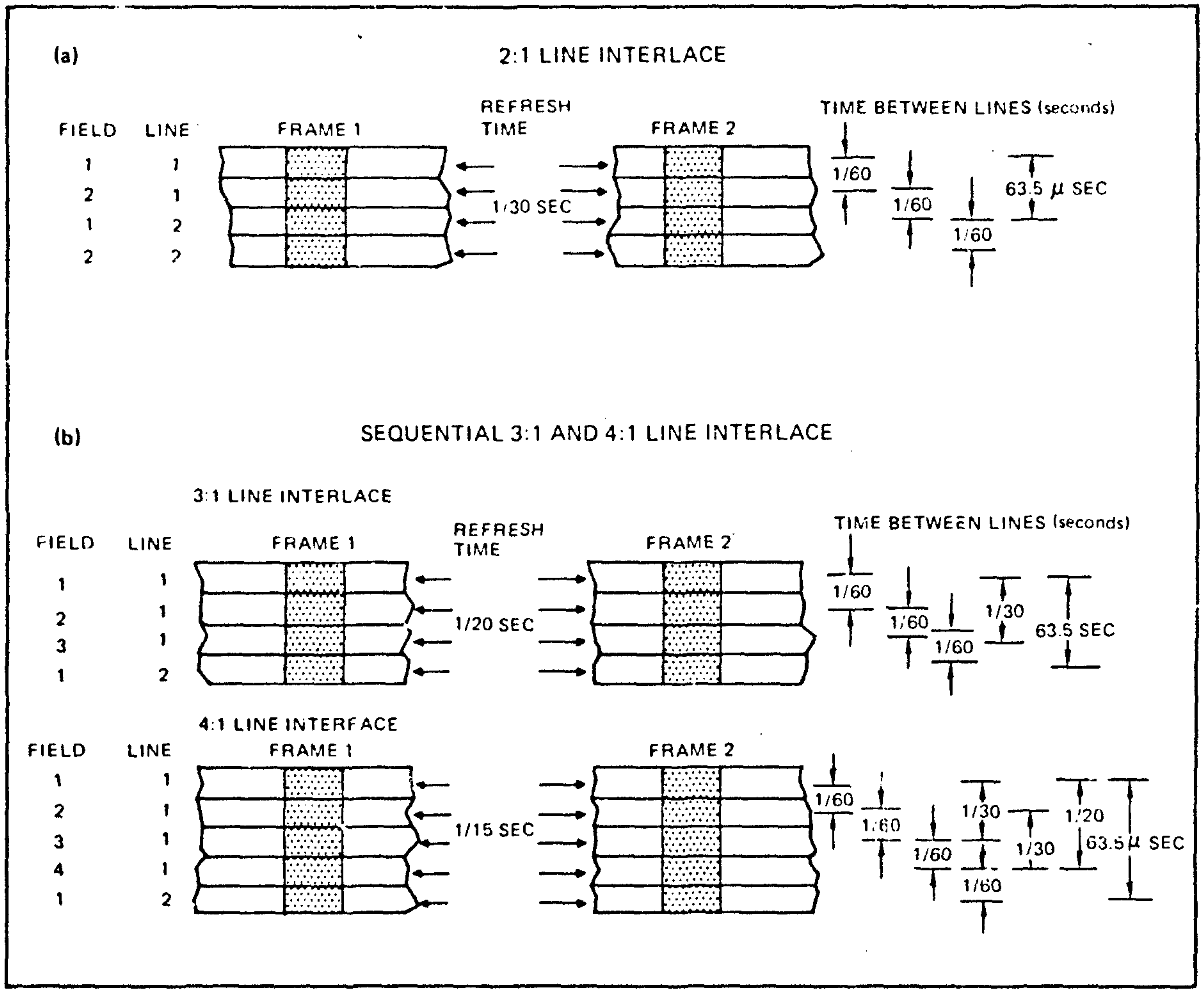


Figure 4.2-1. Relationship Between Interlace and Flicker, Line Crawl, Scintillation, and Snow (Continued) (text on preceding page)

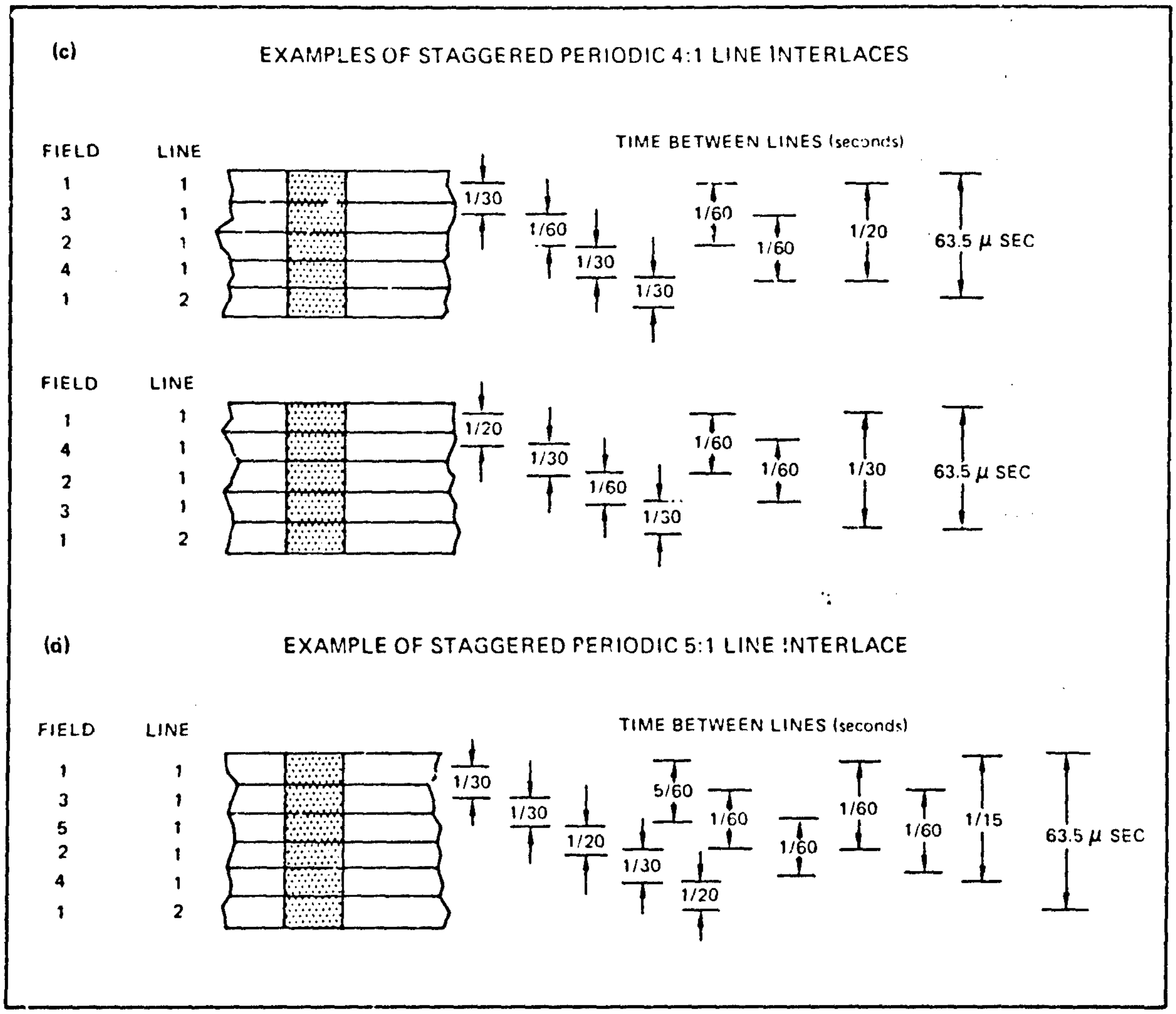


Figure 4.2-1. Relationship Between Interlace and Flicker, Line Crawl, Scintillation, and Snow (Continued)

(e)

APERIODIC 4:1 LINE INTERLACE

INTERLACE SEQUENCE (FIELD)

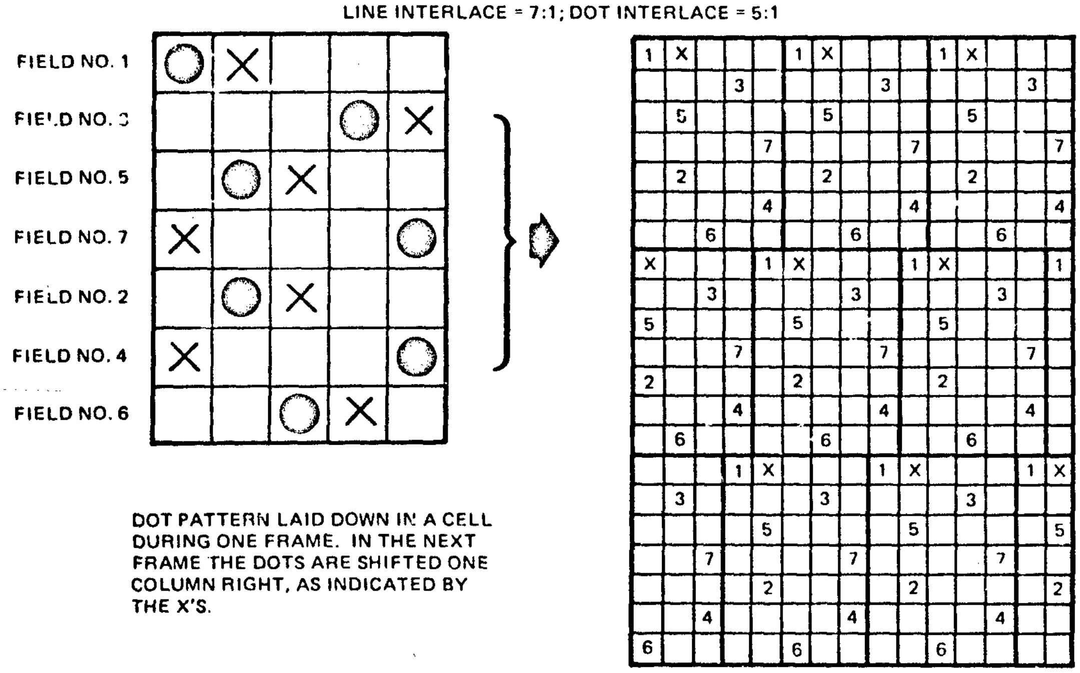
1
3
2
4
1

	TIME BETWEEN LINES	
FIELD NO.	TIME SINCE LINE ABOVE	TIME SINCE LINE BELOW
1	1 FIELD	2 FIELD
2	3 FIELD	2 FIELD
3	2 FIELD	1 FIELD
4	2 FIELD	3 FIELD

REF. 4,C

(f)

EXAMPLE OF MIXED LINE-DOT INTERLACE
LINE INTERLACE = 7:1; DOT INTERLACE = 5:1



DOT PATTERN LAID DOWN IN A CELL DURING ONE FRAME. IN THE NEXT FRAME THE DOTS ARE SHIFTED ONE COLUMN RIGHT, AS INDICATED BY THE X'S.

REF. 7, C

Figure 4.2-1. Relationship Between Interlace and Flicker, Line Crawl, Scintillation, and Snow (Continued)

SECTION 4.2 CATHODE RAY TUBE FLICKER, LINE CRAWL, AND SCINTILLATION

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION

As far as is known, no laboratory studies have been performed dealing with image interpreter performance as a function of *flicker, line crawl,* or *scintillation*. The studies that have been performed have used either subjective judgments of such things as image quality and visual annoyance, or have objectively measured the *critical fusion frequency* (CFF). (See Section 3.2.10 for a discussion of the factors contributing to CFF.) Both types will be reported here.

Two of the studies dealing with CFF did not use scanned rasters. The first of these (Figure 4.2-4) used a single line, as might be found in a graphics or alphanumeric display, and the second (Figures 4.2-5 and 4.2-6) used a single, defocused, stationary spot and changed its brightness by varying the beam current.

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

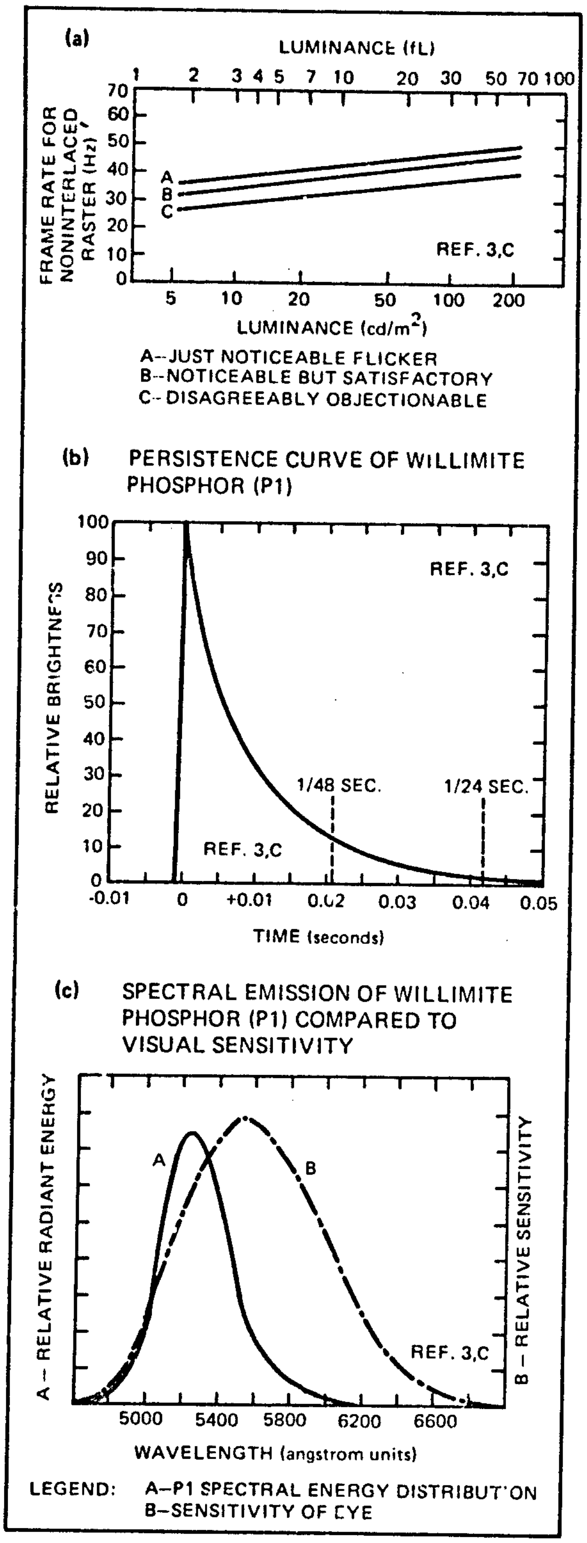


Figure 4.2-2. Effect of Field and Frame Rate for Non-Interlaced and 2:1 Line Interlaced Rasters. Figure 4.3-1(a) presents the results of an early study of flicker in raster scanned CRT's (Ref. 3,C). It is one of the few studies that could be found where line scan was employed. A 15.2-cm (6-inch) display having a willimite phosphor (P1) was used. Figure 4.3-1(b) gives the decay characteristics of this phosphor and 4.3-1(c) gives its spectral distribution. The CRT was viewed from 0.91m (3 feet) in a room with an ambient illumination of about 1.0 cd/m² (0.3 fL). The flicker was judged on a three-point scale: "just noticeable," "noticeable but satisfactory," and "disagreeably objectionable." The number of subjects was not specified.

This study was followed by two others (reported in the same reference) in which a 2:1 interlace was tested. No quantitative data was given for these latter studies. In the first study, it was found that a 24-Hz frame rate with a 48-Hz field rate satisfactorily eliminated flicker. Because of interaction with the standard U.S. power line frequency of 60 Hz, a "ripple" of brightness was created, which traveled across the image. The second study found that a 30-Hz frame rate with 60-Hz fields satisfactorily eliminated the "ripple." This was the system later adopted by the NTSC.

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

Figure 4.2-3. Effect of Dot Interlace Order and Phosphor Persistence on Flicker in Alphanumeric CRT Displays. Twenty-one different dot interlace patterns were tested using two different phosphors to determine their effects on flicker (Ref. 9,C). The authors used the term "flicker," although scintillation and snow are the usual types of problems encountered in dot scan systems. A frame was defined as the activation of each spot in the display one time and only one time. Thus frame rates and refresh rates are synonymous. A *jump scan* beam movement was used, with a maximum of 12 μsec between dot locations. For the progressive scans (numbers 18 and 20 in the accompanying table, the 2:1 interlace (numbers 4 and 14), the 4:1 interlace (numbers 7 and 16), and the half-screen interlace (numbers 19 and 21), all dots in one row for the horizontal cases, or one column for the vertical cases, were scanned before the next row was started. The sequence of rows or columns was determined by the interlace order (see Figure 4.2-1). For the dot-line system (number 1 in the table), a 4:1 dot interlace order was used with a progressive line scan; meaning that every fourth dot on a line was activated during the single space—thus four fields were required to complete the frame. The random dot scan pattern (number 12) consisted of activating the dots randomly, regardless of the scan line they fell in. A frame consisted of activating all the dots one time. Frame times and refresh times were equal.

For the matrix scans (called pseudo-random by the authors), the area of the tube comprising the message was broken into cells of dots of the sizes shown in the table, and either one or four randomly chosen points in each cell were scanned before the beam went to the next cell. In the "all points" condition, the total number of points in a cell were scanned in random order before the beam went to the next location. The apparent discrepancy between the 2x2 (4) condition, and the 2x2 (all) condition is not explained.

Two *long persistence* phosphors were studied—P12 and P38. Their published persistence curves (Ref. 2) and those measured in this study are shown in 4.3-2(b). The measured luminance of the spots used to generate the characters was 238 cd/m^2 (69.5 fL), and the background luminance was 9.5 cd/m^2 (2.8 fL). Ambient illumination was 55 footcandles.

The alphanumeric display consisted of four rows of upper-case letters, comprising a message made up of 40 letters. The type font was unspecified. The display consisted of a total of 649 dots. The viewing distance was "about 19 inches" (48.2 cm) and at that distance each spot subtended approximately 5 arc minutes at the eye. Two subjects were used, and each made 40 judgments for every interlace technique.

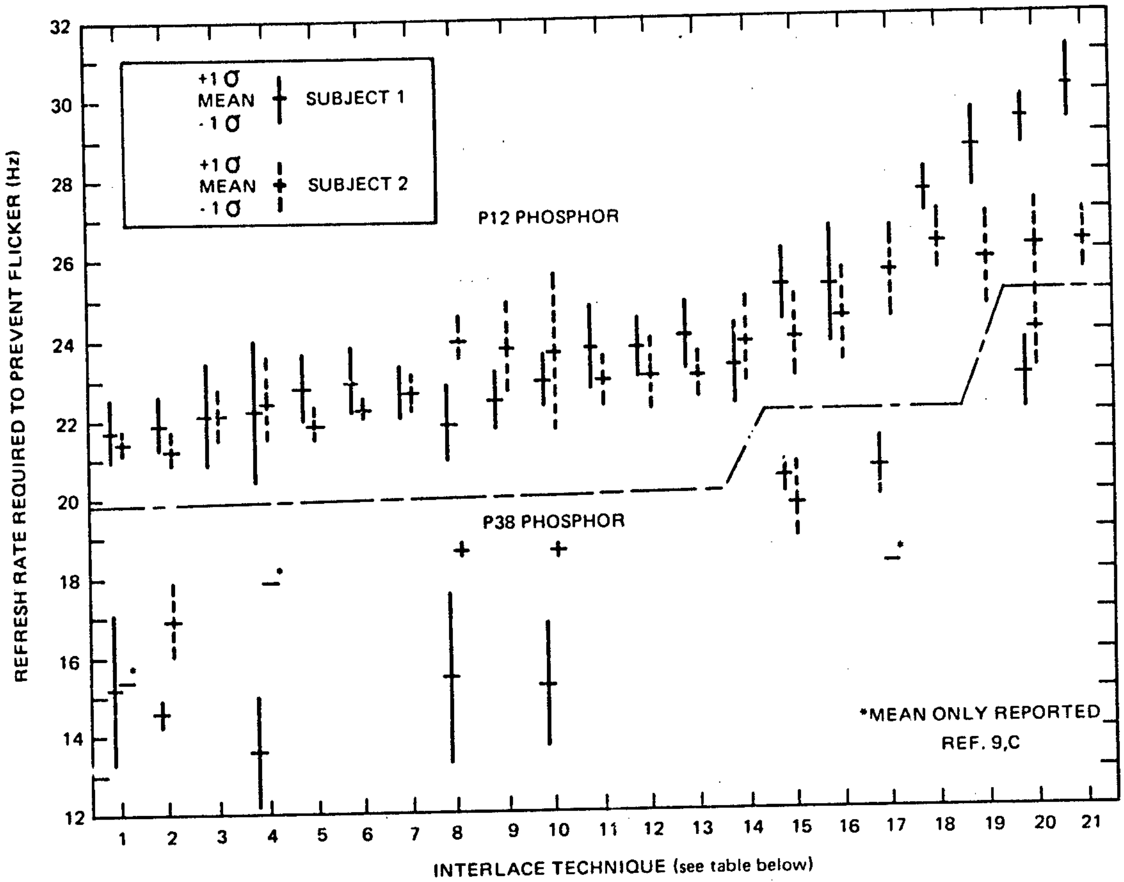
Figure 4.3-2(a) gives the means and standard deviation for the two subjects for each interlace condition. The data have been arranged for the P12 phosphor by increasing refresh rate for the combined means of the two subjects. No tests of significance were reported for this data; however, the longer persistence P38 phosphor (1.02 sec) appears to require lower refresh rates than the P12 (210 msec). It must also be noted that both of these phosphors have considerably longer decay times than the P4 used for most black-and-white CRT picture monitors (60 μsec for the yellow component of the sulfide P4).

Figure 4.3-2(c) shows the relative bandwidth requirements for each of the 21 interlace conditions using the refresh rate for the P12 phosphor under the standard 2:1 horizontal interlace as a norm. The combined means of the two subjects were used as the best estimate of the required rate.

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

(a)

INTERLACE TECHNIQUES



INTERLACE TECHNIQUES

1 DOT-LINE INTERLACE
2 MATRIX 6x6 (1)
3 MATRIX 10x10 (1)
4 2:1 LINE INTERLACE (H)
5 MATRIX 20x20 (all)
6 MATRIX 2x2 (4)
7 4:1 LINE INTERLACE (V)
8 MATRIX 2x2 (1)
9 MATRIX 10x10 (4)
10 MATRIX 20x20 (1)
11 MATRIX 6x6 (4)
12 RANDOM DOT
13 MATRIX 10x10 (all)
14 2:1 LINE INTERLACE (V)
15 MATRIX 6x6 (all)
16 4:1 LINE INTERLACE (H)
17 MATRIX 2x2 (all)
18 VERTICAL PROGRESSIVE (no line interlace)
19 ½ SCREEN INTERLACE (H)
20 HORIZONTAL PROGRESSIVE (NO LINE INTERLACE)
21 ½ SCREEN INTERLACE (V)

H = HORIZONTAL RASTER
V = VERTICAL RASTER
(NUMBERS) = NUMBER OF DOTS ACTIVATED IN MATRIX CELL BEFORE ADVANCING TO NEXT CELL

REF. 9,C

Figure 4.2-3. Effect of Dot Interlace Order and Phosphor Persistence of Flicker in Alphanumeric CRT Displays (Continued) (text on preceding page)

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

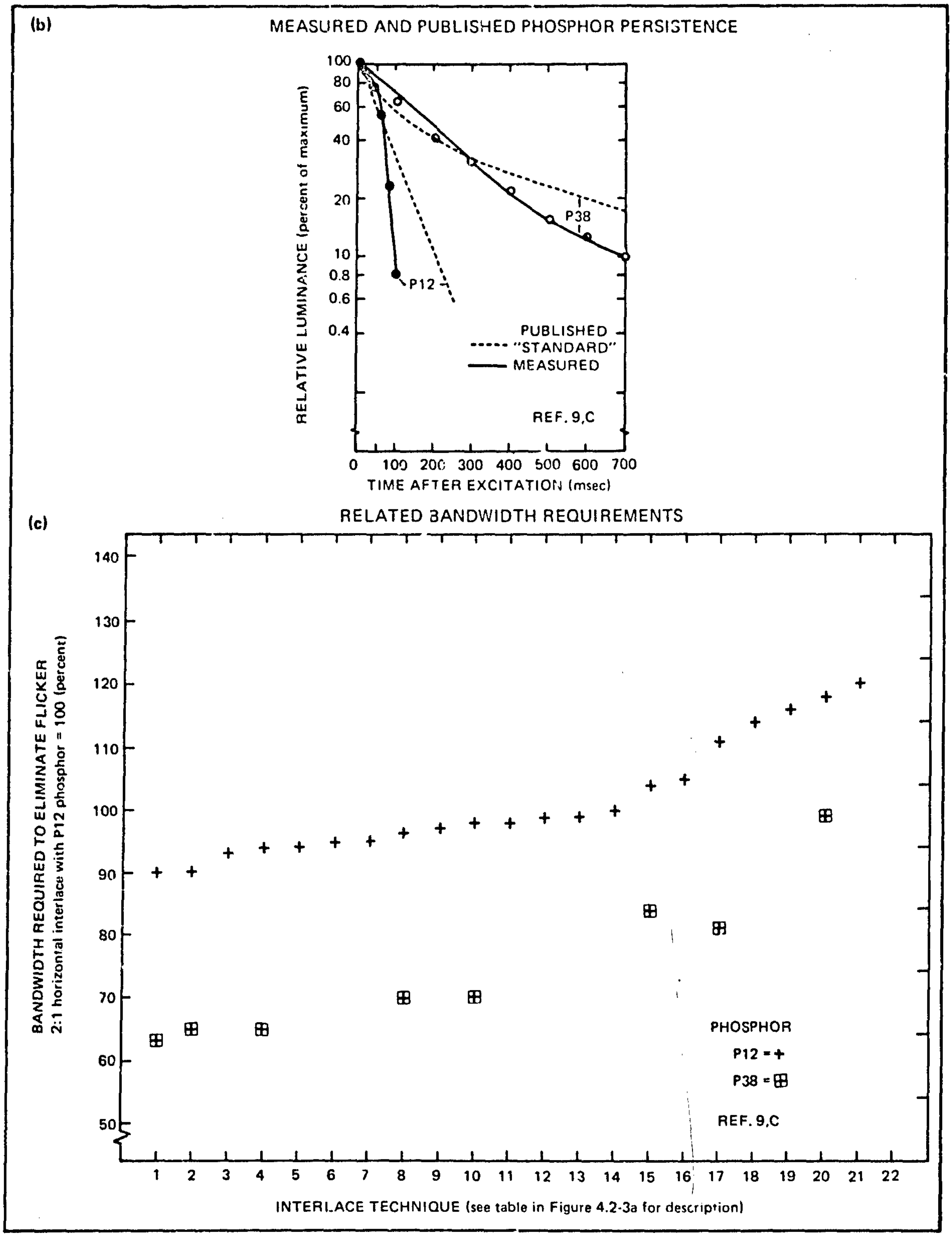
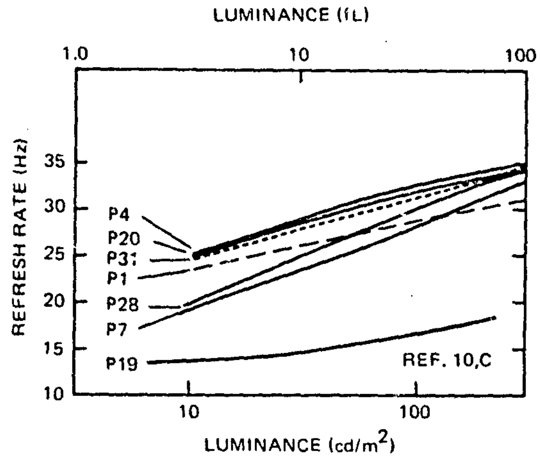


Figure 4.2-3. Effect of Dot Interlace Order and Phosphor Persistence of Flicker in Alphanumeric CRT Displays (Continued)

4.2.1 LABORATCRY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

(a) LOWEST REFRESH RATE WHICH WILL GIVE FREEDOM FROM FLICKER FOR 50% OF THE OBSERVERS



(b) LOWEST REFRESH RATE WHICH WILL GIVE FREEDOM FROM FLICKER FOR 90% OF THE OBSERVERS

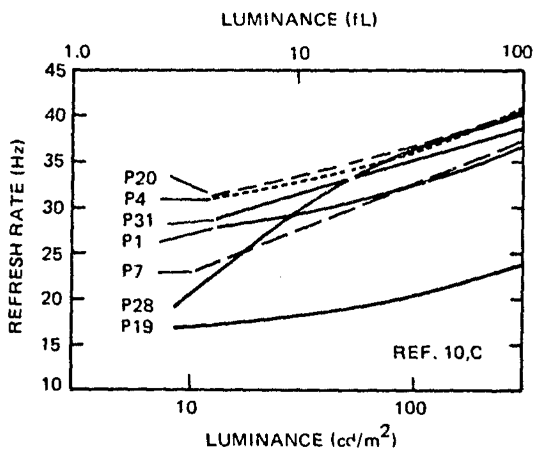


Figure 4.2-4. Flicker Suppression Refresh Rates for Single Short Lines and Several Phosphor Types. Alphanumeric characters and graphic information presented on CRT's are typically made up of single spots or relatively thin lines. The data shown here were gathered in an investigation of the refresh rate required to prevent the flicker of short line segments (Ref. 10,C). The segments were 0.02 inch wide (0.5 mm) and 0.5 inch long (12.7 mm). The viewing distance was not given so the visual angles subtended by the segment are not known. They were presented on a background of 10 cd/m^2 (3 fL). The number of observations was not stated.

The data were reported for a range of refresh rates and line brightnesses for the seven phosphor types shc ,n here.

The differing persistences of the phosphors was rejected by the author as the sole cause of the differences in refresh rates required to eliminate flicker. P28, for instance, is a long-persistence phosphor and at high brightness levels its required refresh rate is above that for P1, a medium, short-persistence phosphor. The accompanying table lists the phosphors in order from the highest to lowest refresh rate required to eliminate flicker at 171 cd/m^2 (50 fL). The suggestion is made that the high *primary flash* of the P28 may account for its unusual position in the table. "Primary flash" is a term sometimes used to describe the very bright fluorescence of a *cathode luminescent* phosphor when it is being bombarded by the electron beam of the CRT (Ref. 11).

The author also states that to prevent flicker in peripheral vision, refresh rates must be 3 to 5 Hz above the rates for the *fovea*, but no data are given to support this position. However, in support of the general statement that higher frequencies are needed to suppress flicker in the periphery as compared to the fovea, see Section 3.1.10, particularly Figure 3.2-49.

PHOSPHOR	REFRESH RATE (Hz) THRESHOLD OF AVERAGE PERSON AT (171 cd/m^2) (50 fL)	PERSISTANCE (seconds) TIME FOR BRIGHTNESS TO FALL TO 10% OF INITIAL VALUE
P4 blue component	33.5	40 sec
yellow component		12.5 msec
P20	32.7	0.05 ms to 1.8 msec
P31	32.4	38 μ sec
P28	31.4	550 msec
P7 (blue component)	29.8	43 μ sec
(yellow component)		400 msec
P1	29.2	24.5 msec
P19	17.5	220 msec
	REF. 10,C	REF. 12

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

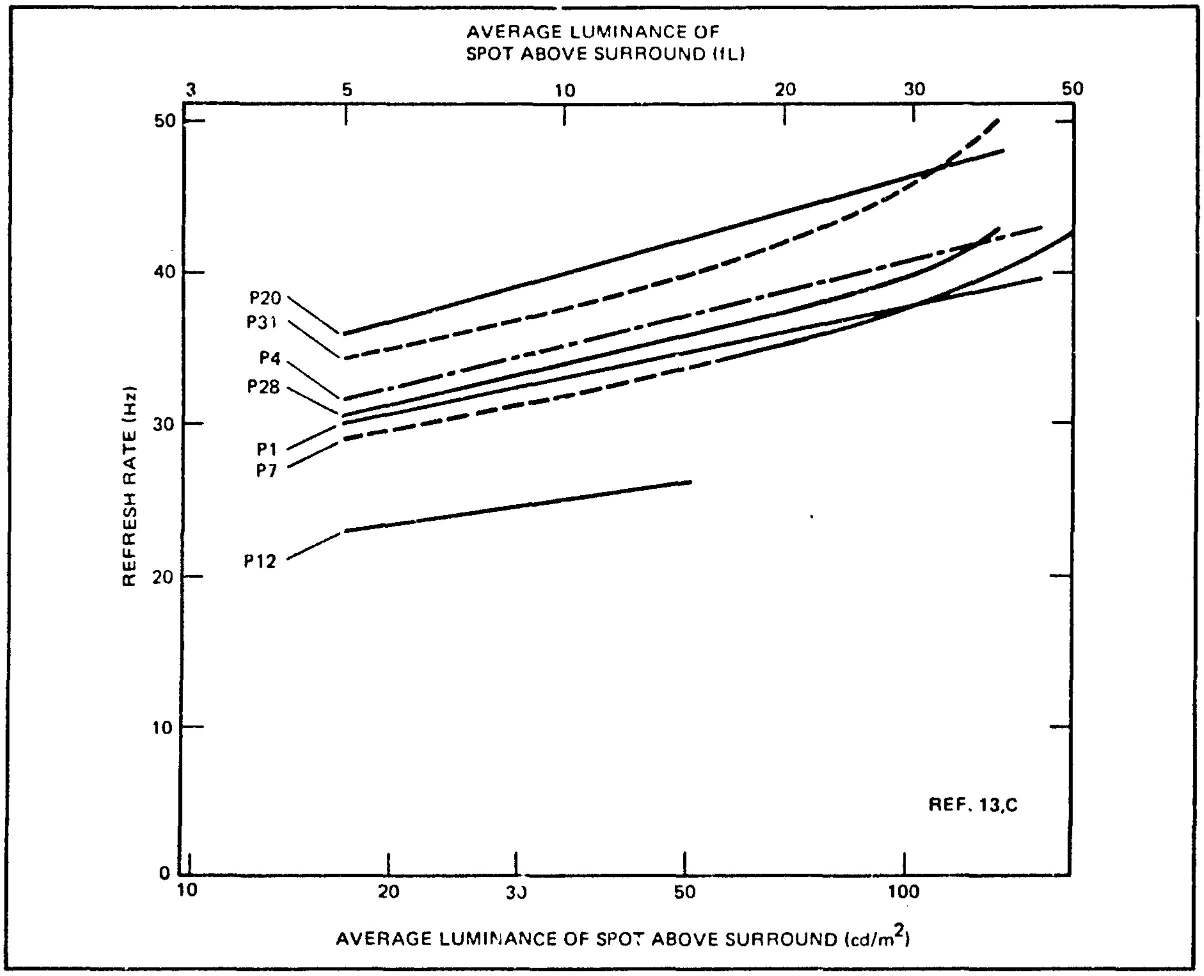


Figure 4.2-5. Flicker Suppression Refresh Rates for a Small Area and Several Phosphor Types (continued)

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

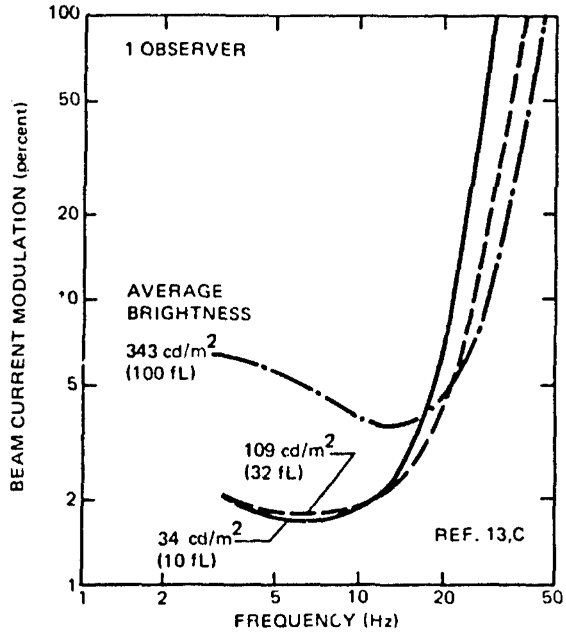
PHOSPHOR	REFRESH RATE REQUIRED TO ELIMINATE FLICKER (Hz)		PUBLISHED PERSISTENCE *
	34 cd/m^2 (10 fL)	100 cd/m^2 (30 fL)	
P12	26.5	—	210 msec
P7 (yellow component)	31.3	37.7	400 msec
P1	33.2	37.0	24.5 msec
P28	34.0	39.7	550 msec (measured >2 msec)
P4 (silicate)	35.3	40.5	
(blue component)			40 μ sec
(yellow component)			12.5 msec
P31	37.5	46.0	38 μ sec
P20	40.3	47.3	0.05 msec to 1.8 msec
	REF. 13,C	REF. 13,C	REF. 12

* REF. 13

**DECAY TIME IS A FUNCTION OF BEAM CURRENT

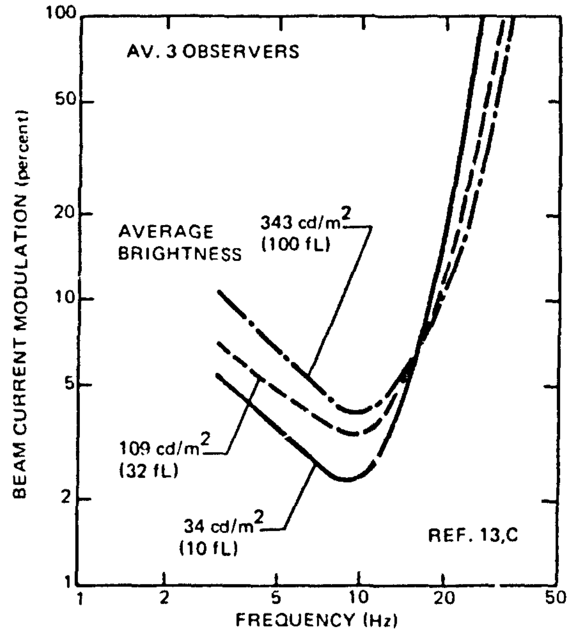
Figure 4.2-5. Flicker Suppression Refresh Rates for a Small Area and Several Phosphor Types. The refresh rates reported in this figure were obtained using a single illuminated area 3.8 mm (5/32 in) in diameter and a beam having a 2-percent duty cycle (Ref. 13,C). This area was defined by a hole in a mask placed over the face of the tube. The area was activated by a stationary beam that had been defocused sufficiently to form a large spot. The area around the spot reflected 10 cd/m^2 (3 fL) from the ambient room illumination. The background luminance produced by reflection of the ambient light from the face of the tube was not reported. All luminance values except the maximum were obtained by placing neutral density filters in the opening of the mask. The viewing distance was 30 cm (12 in) to 38 cm (15 in) making the target subtense visual angle of between 36 arc minutes and 44 arc minutes. The data shown here are the averages for three observers. The number of observations for each is not reported. Published decay times are given in the accompanying table. The displacement of the P28 phosphor relative to its published decay times led the author to measure the sample he had. He found a 2 msec rather than the published 550 msec decay time.

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)



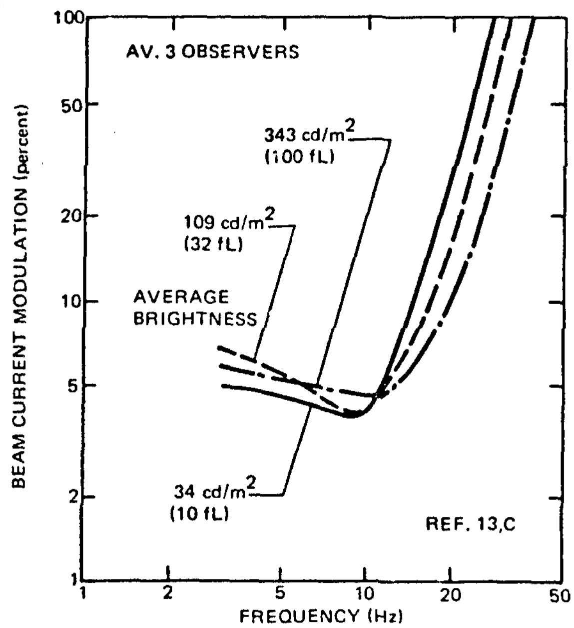
SINE MODULATION CRITICAL FLICKER FREQUENCY FOR PHOSPHOR P31

DECAY TIME = 38 μSEC



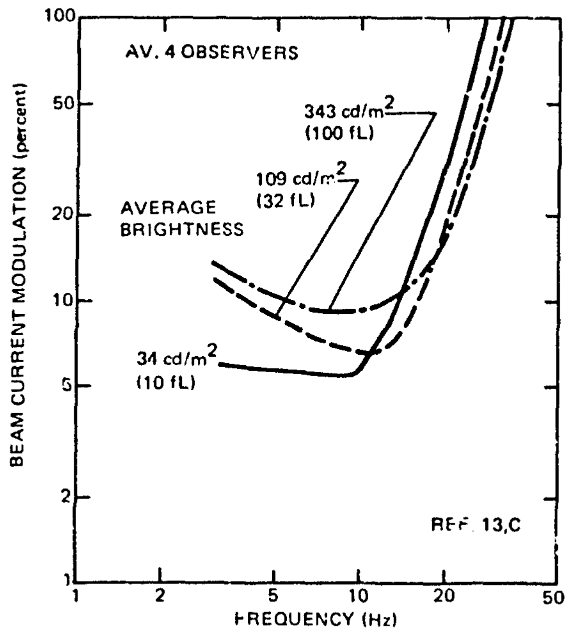
SINE MODULATION CRITICAL FLICKER FREQUENCY FOR SILICATE P4

DECAY TIME = 40 μSEC FOR BLUE COMPONENT
12.5 MSEC FOR YELLOW COMPONENT



SINE MODULATION CRITICAL FLICKER FREQUENCY FOR PHOSPHOR P7

DECAY TIME = 400 μSEC FOR YELLOW COMPONENT



SINE MODULATION CRITICAL FLICKER FREQUENCY FOR PHOSPHOR P1

DECAY TIME = 24.5 MSEC

Figure 4.2-6. CRT Flicker as a Function of Beam Modulation and Phosphor Type (Continued)

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

Figure 4.2-6. CRT Flicker as a Function of Beam Modulation and Phosphor Type. The conditions of this study were the same as for those reported in the previous figure except that the CRT beam current was modulated sinusoidally at various amplitudes rather than pulsed on and off (Ref. 13,C). The illuminated area was a 0.39-cm (5/32-in) circular opening in a mask placed over the CRT faceplate. The luminances reported are the average for the sine-wave modulation ([maximum + minimum]/2). Except for the highest average luminance, all others were obtained by placing neutral density filters in the mask opening. The area around the mask opening reflected 10 cd/m^2 (3 fL) from the ambient room illumination. The viewing distance was between 30 cm (12 in) and 38 cm (15 in), making the target subtend a visual angle of between 36 arc minutes and 44 arc minutes.

Seven phosphors were tested having a range of persistence from 38 μsec to 550 msec. They were the same seven reported in the previous figure, P1, P4, P7, P12, P20, P28, and P31. Persistence times for all seven can be found in that figure.

The results for four of the phosphors are reported here. As with the pulse modulated beam of the previous figure, the frequency needed to suppress flicker was strongly dependent upon the phosphor persistence.

*

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

5:1 LINE INTERLACE

LINE POSITION ON DISPLAY FOR EACH FIELD

SEQUENTIAL FIELD SEPARATION (lines)			
1	2	3	4
1	2	3	4
2	4	3	4
3	2	5	3
4	5	2	5
5	3	4	2
1	1	1	1

7:1 INTERLACE

LINE POSITION ON DISPLAY FOR EACH FIELD

SEQUENTIAL FIELD SEPARATION (lines)					
1	2	3	4	5	6
1	1	1	1	1	1
2	5	6	3	4	3
3	2	4	5	7	4
4	6	2	7	3	5
5	3	7	2	6	4
6	7	5	4	3	2
7	4	3	6	5	2
1	1	1	1	1	1

8:1 INTERLACE

LINE POSITION ON DISPLAY FOR EACH FIELD

SEQUENTIAL FIELD SEPARATION (lines)						
1	2	3	4	5	6	7
1	1,5	1	1,3,5,7	1	1,5	1
2		4		1		8
3	2,6	7		3	2,6	7
4		2		8		6
5	3,7	5	2,4,6,8	6	3,7	5
6		8		2		4
7	4,8	3		7	4,8	3
8		6		5		2

REF. 4, C

Figure 4.2-7. Effect of Sequential and Staggered Interlace on Flicker and Line Crawl

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

Figure 4.2-7. Effect of Sequential and Staggered Interlace on Flicker and Line Crawl. All higher order sequential line-interlaced rasters have unacceptable line crawl characteristics. To prevent line crawl, certain staggered sequences have been found better than others, particularly when long persistence phosphors such as P38 are used in the CRT. The data presented here are from Ref. 4,C. Sequential scanning is illustrated in the first column of each of the accompanying diagrams. The lines from sequential fields are arranged spatially in order by the time sequence of the fields. The other columns represent staggered orders that are periodic. For even-order systems, staggered spacing which have common denominators with the interlace order result in duplications of lower order interlace relationships. Figure 4.3-3(c) illustrates this situation. For the 8:1 interlace sequential field, separations of two and six lines result in interlaces that duplicate a 4:1 system, and a separation of four lines duplicates a 2:1 system.

The results of observations on CRT's having *flat field* luminance showed that line crawl even for short persistence phosphors can be greatly reduced by a staggered interlace in which sequential fields are written as close to N/2 lines apart as the interlace order will permit. (N = interlace order.) For instance, for a 5:1 interlace, 5/2 = 2.5. Since the separation of the lines must be a whole number in order to prevent line overlap, either 2 or 3 must be chosen, and will result in the least objectionable line crawl. For the long persistence phosphor screen tested, P38, a 2-1/2 times increase in subjective resolution was reported for the 3-line spaced, 5:1 interlace over the 2:1 interlace. The increase was less, but not specified for the P4 screen.

Little improvement in resolution was reported for 7:1 and 8:1 interlace orders over 5:1. 7:1 looked slightly better on the long persistence screen (P38), and 5:1 looked better on the short persistence screen because of reduced scintillation. It was reported that there was "little" large-field flicker on the P4 screen. Highlight brightness was measured at 34 cd/m^2 (10 fL) in a darkened room and 343 cd/m^2 (100 fL) in a "well illuminated laboratory." Observers were "about a dozen" of the author's associates. In interpreting these results, it must be kept in mind that long persistence phosphors are not suitable for displaying moving images. The persistence causes the image to smear.

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

SUBJECTIVE ASSESSMENT OF DOT INTERLACE ORDERS
FOR 2:1 LINE INTERLACE FOR R = 1

A ↓	B ↓	A →	3	3	4	4	5	5	5	5	7	7	7	7	7	7	8	8	8	8
		C →	1	2	1	3	1	2	3	4	1	2	3	4	5	6	1	3	5	7
3	1,2		+	+																
4	2				+	+														
5	1,4						-	+	+	-										
5	2,3						?	?	?	?										
7	1,6										-	+	?	?	+	-				
7	2,5										-	?	?	?	?	-				
7	3,4										?	-	+	+	-	?				
8	2,6																?	+	+	?
8	4																L+	L+	L+	L+

LEGEND:

A = DOT INTERLACE ORDER
B = REMAINDER FROM DIVISION; NUMBER OF DOTS PER LINE / DOT INTERLACE ORDER
C = REMAINDER FROM DIVISION; NUMBER OF LINES PER FRAME / DOT INTERLACE ORDER
R = REMAINDER FROM DIVISION; NUMBER OF LINES PER FRAME / LINE INTERLACE ORDER
\+ = ACCEPTABLE
\- = UNACCEPTABLE
? = BORDERLINE
L+ = SAME AS ACCEPTABLE LOWER ORDER CASE
L- = SAME AS UNACCEPTABLE LOWER ORDER CASE

REF. 7,C

Figure 4.2-8. Subjective Assessment of Dot Interlace for 2:1 Line Interlace When R = 1 (continued)

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

Figure 4.2-8: Subjective Assessment of Dot Interlace for 2:1 Line Interlace when R = 1. This figure and the five following it (Figures 4.2-9 through 4.2-13) show the judged acceptability for various combinations of line and dot interlace ratios in high-order line-dot interlace systems, using a long persistence (P38) phosphor. Systems up to 7:1 line interlace and 5:1 dot interlace are covered. The acceptability of specific combinations was judged by a small group of technical personnel. No information was provided on the number of observers, their experience, the number of judgments made by each, or the viewing distance (Ref. 7,C). The technique for using the charts in each figure is detailed here. The remainder of the figures have numerical examples to assist the reader in their use.

To use the charts, it is necessary to calculate values for the terms A, B, C, and R. B is calculated using the formula:

$$B = \frac{\text{number of dots per line}}{\text{dot interlace order}}$$

C is found by the formula:

$$C = \frac{\text{number of lines per frame}}{\text{dot interlace order}}$$

The number of dots per line, assuming equal horizontal and vertical resolution, is 4/3 x the number of active TV lines per frame, and is expressed as a whole number.

A is the dot interlace order.

R is the numerator of the remainder from the division:

$$\frac{\text{Number of active lines per frame}}{\text{Line interlace order}}$$

In using the tables in this and the following figures, it is well to calculate R first, because data are not given for some values of R, therefore no information on the acceptability of the interlace orders for such values is available.

The following is an example of the method of using the chart. A TV system of 493 active lines is assumed with interlace orders of 2:1 for the line interlace and 5:1 for the dot interlace. For such a system, R is found by:

$$\frac{493}{2} = 246\tfrac{1}{2}; \text{ therefore } R = 1$$

The heading at the top of the table indicates that it can be used for this value of R.

For this example:

Dots per line = 4/3 x 493 = 657.3 = 657 (rounded)

B is the remainder of the division:

$$\frac{657}{5} = 131\ 2/5, \text{ therefore } B = 2$$

C is the remainder of the division:

$$\frac{493}{5} = 98\ 3/5; \text{ therefore, } C = 3$$

To find the judged acceptability of such a system, the table is entered at line A5-B2 and column A5-C3, as shown on the chart. A "?" is found at the intersections o these lines, indicating that this line-dot interlace system was found to have borderline acceptability from the standpoint of line flicker, line crawl, and snow.

The judgments of acceptability were made on a CRT mo itor having a P38 phosphor and have questionable applic bility to phosphors with shorter persistence. Alphanumeric material was displayed on the screen that had approximately 15 scan lines per character height. Highlight brightness was 10 cd/m^2 (3 fL), and observations were made in a "darkened room." A 60-Hz field rate wa used. Frame rates depend upon the dot interlace order and can be found by multiplying the dot interlace order by the line interlace order and dividing the field rate by the product. For example for a 5:1 dot interlace and the 3:1 line interlace:

$$\frac{60}{5(3)} = \frac{60}{15} = 4 \text{ Hz}$$

Tables for other line interlace orders and R values are given as follows:

Line interlace order	R values	Figure
3:1	1 and 2	4.2-9
4:1	1 and 3	4.2-10
5:1	2 and 3	4.2-11
7:1	2 and 5	4.2-12
7:1	3 and 4	4.2-13

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

SUBJECTIVE ASSESSMENT OF DOT INTERLACE ORDERS
FOR 3:1 LINE INTERLACE
(if R = 1, use C_1; if R = 2, use C_2)

A ↓	B ↓	A →	2	4	4	4	5	5	5	5	7	7	7	7	7	7	8	8	8	8	8	8	8
		C_1 →	1	1	2	3	1	2	3	4	1	2	3	4	5	6	1	2	3	4	5	6	7
		C_2 →	1	3	2	1	4	3	2	1	6	5	4	3	2	1	7	6	5	4	3	2	1
2	1		+																				
4	1,3			-	+	+																	
4	2			L+	L+	L+																	
5	1,4						-	?	-	?													
5	2,3						?	-	+	+													
7											-	+	-	?	-	?							
7	2,5										-	-	-	-	+	+							
7	3,4										-	-	?	+	-	?							
8	1,7																-	+	?	L-	?	+	?
8	2,6																L-	L+	L+	L-	L-	L+	L+
8	3,5																?	+	-	L-	?	+	?
8	4																L+	L-	L+	L-	L+	L-	L+

LEGEND:

A = DOT INTERLACE ORDER

B = REMAINDER FROM DIVISION: $\frac{\text{NUMBER OF DOTS PER LINE}}{\text{DOT INTERLACE ORDER}}$

C1, C2 = REMAINDER FROM DIVISION: $\frac{\text{NUMBER OF LINES PER FRAME}}{\text{DOT INTERLACE ORDER}}$

R = REMAINDER FROM DIVISION: $\frac{\text{NUMBER OF LINES PER FRAME}}{\text{LINE INTERLACE ORDER}}$

+ = ACCEPTABLE
- = UNACCEPTABLE
? = BORDERLINE
L+ = SAME AS ACCEPTABLE LOWER ORDER CASE
L- = SAME AS UNACCEPTABLE LOWER ORDER CASE

REF. 7, C

Figure 4.2-9. Subjective Assessment of Dot Interlace for 3:1 Line Interlace when R = 1 or R = 2

A numerical example of how to use this table is given below. For a complete description of the calculations, see Figure 4.2-8. The system used for this example has 493 active TV lines, a 3:1 line interlace ratio, and a 5:1 dot interlace ratio, and a 60-Hz field rate and a 4:3 aspect ratio, therefore:

Dots per line = 4/3 x 493 = 657

(The rounded whole number is used)

For B: $\frac{657}{5}$ = 131 2/5 therefore B = 2

For C: $\frac{493}{5}$ = 98 3/5 therefore C = 3

For R: $\frac{493}{3}$ = 164 1/3 therefore R = 1

for the frame rate:

$$\frac{60}{5(3)} = \frac{60}{15} = 4 \text{ Hz}$$

In using the table, it will be noted that some row entries under B have two numbers. These rows are to be used for either of these numbers. Since R = 1 in the example above, the entries under the column labeled C1 are to be used. The acceptability of the system in this example is shown by the symbol at the intersection of row A5-B2 and column A5-$C_1$3, as shown in the chart.

Caution: The results shown in the chart are for a long persistence phosphor (P38) and have questionable applicability for phosphors of shorter persistence.

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

SUBJECTIVE ASSESSMENT OF DOT INTERLACE ORDERS
FOR 4.1 LINE INTERLACE (if R - 1, use C_1, if R = 3, use C_2)

A ↓	B ↓														
	A →	3	3	5	5	5	5	7	7	7	7	7	7	8	8
	C_1 →	1	2	1	2	3	4	1	2	3	4	5	6	1	5
	C_2 →	2	1	4	3	2	1	6	5	4	3	2	1	7	3
3	1,2	?	+												
5	1,4			-	?	+	+								
5	2,3			?	+	-	?								
7	1,6							-	?	?	-	?	?		
7	2,5							-	-	-	?	?	-		
7	3,4							-	-	+	?	+	?		
8	4													?	+

LEGEND:

A = DOT INTERLACE ORDER

B = REMAINDER FROM DIVISION; $\frac{\text{NUMBER OF DOTS PER LINE}}{\text{DOT INTERLACE ORDER}}$

C_1, C_2 = REMAINDER FROM DIVISION; $\frac{\text{NUMBER OF LINES PER FRAME}}{\text{DOT INTERLACE ORDER}}$

R = REMAINDER FROM DIVISION; $\frac{\text{NUMBER OF LINES PER FRAME}}{\text{LINE INTERLACE ORDER}}$

+ = ACCEPTABLE
- = UNACCEPTABLE
? = BORDERLINE
L+ = SAME AS ACCEPTABLE LOWER ORDER CASE
L- = SAME AS UNACCEPTABLE LOWER ORDER CASE

REF. 7, C

Figure 4.2-10. Subjective Assessment of Dot Interlace for 4:1 Line Interlace When R = 1 or R = 3

A numerical example of how to use this table is given below. For a complete description of the calculations, see Figure 4.2-9. The system used for this example has 493 active TV lines, a 4:1 interlace ratio, and a 5:1 dot interlace ratio, and a 60 Hz field rate and a 4:3 aspect ratio. Therefore:

For R: $\frac{493}{4}$ = 123 1/4; therefore, R = 1. Checking the table it is found that the table can be used for this value of R.

Dots per line = 4/3 x 493 = 657

for B, $\frac{657}{5}$ = 131 2/5, therefore, B = 2

for C, $\frac{493}{5}$ = 98 3/5, therefore, C = 3.

In using the table, it will be noted that some row entries under B have two numbers. These rows are to be used for either of these numbers. Since R = 1 in the example above, the entries under the column labeled C1 are to be used. The acceptability of the system in this example is shown by the symbol at the intersection of row A5-B2 and column A5-$C_1$3, as shown in the chart.

Caution: The results shown in the chart are for a long persistence phosphor (P38) and have questionable applicability for phosphors of shorter persistence (Ref. 7,C).

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

SUBJECTIVE ASSESSMENT OF DOT INTERLACE ORDERS
FOR 5:1 LINE INTERLACE (if R = 2, use C_1; if R = 3, use C_2)

A ↓	B ↓																								
A →		2	3	3	4	4	4	6	6	6	6	6	7	7	7	7	7	7	8	8	8	8	8	8	8
C_1 →		1	1	2	1	2	3	1	2	3	4	5	1	2	3	4	5	6	1	2	3	4	5	6	7
C_2 →			2	1	3	2	1	5	4	3	2	1	6	5	4	3	2	1	7	6	5	4	3	2	1
2	1	+																							
3	1,2		-	?																					
4	1,3				?	-	-																		
4	2				L+	L-	L+																		
6	1,5							+	-	-	+	?													
6	2,4							L-	L-	L-	L-	L-													
6	3							L+	L+	L+	L+	L+													
7	1,6												?	-	?	-	-	+							
7	2,5												+	?	-	?	·	?							
7	3,4												-	?	-	?	-	?							
8	1,7																		-	-	?	L-	-	+	?
8	3,5																		+	+	-	L-	+	+	?
8	4																		L+	L-	L+	L-	L+	L-	L+

LEGEND:

A = DOT INTERLACE ORDER

B = REMAINDER FROM DIVISION; $\frac{\text{NUMBER OF DOTS PER LINE}}{\text{DOT INTERLACE ORDER}}$

C_1, C_2 = REMAINDER FROM DIVISION; $\frac{\text{NUMBER OF LINES PER FRAME}}{\text{DOT INTERLACE ORDER}}$

R = REMAINDER FROM DIVISION; $\frac{\text{NUMBER OF LINES PER FRAME}}{\text{LINE INTERLACE ORDER}}$

+ = ACCEPTABLE
- = UNACCEPTABLE
? = BORDERLINE
L+ = SAME AS ACCEPTABLE LOWER ORDER CASE
L- = SAME AS UNACCEPTABLE LOWER ORDER CASE

REF. 7, C

Figure 4.2-11. Subjective Assessment of Dot Interlace for 5:1 Line Interlace When R = 2 or R = 3

A numerical example of how to use this table is given below. For a complete description of the calculations, see Figure 4.2-8. The system used for this example has 493 active TV lines, a 5:1 interlace ratio, and a 6:1 dot interlace ratio, and a 60-Hz field rate, and a 4:3 aspect ratio. Therefore:

For R: $\frac{493}{5}$ = 98 3/5; therefore, R = 3

Dots per line = 4/3 x 493 = 657

For B: $\frac{657}{6}$ = 109 3/6; therefore, B = 3

For C: $\frac{493}{6}$ = 82 1/6; therefore, C = 1

In using the table it will be noted that some row entries under B have two numbers. These rows are to be used for either of these numbers. Since R = 3 in the example above, the entries under the column labeled C_2 are to be used. The acceptability of the system in this example is shown by the symbol at the intersection of row A6-B3 and column A6-$C_2$1, as shown by the dotted lines in the chart.

Caution: The results shown in the chart are for a long persistence phosphor (P38) and have questionable applicability for phosphors of shorter persistence (Ref. 7,C).

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

SUBJECTIVE ASSESSMENT OF DOT INTERLACE ORDERS
FOR 7:1 LINE INTERLACE (if R = 2, use C_1; if R = 5, use C_2)

A ↓	B ↓										
A →		2	3	3	4	4	4	5	5	5	5
	C_1 →	1	1	2	1	2	3	1	2	3	4
	C_2 →		2	1	3	2	1	4	3	2	1
2	1	+									
3	1,2		+	?							
4	1,3				-	-	+				
4	2				L+	L-	L+				
5	1,4							+	-	?	-
5	2,3							-	?	-	+

LEGEND:

A = DOT INTERLACE ORDER

B = REMAINDER FROM DIVISION; $\frac{\text{NUMBER OF DOTS PER LINE}}{\text{DOT INTERLACE ORDER}}$

C_1, C_2 = REMAINDER FROM DIVISION; $\frac{\text{NUMBER OF LINES PER FRAME}}{\text{DOT INTERLACE ORDER}}$

R = REMAINDER FROM DIVISION; $\frac{\text{NUMBER OF LINES PER FRAME}}{\text{LINE INTERLACE ORDER}}$

+ = ACCEPTABLE
- = UNACCEPTABLE
? = BORDERLINE
L+ = SAME AS ACCEPTABLE LOWER ORDER CASE
L- = SAME AS UNACCEPTABLE LOWER ORDER CASE

REF. 7, C

Figure 4.2-12. Subjective Assessment of Dot Interlace for 7:1 Line Interlace When R = 2 or R = 5

A numerical example of how to use this table is given below. For a complete description of the calculations, see Figure 4.2-8. The system used for this example has 492 active TV lines, a 7:1 interlace ratio, and 5:1 dot interlace ratio, and a 60-Hz field rate, and a 4:3 aspect ratio. Therefore:

For R: $\frac{492}{7}$ = 70 2/7; therefore, R = 2

Dots per line = 4/3 x 492 = 656

For B: $\frac{656}{5}$ = 131 1/5; therefore, B = 1

For C: $\frac{492}{5}$ = 98 2/5; therefore, C = 2

In using the table, it will be noted that some row entries under B have two numbers. These rows are to be used for either of these numbers. Since R = 2 in the example above, the entries under the column labeled C_1 are to be used. The acceptability of the system in this example is shown by the symbol at the intersection of row A5-B1 and column A5-$C_1$2 as shown in the chart.

If R had been equal to 3 or 4, the chart in Figure 4.3-13 would have been used.

Caution: The results shown in the chart are for a long persistence phosphor (P38) and have questionable applicability for phosphors of shorter persistence (Ref. 7,C).

4.2.1 LABORATORY STUDIES ON CRT FLICKER, LINE CRAWL, AND SCINTILLATION (CONTINUED)

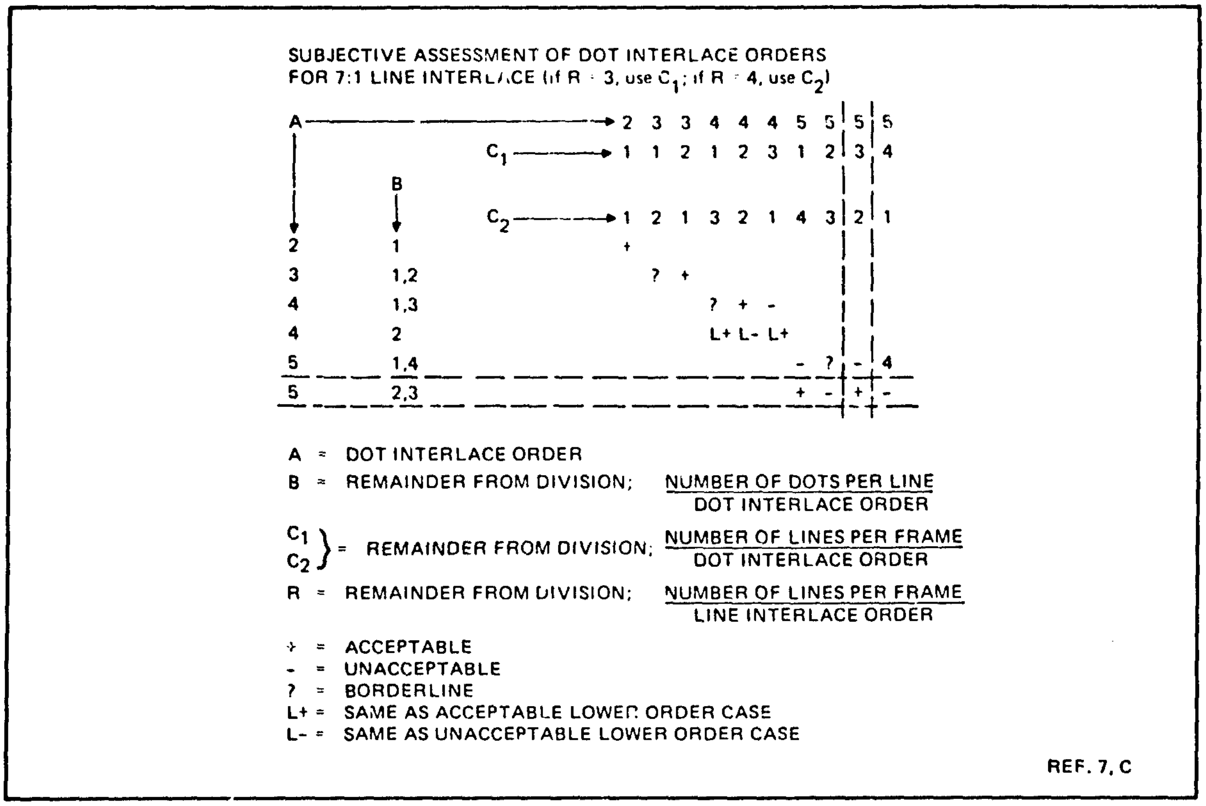


Figure 4.2-13. Subjective Assessment of Dot Interlace for 7:1 Line Interlace When R = 3 or R = 4

A numerical example of how to use this table is given below. For a complete description of the calculations, see Figure 4.2-8. The system used for this example has 493 active TV lines, a 7:1 interlace ratio, a 5:1 dot interlace ratio, and a 60-Hz field rate, and a 4:3 aspect ratio. Therefore:

For R: $\frac{493}{7} = 70\ 3/7$, therefore R = 3

Dots per line $= 4/3 \times 493 = 657$

For B: $\frac{657}{5} = 131\ 2/5$; therefore, B = 2

For C: $\frac{493}{5} = 98\ 3/5$; therefore, C = 3

In using the table, it will be noted that some row entries under B have two numbers. These rows are to be used for either of these numbers. Since R = 3 in the example above, the entries under the column labeled C_1 are to be used. The acceptability of the system in this example is shown by the symbol at the intersection of row A5-B2 and column A5-$C_1$3, as shown in the chart.

Caution: The results shown in the chart are for a long persistence phosphor (P38) and have questionable applicability for phosphors of shorter persistence (Ref. 7.C).

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SECTION 4.3 DATA FROM LABORATORY STUDIES ON SAMPLED IMAGERY

The data presented in this section are intended to help the designer or purchaser of electro-optical imaging equipment understand the effect that various levels of equipment performance has on the quality and usefulness of the imagery which is produced. To this end laboratory data on interpreter performance and image quality are presented here. Unfortunately, the information is fragmented and of very uneven quality. No good body of experimental data exists that encompasses the range of information needed. Even with the data available, it is frequently impossible to relate, with any accuracy, the results of different studies on the same topic. Whenever possible, the reported data have been put in common units. In some cases this was impossible because the method of deriving the units reported was not given or data on the levels of one or more basic operating parameters were not given. For these reasons it is often impossible to make quantitative comparisons among the studies; however, the qualitative comparisons, while not so desirable as quantitative ones, can provide insight and guidance in many cases.

Frequently, the data have been collected to support real-time reconnaisance studies and involve moving imagery and high obliquity angles. The results of several such studies have been included because they augment areas where information is scarce.

Some of the studies which are reported are from image-quality research conducted by the broadcast television industry, where the goal is to produce picture quality adequate to meet the needs of home entertainment. Translating from such a quality base to information content is a suspect procedure, but in some instances (where no other data are available) at least trends, and perhaps general limits, can be set. Because reliance on the results of only one study could be misleading, a larger number of studies have been included on some topics in order to obtain a more representative range of results.

For each topic, the data obtained from some measure of objective performance using CRT imagery are presented first, followed by data from subjective CRT image quality studies. Data from studies using transparencies made on line-scan image generators are presented last. Data acquired under low-light-level conditions have not been included.

4.3.1 BANDWIDTH AND RESOLUTION

These two topics are treated together because of their interdependence. Interlace and quantizing levels, which also are closely related to bandwidth and resolution, are reported separately in Section 4.3.4 to simplify the organization of the material. One of the most valuable observations to be gained from the data presented here is that bandwidth *per se* is not a good single factor by which the potential value of the system can be judged. The performance of the system as a whole is determined by the interaction of many elements, any of which can degrade the potential advantages of increased bandwidth.

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

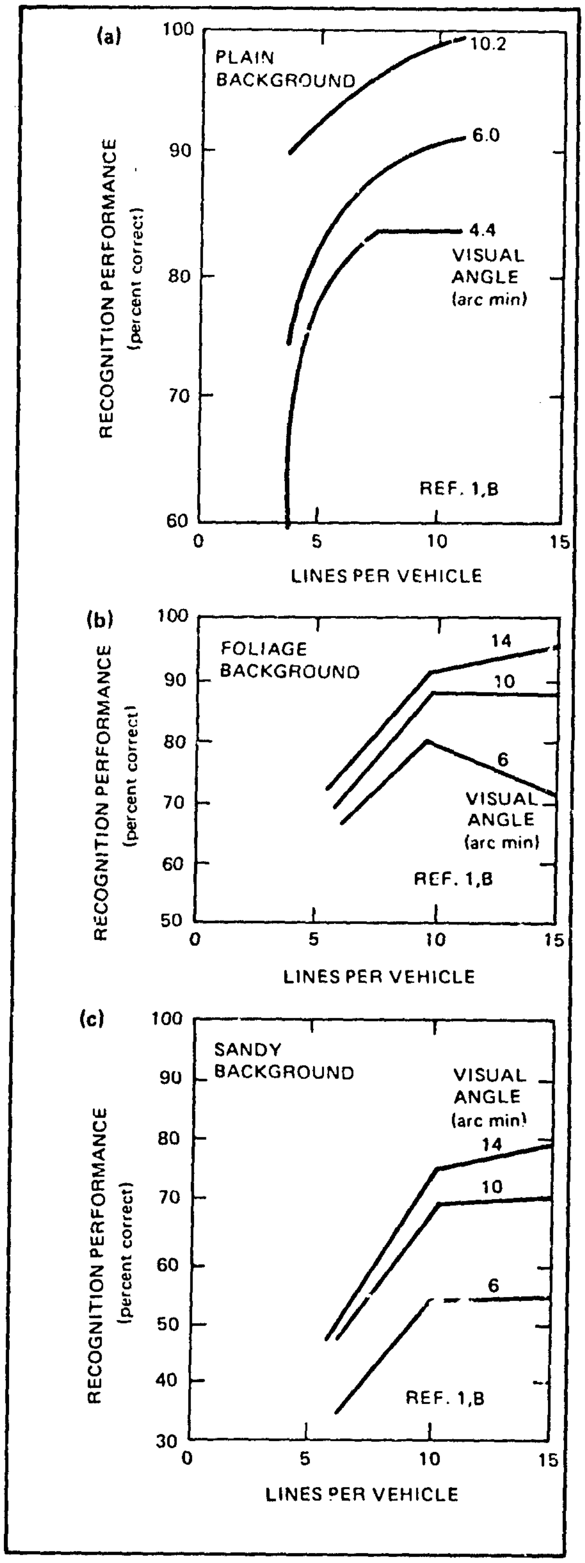


Figure 4.3-1. Vehicle Recognition as a Function of the Number of Scan Lines and Visual Angle Subtended on a CRT Display. The effect on target recognition performance of the number of scan lines and the visual angle subtended on a CRT display are shown in these graphs (Ref. 1,B).

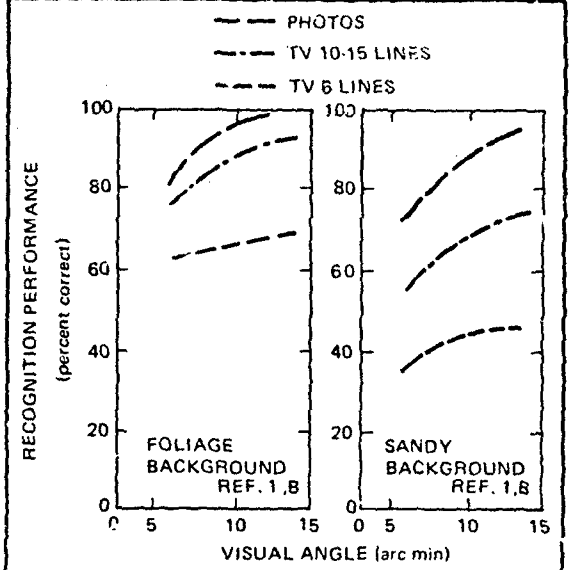
The imagery was generated on the CRT by a closed-circuit television camera viewing photographs of scale models of nine different types of military vehicles. For the data shown in Figure 4.3-1(a), the photographs were side views of the vehicles against a plain background. For Figures 4.3-1(b) and 4.3-1(c), the views were 60-degree obliques (from nadir). In Figure 4.3-1(b), the vehicles were located against a foliage background and in Figure 4.3-1(c), they were located against a sandy background.

The number of TV lines subtended by the targets was varied by changing the distance from the TV camera to the photograph. (The scale also changed in this process.) The visual angle subtended by the target was changed by changing the viewing distance to the display.

For each set of data, nine combinations of visual angle and subtended TV lines were tested. For Figure 4.3-1(a), these were 3.7, 7.0, and 10.8 lines per vehicle and 4.4, 6.0, and 10.2 minutes of visual angle. For Figures 4.3-1(b) and 4.3-1(c), they were 6, 10, and 15 lines per vehicle and 6, 10, and 14 minutes of visual angle. Highlight luminance was approximately 62 cd/m^2 (18 fL) for Figure 4.3-1(a) and 137 cd/m^2 (40 fL) for Figures 4.3-1(b) and 4.3-1(c). The ambient illumination on the face of the CRT was less than 0.003 L/cm^2 (3 fc). The display contrast ratio and target-to-background contrast were not reported. Nine subjects participated in all three studies, though not the same nine for all three. Each subject made one observation for each condition of line and visual subtend angle.

A 525-line, 2:1 interlaced closed-circuit TV was used having a bandwidth of 10 Hz to 10 MHz and a signal-to-noise ratio of greater than 30 dB. A P4 phosphor was used in the monitor.

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)



TARGET SIZE COMPARISON TV VERSUS DIRECT VIEW OF PHOTO			
PERFORMANCE LEVEL (% correct)	PHOTO TARGET SIZE (arc min)	TV TARGET SIZE (10-15 lines) (arc min)	RATIO: TV TO PHOTO
FOLIAGE BACKGROUND			
80	6.0	7.4	1.2
85	6.7	9.0	1.3
90	7.8	11.3	1.4
93	8.9	13.9	1.5
SANDY BACKGROUND			
70	6.0	10.6	1.7
73	6.4	12.0	1.9
75	6.7	13.9	2.1

Figure 4.3-2. Comparison of Target Recognition Performance on Photographs and CRT Displays. The top line in each of the accompanying graphs represents the target recognition performance for direct viewing of photographs of nine types of military vehicles. The second and third lines represent performance for the same images when displayed on a closed-circuit television system. The legend for these two lines refers to the number of TV lines subtended by the target. The targets were viewed against two types of background—foliage and sandy. The performance was poorer for the sandy background.

The table shows the visual angles required for equal target recognition performance for both direct viewing and CRT display types.

The final column shows the ratio by which the TV image had to be enlarged over the photograph in order to achieve equivalent performance (Ref. 1,B).

The nine subjects were the same ones who participated in the study reported in Figure 4.3-1. Details of the experimental apparatus can be found in the discussion of Figure 4.3-1.

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

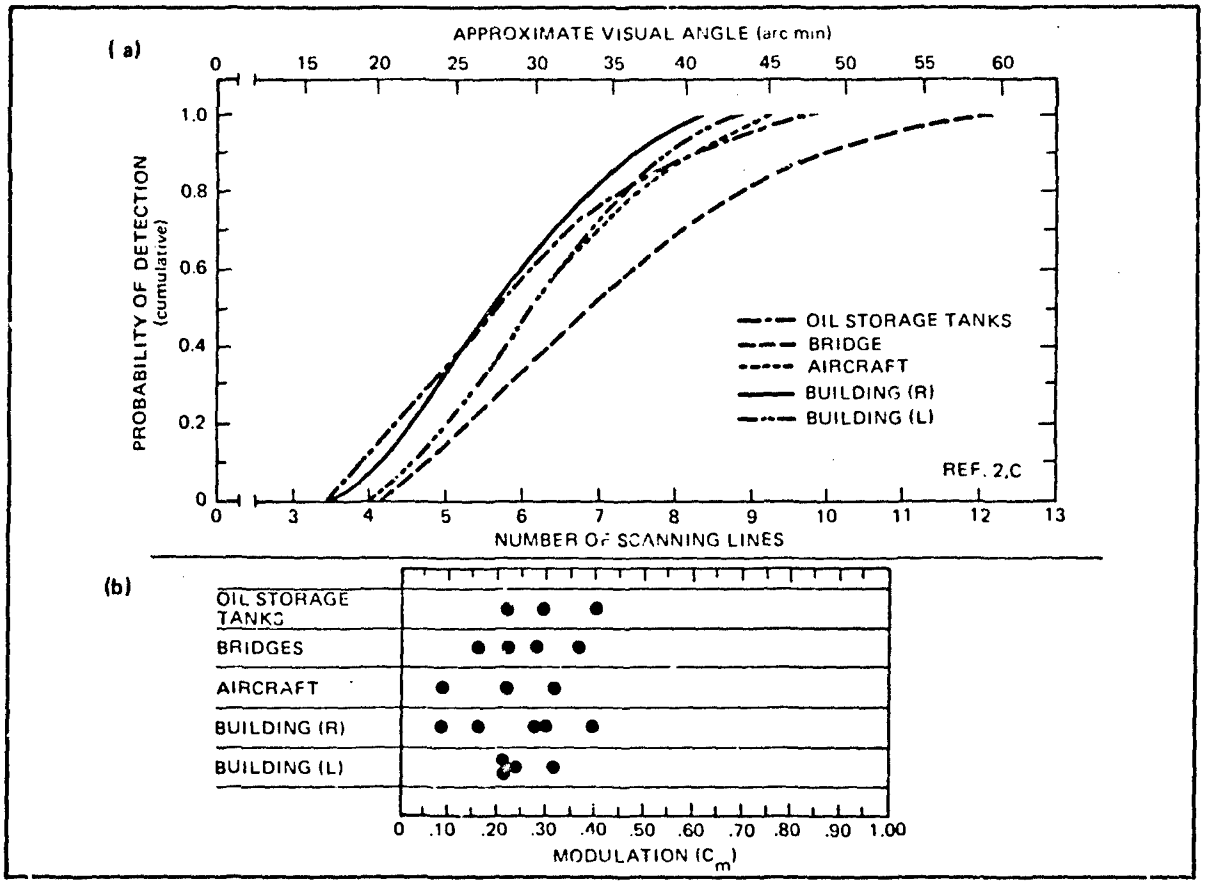


Figure 4.3-3. Search with Forward-Looking Television. For this study, a closed-circuit television camera was moved toward a terrain model upon which were located five classes of targets—oil storage tanks, bridges, aircraft, and two types of buildings, rectangular (R) and L-shaped (L). The targets were located at different distances to the right and left of the flightpath; they also differed in size between the classes and in orientation to the flightpath within each class. The camera was mounted as though it were pointing forward from the nose of the aircraft. The camera motion simulated an aircraft in a shallow (15-degree) dive moving at 660 km/hr (410 miles/hr). Targets in the center of the screen were seen at 75-deg. obliquity. The observer searched the display and reported the location of each target he found. The range from the aircraft to the target was calculated at the moment he reported sighting the target. The number of TV lines sub tended by each target was counted on the screen for five different distances, and the results were used to calculate the number of TV lines subtended by each target at intermediate distances.

The number of scanning lines per target and the visual angles were reported on two separate graphs in the original report. In combining the original charts for presentation here, some inaccuracies must be assumed (probably no greater than 5 percent). Therefore, the visual angles are shown as approximate.

The observers were ten employees of North American Aviation, Inc.

The display was a commercial closed-circuit television with a rated 8-MHz bandwidth and 35-dB signal-to-noise ratio (method of measurement not specified). Vertical resolution was measured using a fan-shaped bar target. Resolution was found to be nonlinear with respect to distance from the target. For close distances, it was approximately a factor of 2 worse than would be predicted. The authors suggest this might have been due to the fact that the focus was fixed at 1.07m (3.5 ft) while the camera moved from 2.29m (7.6 ft) to 0.23m (0.94 ft) in simulating the flight. The luminance of the display was not reported.

The target contrasts are shown in part (b) of this figure. Plots of the results as function of target contrast and orientation failed to show a relationship between these two factors and the results; however, the location of the building targets was found to affect the score.

The large target size (15 to 60 arc minutes) needed for identification is, in the opinion of the authors, an artifact of the scanning process. It is their opinion that had more scanning lines subtended the targets, as with a higher resolution system, they would have been recognized at smaller visual angles (Ref. 2,C).

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

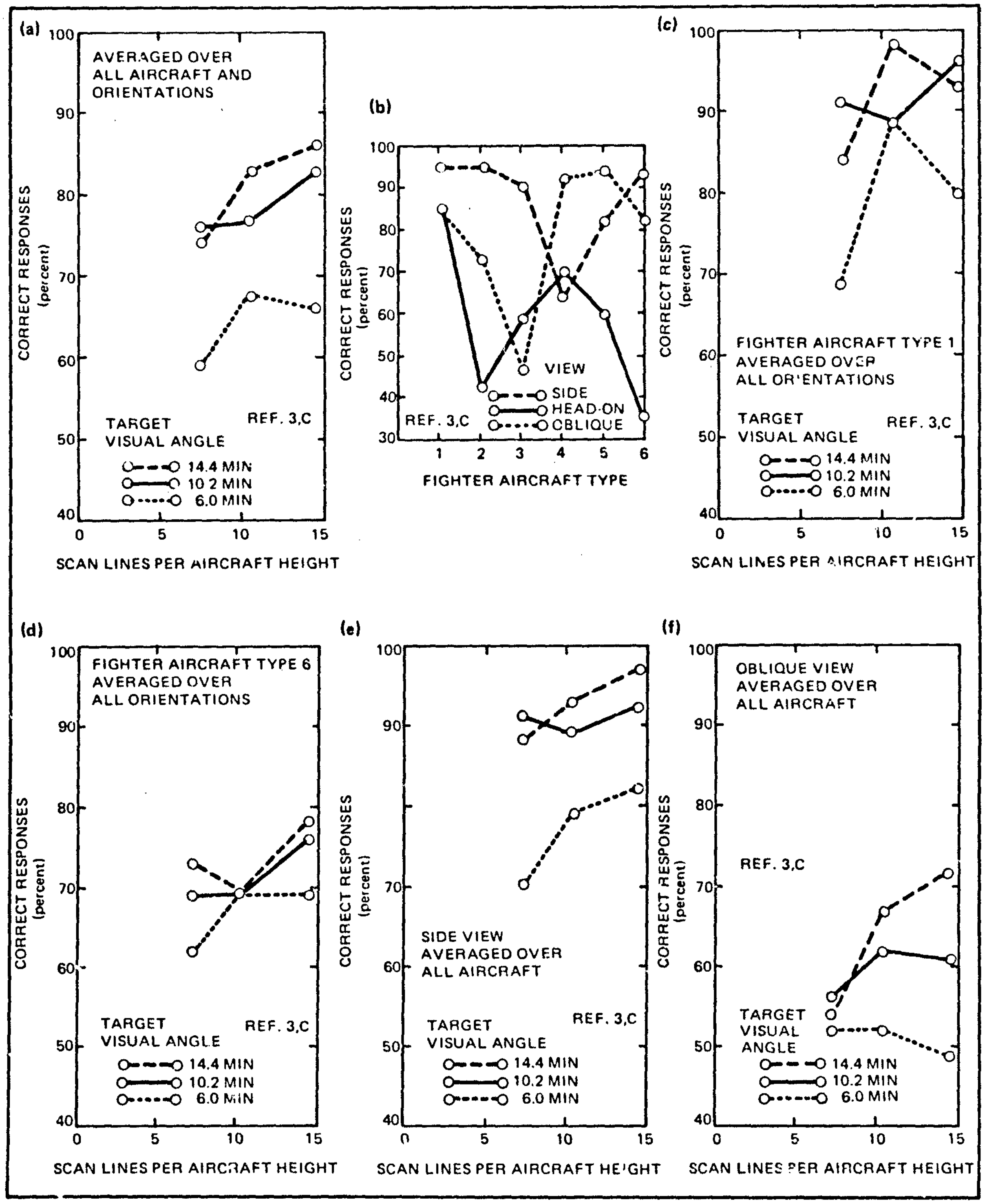


Figure 4.3-4. Effect of Scan Lines, Image Size, and Target Orientation on TV Aircraft Identification. (continued)

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

Figure 4.3-4. Effect of Scan Lines, Image Size, and Target Orientation on TV Aircraft Identification. Still photographs of seven different types of fighter aircraft taken at three different orientations were presented one at a time on a closed-circuit television monitor. The subject's task was to identify which of the seven was being presented. The three orientations consisted of a side view, a front view, and a high oblique. Target size in terms of visual angle was changed by changing the viewing distance to the display. The number of TV lines subtended by the target was counted over the vertical extent of its image on the display (Ref. 3,C).

Part (a) of this figure shows the percent of correct responses averaged over all aircraft and orientations. It is important in interpreting this figure to realize that performance varied greatly as a function of aircraft orientation and type. Part (b) of this figure shows the percent of correct responses as a function of these two variables. The data were averaged over all target sizes and scan line conditions.

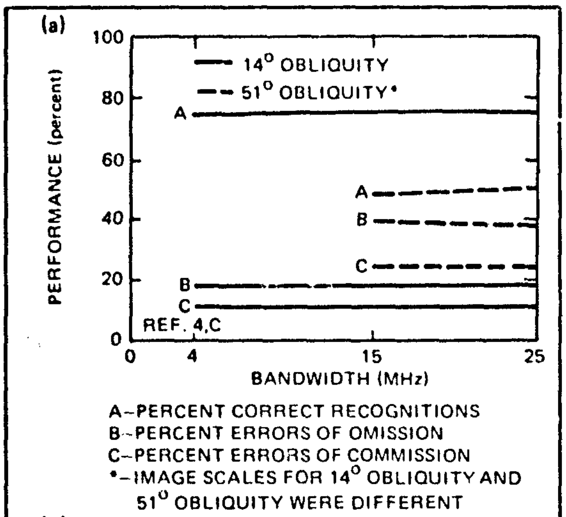
Parts (c) and (d) represent the differences of performance measured in this study as a function of aircraft type. Parts (e) and (f) show similar extremes as a function of orientation.

These data are excellent examples of the critical effect the interpreter's visual task has on his performance for any given set of equipment capabilities.

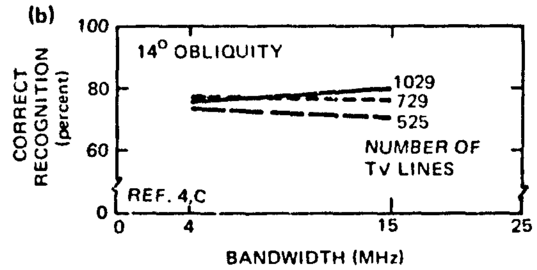
Fifteen subjects were used; 14 were pilots and 1 was a bombardier-navigator. The television system used was a 525-TV-line system with a bandwidth of 10 MHz. It used a 2:1 interlace with a 30-Hz frame rate and a 60-Hz field rate. The signal-to-noise ratio was greater than 30 dB. Ambient illumination on the faceplate of the CRT was less than 3.4 cd/m^2 (1 fL). Monitor highlight luminance was 600 cd/m^2 (175 fL) for a target luminance of approximately 342 cd/m^2 (100 fL). Target contrasts were not reported.

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

(a)



(b)



(c)

DIRECTION OF RESOLUTION	NUMBER OF TV LINES 525	729	1029	SYSTEM LIMIT
HORIZONTAL**	495	694	994*	800
HORIZONTAL X.7 KELL FACTOR	346	485	696	
VERTICAL:**				
4 MHz	312	224	159	800
15 MHz	1171*	842*	597	800
25 MHz	1952*	1406*	996*	800

*Exceeds system limit
**Vertical raster, conventional relationship reversed.

Figure 4.3-5. Target Recognition as a Function of Bandwidth and Scan Lines for CRT Displays. The experimental apparatus used to obtain the results reported in this figure was also used to gather the data shown in Figures 4.3-6 through 4.3-8 and Figures 4.3-21 through 4.3-23. The elements of the experimental setup that are common to all of these figures will be described here, along with the features unique to the collection of the data reported in this figure. Only dissimilar features will be reported for the other figures.

All of the studies involved the use of television for real-time search. The imagery was presented on a black-and-white television monitor mounted in a mockup of an aircraft control cabin. The imagery was first collected by a 35-mm motion picture camera moving over a terrain model in simulated reconnaissance flights, and the film was later projected into a television camera to provide imagery for the test. The terrain model was illuminated to give the appearance of daylight conditions.

The target set consisted of a combined total of 63 targets and navigation check points. The objects themselves ranged from groups of tanks, missile transporters, and fighter aircraft to road intersections, groups of buildings, POL storage areas, and an airfield. Target contrast (C_m) was measured on the model and ranged from 0.09 to 0.60 (for a definition of C_m see Figure 3.1-11). The contrasts of the targets on the TV monitor were not reported nor was the angle subtended at the eye for the targets as displayed on the monitor or the number of active lines they subtended.

The targets were presented one at a time and the subject was informed just before each target entered the field of view, but he was not told the nature of the target (Ref. 4,C). For the data reported in this figure, three TV-line conditions, 525, 729, and 1029; three bandwidths, 4, 15, and 25 MHz; and two obliquities, 14 degrees and 51 degrees (measured from nadir) were studied. For the 51-degree obliquity condition, the 525-TV-line and the 4-MHz conditions were not presented.

Figure 4.3-5(a) shows the results for the bandwidths when the data are averaged over all three TV line numbers and, in conjunction with Figure 4.3-5 (b), illustrates that bandwidth *per se* is not a proper measure of the value of a line scan system for target recognition.

Figure 4.3-5(b) shows the results in terms of correct recognitions for the 4-MHz and 15-MHz conditions as a function of line number. Data on the 25-MHz condition were not reported because these " . . . contributed to the overall *variance* but did not add much resolution to the system above that obtained for 15 MHz . . ."

A slight gain in performance between the 4-MHz and 15-MHz bandwidths was shown for the 1029-line system. The 1029-line system also showed better performance than the 525-line system at the higher bandwidth.

Twenty-one college students served as the observers, and their performance was scored in the following way:

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

$$\text{Percent correct recognitions} = 100 \left(\frac{\text{Number of correct responses}}{\text{Number of assigned targets}} \right)$$

$$\text{Percent omitted recognitions (Percent errors of omission)} = 100 \left(\frac{\text{Number of omitted responses}}{\text{Number of assigned targets}} \right)$$

$$\text{Percent incorrect recognitions (Percent errors of commission)} = 100 \left(\frac{\text{Number of incorrect responses}}{\text{Number of correct and incorrect responses}} \right)$$

No *luminance* values for the monitor were given for the conditions under which these data were collected. A value of "0.31 footcandle of luminance" was given for measurements taken with an illuminometer pointed at the monitor from the observer's station, but there was no way to relate these to the luminance values for specific areas of the monitor.

However, for studies run under slightly different conditions (Figure 4.3-34), a "luminance" of 0.30 to 0.31 footcandle as measured with the illuminometer was associated with luminances of between 82 and 92 cd/m^2 (24 and 27 fL) for the lightest area of the RETMA Gray-Scale Target (Ref. 5).

Ambient illumination in the cockpit was 0.05 footcandle. The viewing distance from the observer's station to the display was not reported.

The resolutions shown in the table 4.3-5(c) differ from those reported by the authors. The technique given in Figure 4.1-8 was used to calculate the values shown here. The monitor was rotated 90 degrees so the conventions for horizontal and vertical resolution are reversed from their usual orientations.

The RETMA gray-scale resolution (Ref. 5) was that shown for the curve marked "medium" in Figure 4.3-34. The SNR of the system was 35 dB. The method of calculating the SNR was not given.

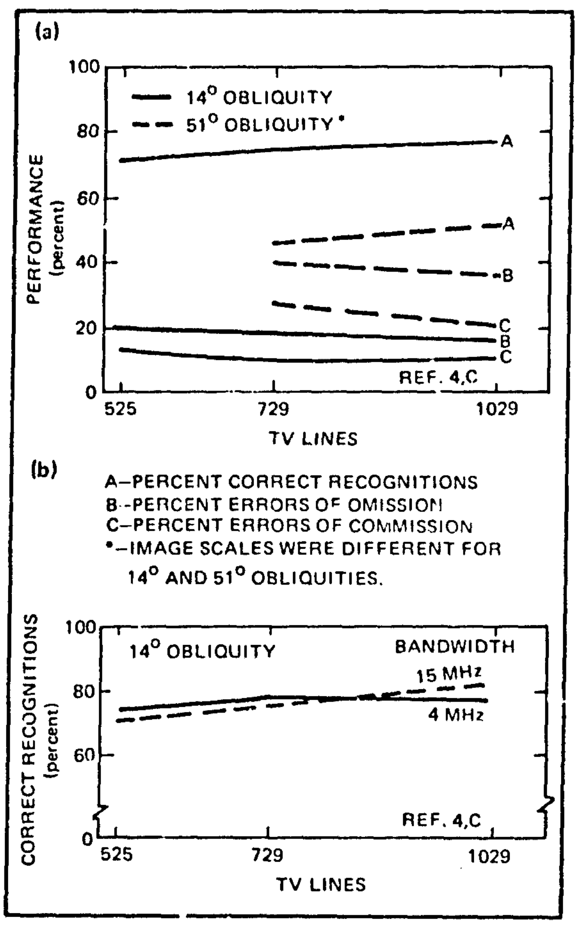


Figure 4.3-6. Target Recognition as a Function of Bandwidth and TV Lines for CRT Displays. The data used to compile the figures for these graphs are identical with those used for Figure 4.3-4. It is presented as a function of the number of TV lines per frame rather than bandwidth as in the previous figure in order to help clarify the relationship between the two. All of the experimental conditions that applied to the data collection for Figure 4.3-5 apply to this figure (Ref. 4,C). The method of calculating the three types of performance was also the same:

$$\text{Percent correct recognitions} = 100 \left(\frac{\text{Number of correct responses}}{\text{Number of assigned targets}} \right)$$

$$\text{Percent omitted recognitions (Percent errors of omission)} = 100 \left(\frac{\text{Number of omitted responses}}{\text{Number of assigned targets}} \right)$$

$$\text{Percent incorrect recognitions (Percent errors of commission)} = 100 \left(\frac{\text{Number of incorrect responses}}{\text{Number of correct and incorrect responses}} \right)$$

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

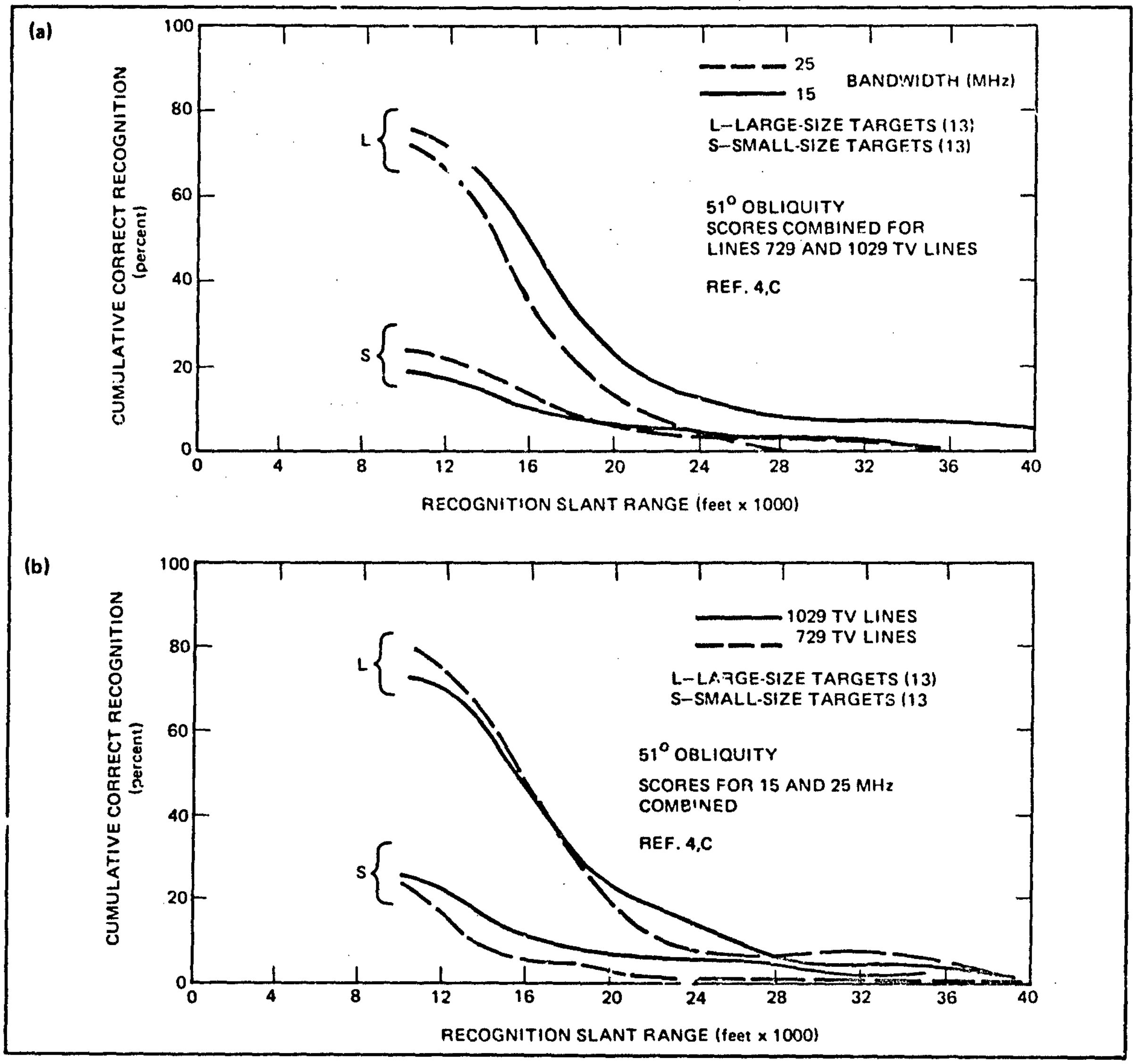


Figure 4.3-7. Effect of Target Size, Bandwidth, and TV Lines on Target Recognition in CRT Displays. The data for these figures were taken from the set of data used for Figures 4.3-5 and 4.3-6 (Ref. 4,C). The general experimental conditions are described in Figure 4.3-5.

The performance scores on 13 of the largest and 13 of the smallest targets were extracted and analyzed to determine the percent of correct detections as a function of the simulated range to the target, bandwidth, and number of TV lines per frame. Only the 729 and 1029 TV lines per frame along with the 15-MHz and 25-MHz bandwidth conditions were used. The data for each line are based on 78 observations per subject (13 targets x 6 trials) for each of the 21 subjects.

The large targets were either groups of four to six POL tanks or a large construction yard. The POL tanks were scaled to 22m in diameter by 12m in height (75 ft by 40 ft). The construction yard was 305m long by 267m wide (1000 by 875 ft).

The small targets ranged from a group of five Army tanks, each scaled to 6.7m long, 3.6m wide, and 3.6m high (22 by 12 by 12 ft) to a group of four small buildings, each scaled to 14.6m long by 9.1m wide by 4.6m high (48 by 30 by 15 ft).

The method of determining slant range was:

Slant range (feet) = Shortest distance from aircraft to target at instant of correct response.

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

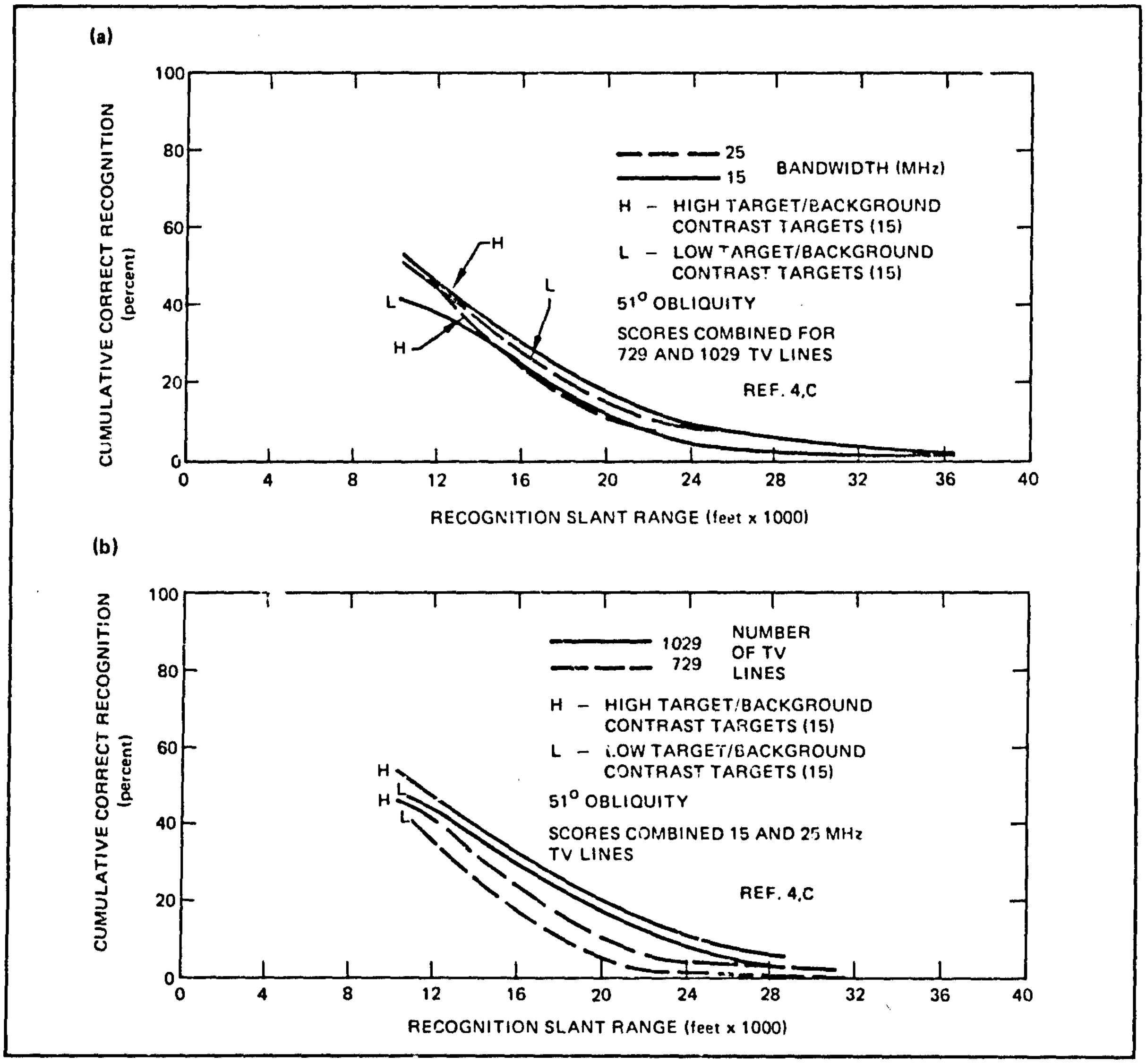


Figure 4.3-8. Effect of Target Contrast, Bandwidth, and TV Lines on Target Recognition in CRT Displays. The data for these figures were taken from the set of data used in Figures 4.3-5 and 4.3-6. The general experimental conditions are explained in Figure 4.3-5 (Ref. 4,C).

The performance scores on 15 high-contrast targets and 15 low-contrast targets from the basic set of 63 targets were extracted to determine the percent of correct detections as a function of bandwidth and number of TV lines per frame. Only the 729 and 1029 TV lines per frame along with the 15-MHz and 25-MHz bandwidth conditions were used. The data for each line in the graphs are based on 90 observations per subject (15 targets x 6 trials) for each of the 21 subjects.

The high-contrast targets ranged from contrasts (C_m) of 0.25 to 0.60. The low-contrast targets ranged from 0.02 to 0.23, and 11 of the 15 targets were of the same type in each set.

The method of determining slant range was:

Slant range (feet) = Shortest distance from aircraft to target at instant of correct response.

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

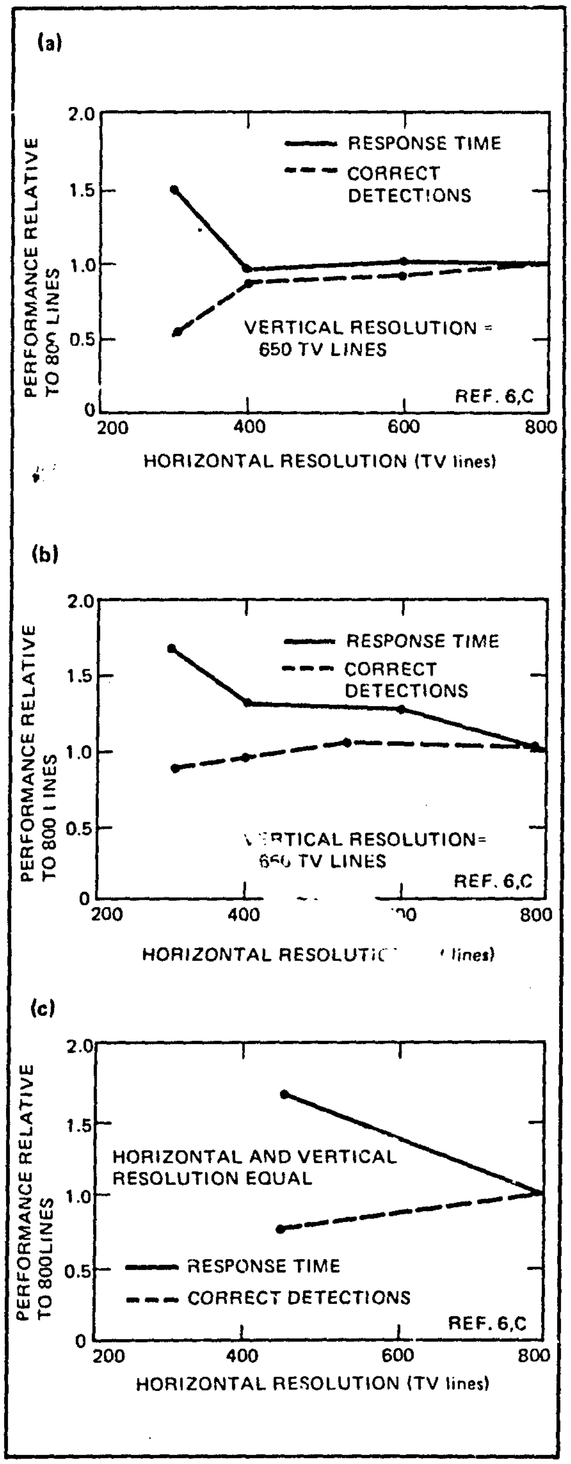


Figure 4.3-9. Relative Target Detection Level and Response Time as a Function of the Display Resolution in TV Lines. These charts summarize the results of three studies on the effect of TV resolution on target detection for ground-level views of an M-48 tank. Two performance measures were taken—correct detections and the time from the appearance of the target on the CRT to the subject's response (response time) (Ref. 6,C).

Figures 4.3-9(a) and 4.3-9(b) show two sets of data collected for the same conditions. The second set (Figure 4.3-9(b) represents a replication of the study which gave the results in 4.3-9(a).

For these studies the vertical resolution of the system was held constant as the horizontal resolution changed. The results from both indicated significant improvements in performance for both detections and response time between horizontal resolutions of 300 TV lines and 400 TV lines, and that performance improvements in terms of time or correct detections were not significant above 400 lines.

In the third study (Figure 4.3-8(c), resolution in the horizontal and vertical directions was equal, and significant improvement in both performance measures was found for the 800 TV line condition.

A 35.6-cm (14-in) monitor was used for the studies reported in 4.3-8(a) and 4.3-8(b). The viewing distance was 1.8m (72 in) from which the targets subtended a visual angle of 18 arc minutes. Resolution was measured with a RETMA TV test pattern (Ref. 5).

Sixteen observers were used in the first study and 20 in the replication. Each subject had 10 trials at each level of resolution. The targets were presented for 0.5 second.

For the study reported in Figure 4.3-8(c), a 53-cm (21-in) monitor and a 36-cm (14-in) monitor were used. Thirty subjects were used for the study. Other conditions were the same as in the other two studies. (Ref. 6,C).

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

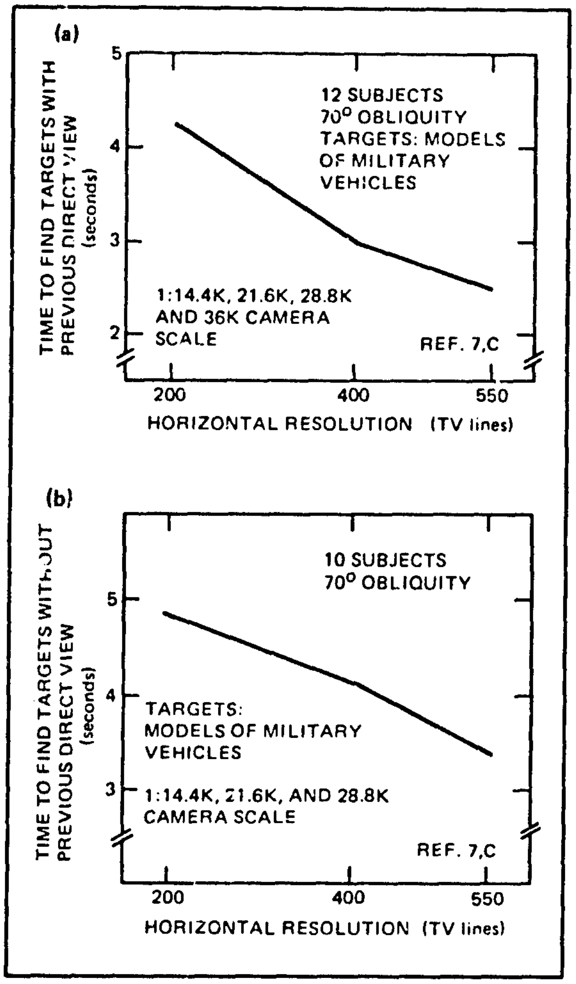


Figure 4.3-10. Time to Find Targets as a Function of Horizontal Resolution on a Cathode Ray Tube. The results presented here were obtained in a study in which horizontal resolution on a CRT was varied by changing spot size on a 525-TV-line closed-circuit television system. Three levels of horizontal resolution were studied by this method—200, 400, and 550 TV lines. Vertical resolution was 490 active TV lines. The increase in spot size should decrease the Kell factor and reduce the effective vertical resolution, but the effects were not reported.

The targets were models of Army trucks, tanks, and guns located on a terrain model. The viewing angle was 70 degrees from nadir. Figure 4.3-10(a) shows the results obtained for 12 subjects who were permitted a 5-second direct view of the target before seeing it on the TV monitors. Figure 4.3-10(b) shows the results for 10 subjects who were not allowed the direct view and who did not see the smallest scale (see below) (Ref. 7,C).

The experiment also involved changes in scale and contrast ratio (gray-scale steps). (See Figures 4.3-11 through 4.3-14 and 4.3-37 and 4.3-38). Three display contrast ratios were used as measured by gray scale steps on the RETMA log gray scale (Ref. 5); these were 5, 7, and 9 shades. Four ranges from the camera to the model were used, which resulted in image scales on the TV camera pickup of 1:14,400, 1:21,600, 1:28,800, and 1:36,000. The scale displayed on the monitor cannot be determined because the ratio of the size of the image in the camera to the size of the display was not specified. The display was 11.7 cm long by 8.9 cm high (4.6 in by 3.5 in) and was viewed from a distance of 60 cm (25 in).

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

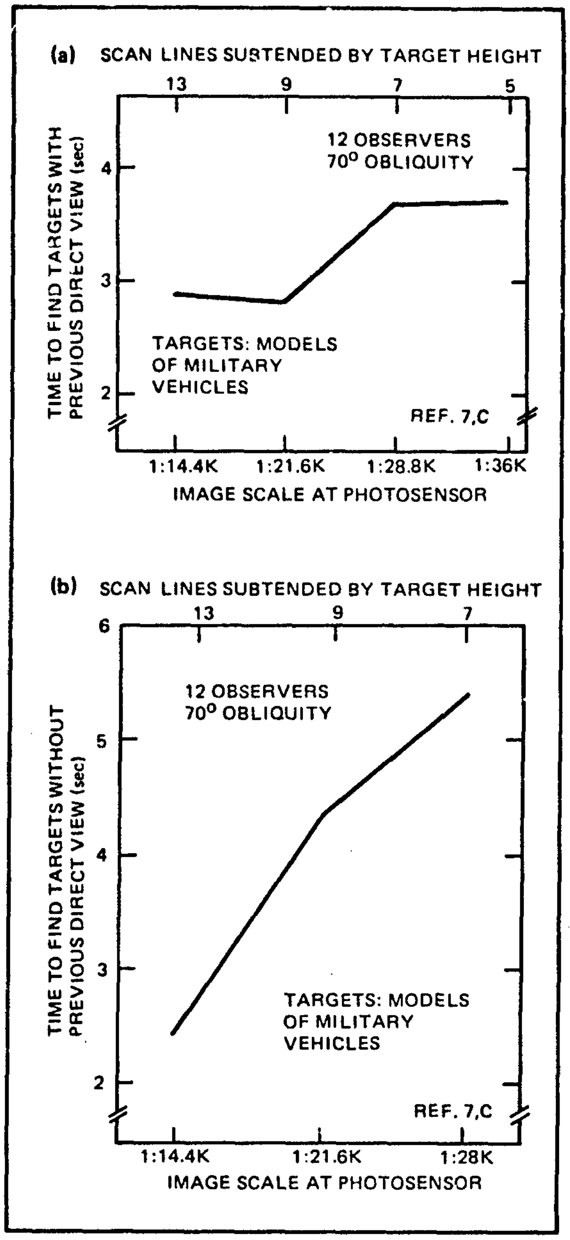


Figure 4.3-11. Time to Find Targets as a Function of Scale at Photosensor and Scan Lines Subtended by the Target. These graphs were compiled from the same data used for Figure 4.3-10 but they were analyzed to extract the effect of scale. The data were reported in terms of simulated slant range in the original report and have been converted for presentation here into scale at the photosensor in the TV camera. Since the ratio of the scanned dimensions on the photosensor to those on the monitor was not reported, the display scale could not be calculated. For Figure 4.3-11(a), the observers were allowed a 5-second direct view of the target just before viewing it on the monitor; in Figure 4.3-11(b), no direct view was given. In addition the smallest scale, 1:36,000, was not presented to the second group. Since the view of the target was a high oblique, the author reported the number of TV lines subtended by the height dimension of the targets that were military vehicles (Ref. 7,C).

The data in Figure 4.3-11(a) are further analyzed in terms of horizontal TV resolution in Figure 4.3-13 and in terms of display contrast ratio in Figure 4.3-38. The details of the study are reported in Figure 4.3-10.

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

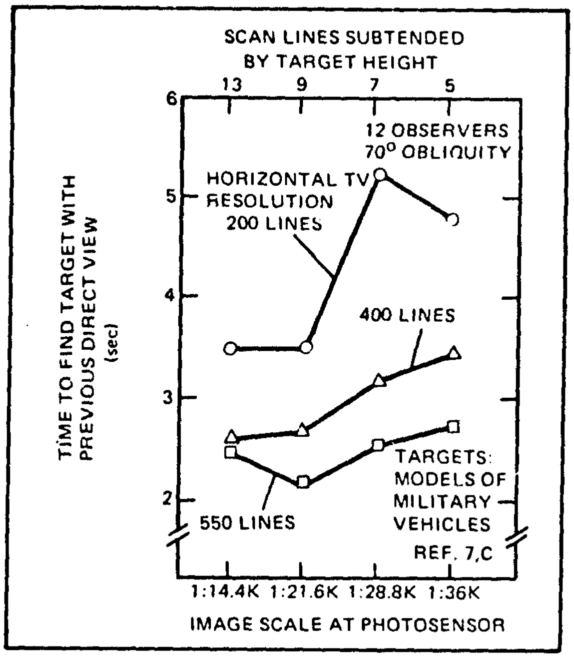


Figure 4.3-12. Time to Find Targets as a Function of Horizontal Resolution, Target Scale on Photosensor, and Lines Subtended by the Target. This graph was compiled from the same data presented in Figure 4.3-10(a), with the effects of horizontal TV resolution separated. A description of the study from which these data were obtained can be found in Figure 4.3-10 (Ref. 7,C).

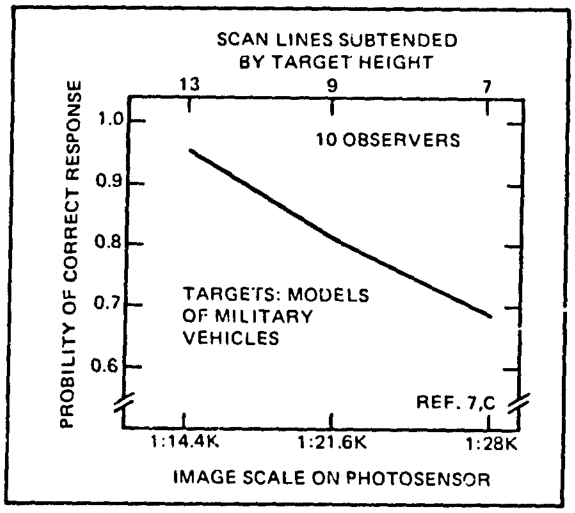


Figure 4.3-13. Probability of Target Recognition as a Function of Image Scale on the Photosensor and Scan Lines Subtended by the Target. The experimental conditions under which these data were collected are described in Figure 4.3-10. The imagery scale on the camera photosensor is used here, rather than the imagery scale on the display, because the latter was not reported. The lines subtended by the target height were reported and are meaningful because of the high obliquity of the imagery (Ref. 7,C).

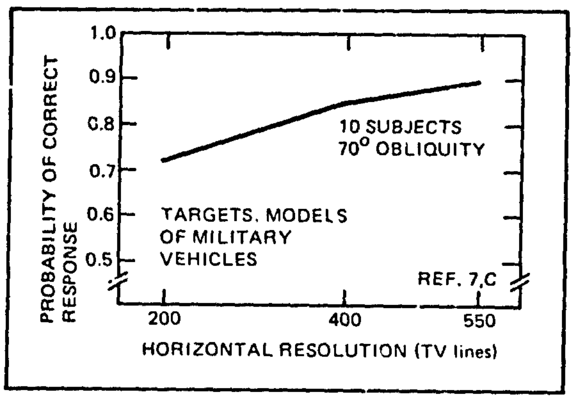


Figure 4.3-14. Probability of Target Recognition as a Function of Horizontal Resolution on Cathode Ray Tubes. The results shown in this figure can be interpreted as giving an indication of the relative improvement in target recognition which takes place as a function of increasing CRT resolution. The data are from the same study as was reported in Figure 3.4-10. The technique used in that study was to degrade horizontal resolution by increasing beam size while keeping the number of TV lines per frame constant (525 in this case). This technique must be considered in interpreting these results. The increase of spot size undoubtedly reduced the actual vertical resolution of the display, but if so, it was not reported (Ref. 7,C).

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

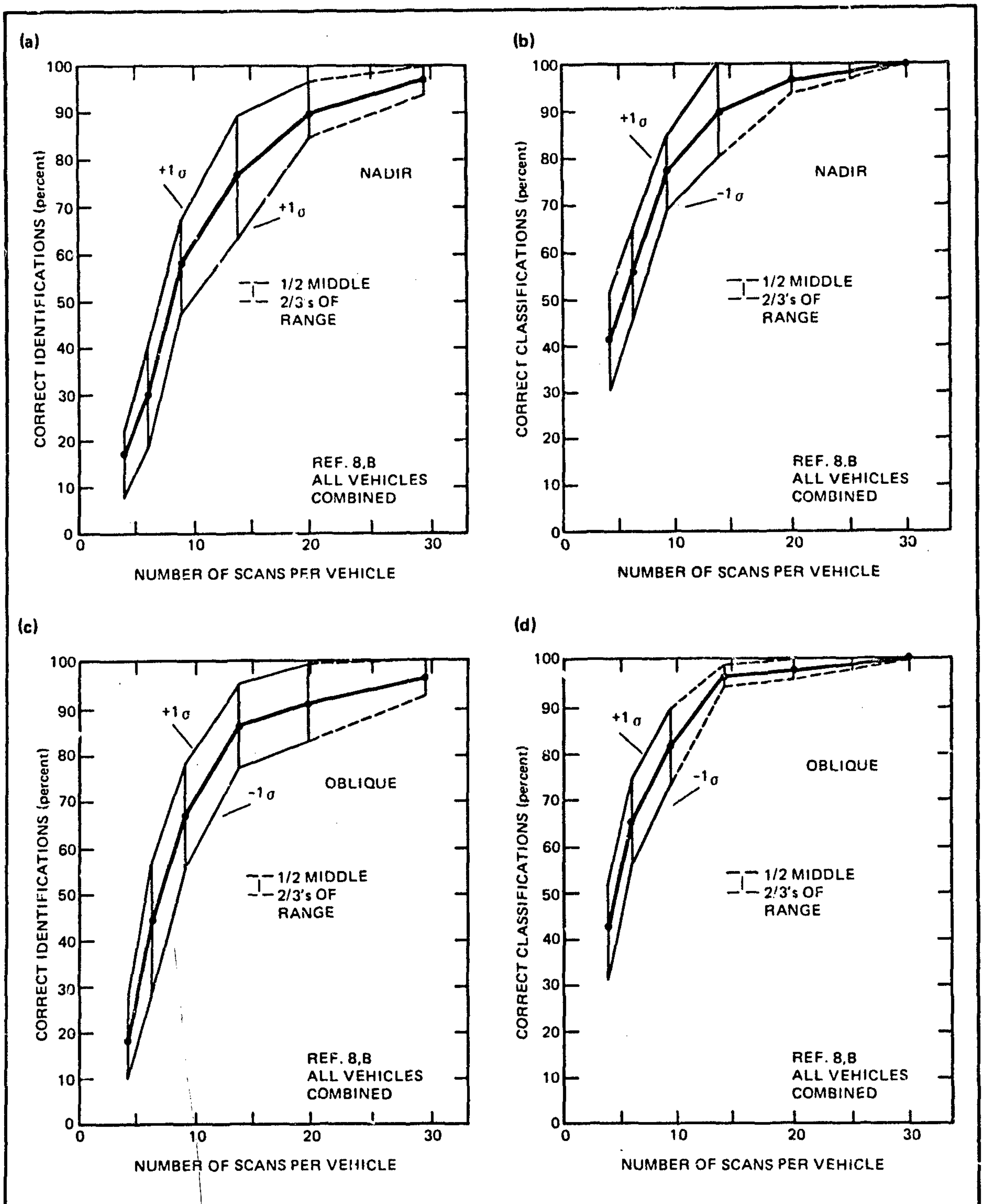
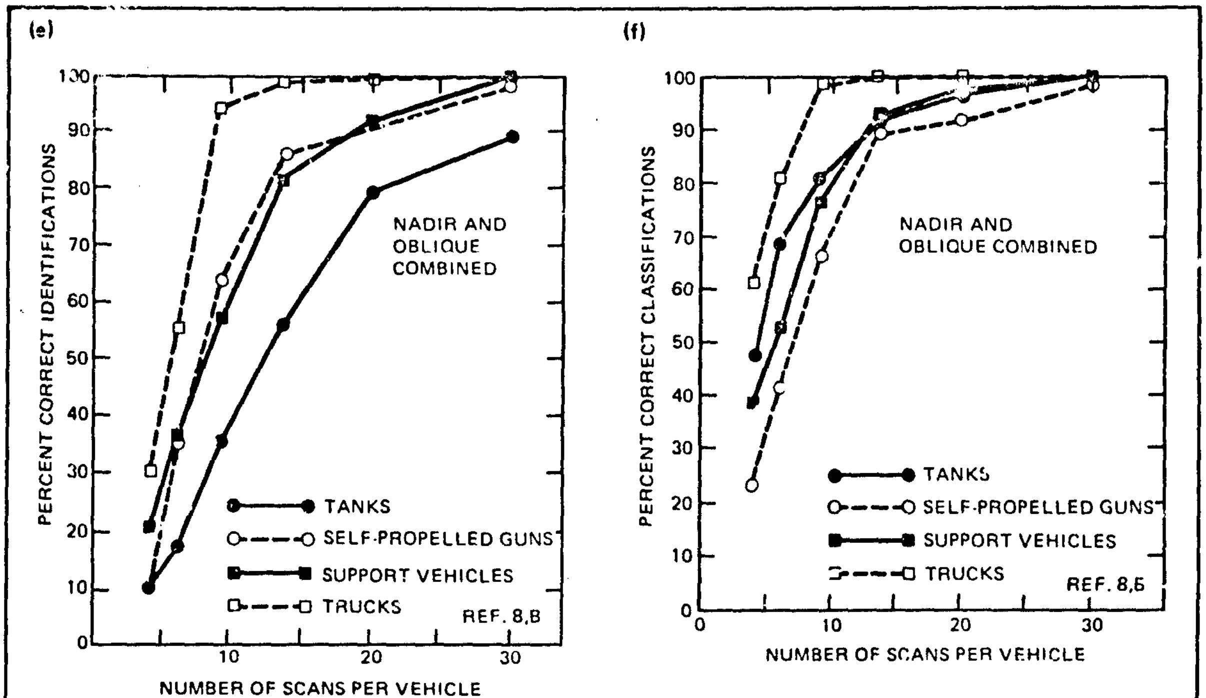


Figure 4.3-15. Vehicle Classification and Identification on Line-Scan Transparencies (Continued)

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)



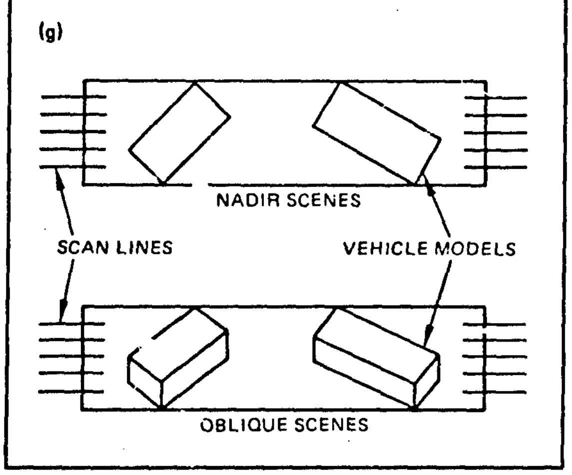


Figure 4.3-15. Vehicle Classification and Identification on Line-Scan Transparencies. The transparencies used in this study were made on a line-scan printer from photographs of scale models of military vehicles mounted on a plain background. The vehicle models were oriented as shown in the sketch, with each vehicle subtending the same number of scan lines for each condition studied. The tests were run at 4, 6, 9, 13.5, 20, and 30 lines per vehicle. The number of lines was adjusted by changing the enlargement of the photograph used in the scanner. The scanner and printer operated with circular spots having approximately Gaussian spread function. The line (raster) spacing was equal to the half-amplitude diameter of the spot (0.66 mm, 0.26 in). Two separate studies were conducted, one with nadir photography and the other with 45-degree oblique photography.

Two tasks were performed in each study—identification and recognition. Identification meant putting a vehicle in the proper class; four classes were used, tanks, self-propelled guns, support vehicles, and trucks. Recognition meant identifying the specific model of the vehicle. To assist in both tasks, the actual models used in the photographs were on display during the test and the subjects could refer to them at any time. Neither the viewing distance, visual angles subtended by the targets, luminance, or contrast were specified. The subjects viewed the material on light tables without optical aids, in well illuminated rooms.

The authors point out that the variability of performance must be taken into account when interpreting the results; for instance, at 13.5 lines in the nadir photograph, part (a) of this figure, the mean score for identification (all vehicles combined) was about 76 percent; the standard deviation (σ) was 14.1 percent; and the total range (not shown) was from 23 to 100 percent. At 20 lines, the standard deviation was reduced to 6.3 and the total range was 60 percent to 100 percent. As parts (e) and (f) of this figure show, the number of lines required was strongly dependent upon the type of vehicle. For identification, differences between the mean scores for the different vehicles (except for between self-propelled guns and trucks) were statistically significant ($p < .01$); for classification differences, the differences between all vehicles were significant ($p < .01$) (Ref. 8,B).

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

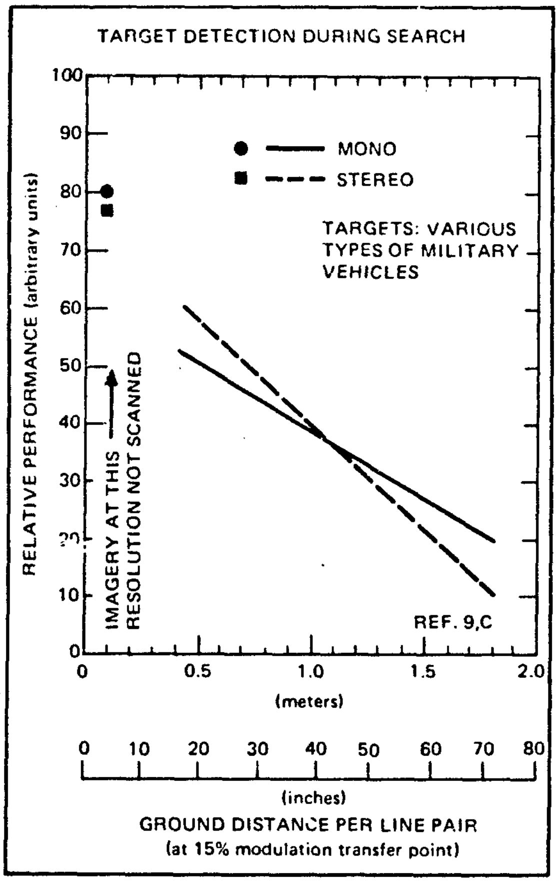


Figure 4.3-16. Detection of Military Vehicles on Line-Scan Transparencies as a Function of Ground Resolution and Stereoscopic and Monoscopic Presentations. Line-scan transparencies were prepared at two levels of ground distance per line pair—0.4m (17 in) and 1.8m (70 in). The transparencies were generated from photographs of scale-model military vehicles located in a terrain model. The photographs, which had a scale of approximately 1:3000 relative to real targets, were scanned by a *flying-spot scanner* whose beam size was varied to simulate the two resolutions. The signal from the scanner was displayed on a CRT and photographed to obtain the test transparencies. The original, unscanned image with a simulated resolution of 11 cm (4 in) per line pair was used along with the two scanned images, as the test material (Ref. 9,C).

Three performance measures were taken—target detection, target discrimination, and depth discrimination. For the target detection task, which is reported in this figure, the interpreter searched the image for a specific, known type of target and reported its location on a reference grid.

The results for the target discrimination task are reported in Figure 4.3-16 and the stereo discrimination task results are given in Figure 4.3-17.

The performance was reported in units that cannot be interpreted as representing directly the percent of correct detections.

There was no significant difference between performance on the stereoscopic and monoscopic imagery at any of the levels; however, interpretation of the stereoscopic imagery was reported as having taken more time.

The imagery was viewed on what was described as a low-wattage, movable light table. The use of optical aids was not reported for the monoscopic imagery, nor was the viewing distance. The stereo imagery was viewed through a Zeiss Aerotype pocket stereoscope.

Thirty experienced PI's were used as subjects and each performed under a portion of the task and imagery conditions. The presentation of the entire set of conditions was balanced over the aggregate group of PI's.

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

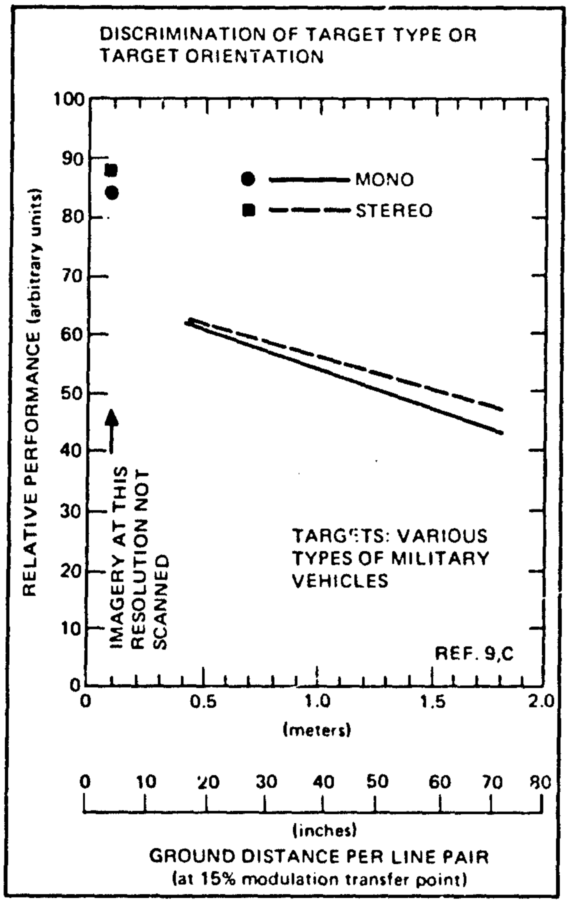


Figure 4.3-17. Discrimination of the Orientation or Type of Army Vehicle on Line-Scan Transparencies as a Function of Resolution and Monoscopic or Stereoscopic Presentation. The test conditions under which these data were gathered are described in Figure 4.3-15. The task in this case was to distinguish the orientation or type of military vehicle located in a designated area of the transparency.

There was no difference in performance between the monoscopic and stereoscopic presentations; however, the interpretation of the stereoscopic imagery was reported to have taken more time (Ref. 9,C).

4.3.1 BANDWIDTH AND RESOLUTION (CONTINUED)

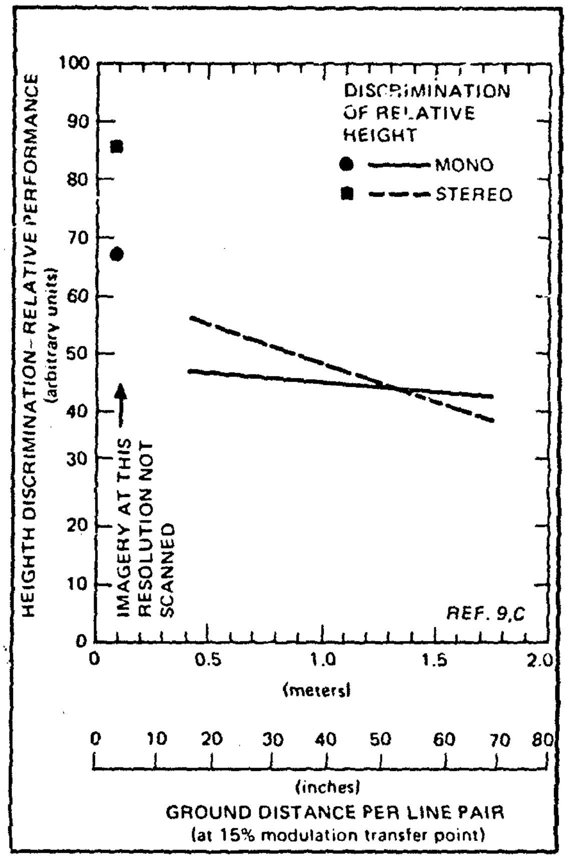


Figure 4.3-18. Height Discrimination in Stereoscopic and Monoscopic Line-Scan Imagery. The test conditions under which these data were collected are described in Figure 4.3-15 (Ref. 9,C). The task in this case was to discriminate the relative heights of objects; i.e., to determine which object was highest in a group of similar objects. (Objects with obvious height relationships, such as a truck versus a car, were excluded.)

There are numerous nonstereo cues to height, particularly in imagery containing some obliquity (as is necessary in the area being viewed for at least one member of a stereo pair). Obliquity cues to height are present, to some extent, in all areas of vertical photography except for a small area around the *principal ray*.

Figure 5.1-14 shows the results of a systematic study of height detection in monoscopic and stereoscopic imagery for conventional photographic systems.

The results shown here suggest that there is an interaction between ground resolution, the effects of scanning, and the usefulness of stereo for height determination.

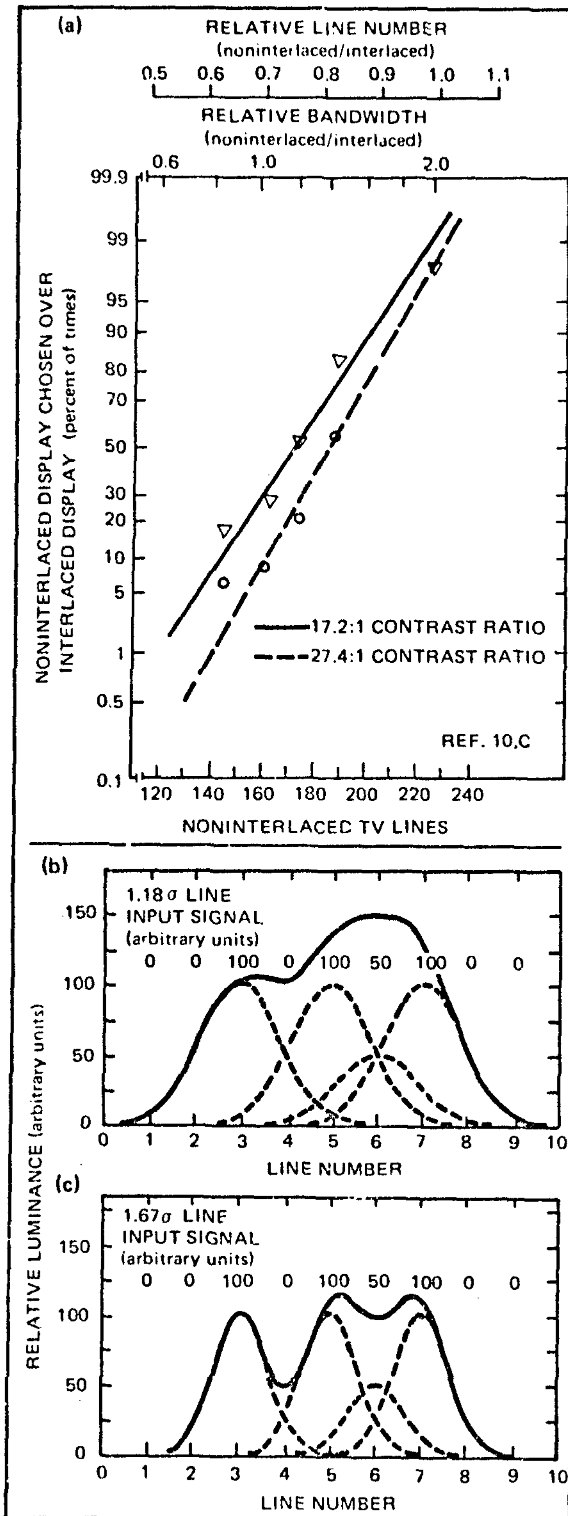
Since neither the convergence angle for the stereo pairs nor the exact nature of the set of objects used in the tests were reported, it is unwise to speculate on the ground resolution at which this might happen in a specific system. The data do, however, indicate that the advantage of stereo declines with increasing resolved ground distance in line-scan systems. It is possible that interference from the line structure in the imagery makes the perception of stereo difficult.

It is also necessary to keep in mind that the 11-cm (4-in) ground resolution imagery was not scanned.

4.3.2 INTERLACE AND BANDWIDTH REQUIREMENTS

The theoretical improvement in resolution, or reduction in bandwidth, which is predicted to follow from higher interlace orders, is seldom realized. The staggered line and dot-line interlace techniques reported in Section 4.2 achieve much of the advantage up to orders of 5:1, but usually at the expense of using long-persistence phosphors that preclude the viewing of any moving objects. The studies on 2:1 interlace reported here that use a short-persistence phosphor indicate a savings of 6 percent to 36 percent in bandwidth can be expected if images of equal judged quality are to be presented.

4.3.2 INTERLACE AND BANDWIDTH REQUIREMENTS (CONTINUED)



COMPARISON OF DISPLAY CONDITIONS

INTERLACE ORDER	TV LINES	BAND-WIDTH (kHz)	FIELD RATE (Hz)	FRAME RATE (Hz)	LINE SPACING 2(X/σ)*	LINE SPACING (% maximum luminance at overlap)
2:1	225	575	30	60	1.18	0.84
1:1	225	1139				
1:1	189	843				
1:1	175	689	60	60	1.67	0.63
1:1	162	590				
1:1	147	486				

*X = LINE SPACING IN LINEAR UNITS

Figure 4.3-19. Effect of 2:1 Interlace on Judged Image Quality. A *paired comparison* test was conducted to compare the image quality of interlaced and noninterlaced TV pictures (Ref. 10,C). The conditions compared are shown in the table (part c). The bandwidths were adjusted to provide approximately equal horizontal and vertical resolution for each case. Each condition was presented at two display contrast ratios—17.2:1 with a highlight brightness of 200 cd/m^2 (60 fL) and 27.4:1 with a highlight brightness of 140 cd/m^2 (40 fL).

The results are presented in terms of the percentage of times a noninterlaced picture of a given line number was judged better than the 225-TV-line interlaced picture (part (a) of this figure). For instance, for the 17.2:1 contrast ratio images, the 160-TV-line noninterlaced picture was chosen over the 225-line interlaced picture 29 percent of the time and the 27.4:1 contrast ratio image 8 percent of the time.

By finding the intersection of the 50-percent choice line and the lines for each contrast ratio, the number of noninterlaced TV lines that would give a picture judged as having equal quality to the interlaced picture can be determined. These values are 173 TV lines for the 17.2:1 case and 183 TV lines for the 27.4:1 case. The bandwidth requirements would be, respectively, 1.18 and 1.67 times the bandwidth for the 225-TV-line interlaced system. The relative bandwidth requirements as a function of either the number of noninterlaced TV lines, or the ratio of these lines to a 2:1 interlaced system, are shown at the top of the graph in part (a).

The effect of the spot size on detail contrast should be considered in interpreting these results. The visual effect of these overlaps is shown in parts (b) and (c). Part (b) represents the interlaced condition and part (c) the noninterlaced conditions.

4.3.2 INTERLACE AND BANDWIDTH REQUIREMENTS (CONTINUED)

The line spacings for the two interlace conditions were chosen from a previous unpublished study by the same author as those judged best for the two conditions. Their differential effect on detailed contrast rendition in the vertical direction can be seen in the figures. The dashed lines show the individual line luminances and spread functions for arbitrary input signals. Because the integration time of the eye is longer than the time between fields (frames for the noninterlaced condition), the brightness of the overlapping areas is summed (see Figure 4.4-1 for additional discussion). The visual response is shown by the solid line. Whereas significant contrast reduction between adjacent lines takes place in both 4.3-19(b) and in 4.3-19(c), it is seen that a 2:1 change in input signal (100 units to 50 units), which represents a contrast (C_m) of 0.33, is virtually eliminated by the spot overlap caused by the 1.18σ line spacing. (See Figure 3.1-10 for a definition of C_m.) This will give the visual effect of a smoother, more blurred image.

The pictures used in this study were head and shoulder views of young women presented on a 12.7 cm by 12.7 cm (5 in by 5 in) raster.

For the 17.2:1 contrast ratio condition, 16 observers who were inexperienced in making image quality judgments each made three judgments for every noninterlace condition. For the 27.4:1 contrast ratio, 15 similar observers followed the same test plan.

4.3.2 INTERLACE AND BANDWIDTH REQUIREMENTS (CONTINUED)

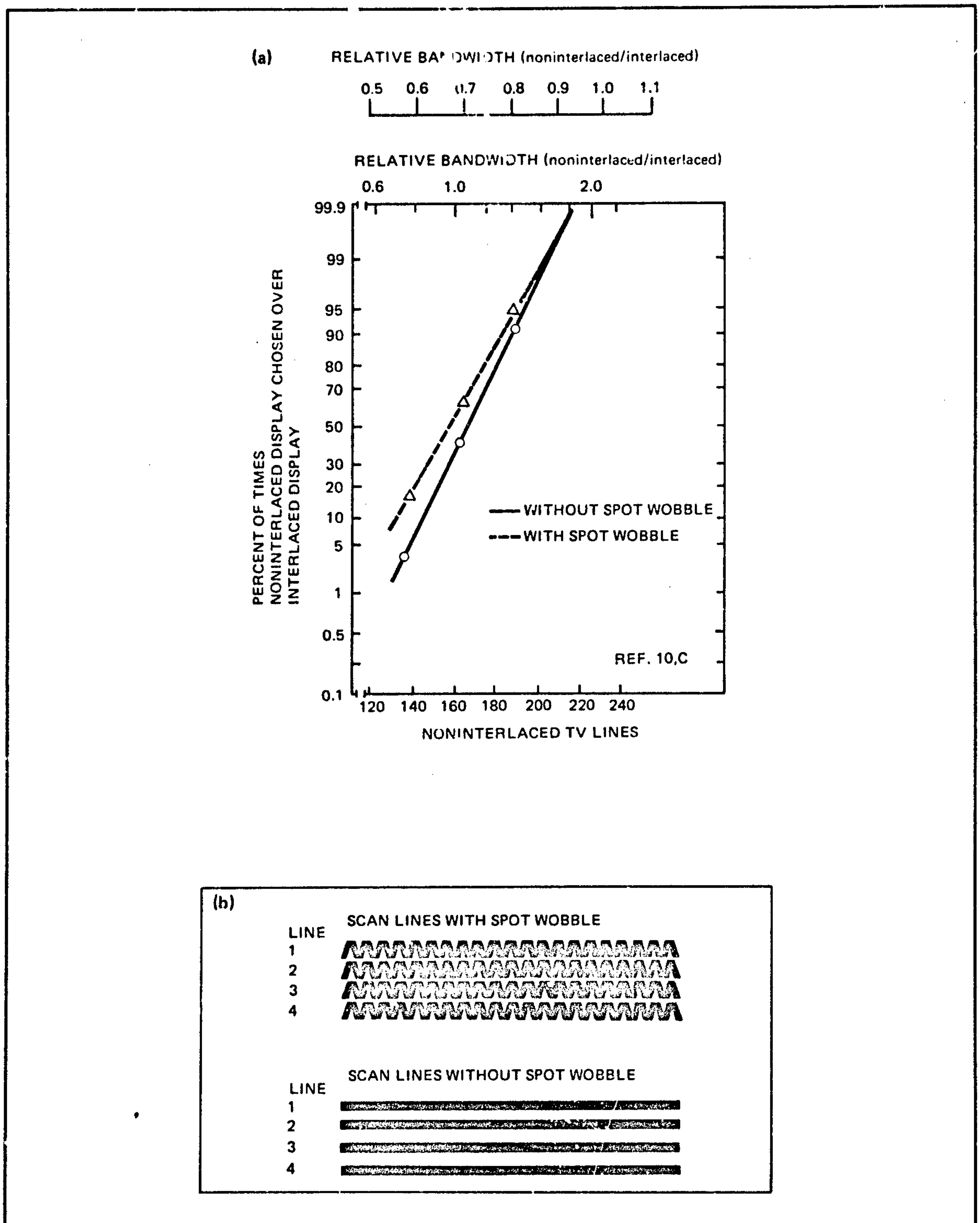


Figure 4.3-20. The Effect of Spot Wobble on the Judged Quality of CRT Images (Continued)

4.3.2 INTERLACE AND BANDWIDTH REQUIREMENTS (CONTINUED)

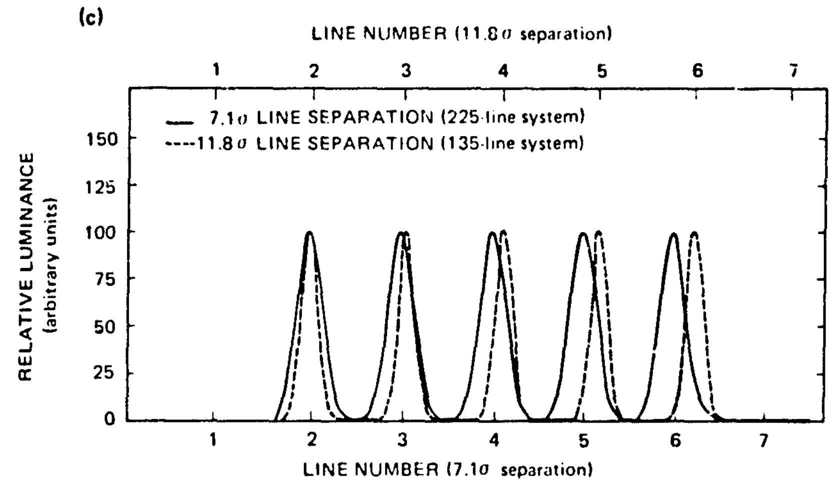


Figure 4.3-20. The Effect of Spot Wobble on the Judged Quality of CRT Images. When the scan lines of a CRT are separated so the line structure becomes distinct, *spot wobble* has a significant positive effect on judged image quality. Spot wobble is the technique of rapidly moving the scanning beam up and down a short distance as it scans each line; this procedure is illustrated in part (b).

To determine the effects of spot wobble, four noninterlaced systems of 135, 162, 189, and 225 TV lines were compared with a 225-TV-line 2:1 interlaced system using the *paired comparisons* technique. The spot wobble was generated by a 7.1-MHz sine wave superimposed on the line scan. The number of "wobbles" per line varied with the TV line number as follows:

	Number of "Wobbles" per Scan Line	
TV Line Number	Noninterlaced	Interlaced
225	186	93
189	111	
162	129	
135	155	

The result is that the areas between the lines tend to "fill in," which presents a more pleasing image.

The images that were presented on the monitor are described in Figure 4.3-19, and the results were analyzed in the same way for this figure.

The lines on the graph in (a) show the percentage of the time the noninterlaced picture was judged to be better than the interlaced picture. At the 50-percent level, the pictures were considered equal, each being chosen half of the time.

For the condition with no spot wobble the 50-percent level for the noninterlaced picture was 165 TV lines. With spot wobble, it was 157 TV lines (Ref. 10,C).

A noninterlaced system of approximately 159 TV lines has a bandwidth equal to a 225-TV-line system using a 2:1 interlace. This study indicated that with spot wobble a noninterlaced system of 157 TV lines had judged image quality equivalent to the 225-line 2:1 interlaced system, suggesting a minor bandwidth saving for the noninterlaced condition, contrary to normal expectation. However, a statistical test indicated that no difference could reliably be inferred. It appears that interlacing provides no bandwidth saving for the conditions of this test.

The effects of the line spacing must be considered in interpreting these results. Line spacing varied from 7.1σ for the 225-line condition to 11.8σ for the 135-line condition. This meant that there was effectively no overlap of luminance between the lines. (The luminance profiles for the 225-line system and the 135-line system are shown in part (c).) This large separation would produce a line structure in the image which was much more pronounced than that seen in systems having a more normal overlap. 1.18σ is used for the 2:1 interlace condition in Figure 4.3-19, for instance, which gives an overlap at the 50-percent brightness level and produces a much "smoother" appearing image. With the large brightness overlap between lines that occurs at the 1.18σ line separation, it is probable that further spread by using spot wobble would degrade the image significantly.

4.3-3 SIGNAL-TO-NOISE RATIO

The data on signal-to-noise ratios (SNR) show that, at the threshold of visual detection, signals can be seen at SNR's in the neighborhood of 0.01 (Figures 4.3-27 and 4.3-28) and that PI performance in terms of both target identification and search time still appear to be improving at SNR's of 37 (Figures 4.3-21 through 4.3-23).

The bandwidth and spectral distribution of the noise strongly influence the effect it has on visual performance. Noise is most disruptive in narrow bands centered on the frequency of the target,
(Figures 4.3-26 and 4.3-27).

At equal energies, narrow bands of high-frequency noise appear more disruptive than equivalent bands of low-frequency noise for sine wave target detection when single frequencies are displayed at a time (Figure 4.3-26). However, in judgements of general picture quality for home entertainment purposes, narrow-band low frequency noisesappears most troublesome (Figure 4.3-32).

When narrow-band noises and wide-band noises of equal energy are compared, the narrow-band noise is found more disruptive (Figure 4.3-27).

The spectral distribution of the noise is important in determining its effect on visual perception. Frequency-dependent weighting functions imposed by transmission systems or coaxial cables affect the judged quality of the displayed image by reducing the high-frequency components (Figures 4.3-31 and 4.3-32).

The commonly accepted method of calculating signal-to-noise ratio for TV systems is:

$$SNR_{dB} = 20 \log \frac{\text{Peak-to-peak signal (volts)}}{\text{rms noise (volts)}}$$

For line-scan transparencies, the influence of signal-to-noise ratio was found to be more pronounced for a difficult identification task than for an easy one (Figure 4.3-33).

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)

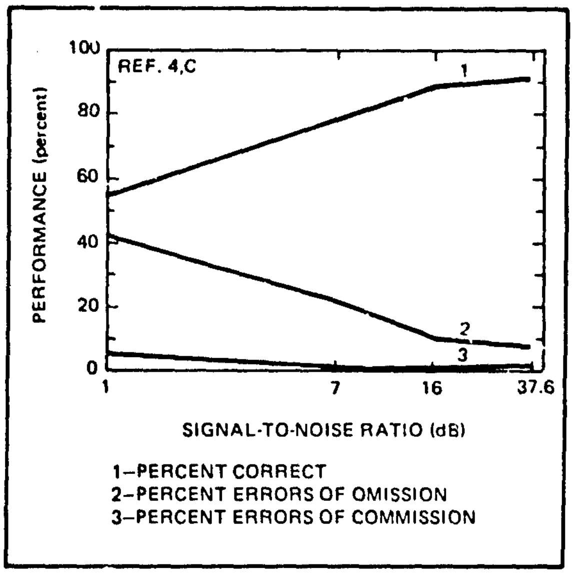


Figure 4.3-21. Target Recognition as a Function of Signal-to-Noise Ratio. The experimental apparatus and imagery used in this study were the same as that described in Figure 4.3-5 (Ref. 4,C); a detailed description can be found there. A subset of 48 targets out of the original 63 targets was used. A combination of 15-MHz bandwidth and 729 TV lines was used. Four signal-to-noise ratios were studied: 1 dB, 7 dB, 16 dB, and 37.6 dB. Methods of SNR measurement and calculation were not reported. The obliquity of the imagery was 7 degrees (measured from nadir). Highlight luminance on the display ranged from 86 cd/m^2 to cd/m^2 (25 fL to 340 fL). Low light luminance ranged from 1.7 cd/m^2 to 411 cd/m^2 (0.5 fL to 120 fL). High light luminance and dark area luminance were measured for the brightest and darkest steps of the RETMA Linear Gray-Scale chart (Ref. 5).

Viewing distance, target visual angles, and scan lines per target were not reported.

The graph in this figure shows the performance as a function of signal-to-noise ratio averaged across all three contrast ratio and image enhancement conditions. Three measures of performance are shown—the percent of correct target identification, the percent of errors of omission, and the percent of errors of commission. The method of calculating the values for the performance measures was:

$$\text{Percent correct recognitions} = 100 \, \frac{\text{Number of correct responses}}{\text{Number of assigned targets}}$$

$$\text{Percent omitted recognitions (Percent errors of omission)} = 100 \, \frac{\text{Number of omitted responses}}{\text{Number of assigned targets}}$$

$$\text{Percent incorrect recognitions (Percent errors of commission)} = 100 \, \frac{\text{Number of incorrect responses}}{\text{Number of correct and incorrect responses}}$$

Performance at 16 dB, as measured by correct recognitions and errors of omission, reached a level where further improvement is difficult to achieve. The 37.6-dB level, however, did show some improvement over the 16-dB level. Twelve college students served as subjects. The data at each point on the curve for percent correct identifications represent 144 observations (12 each for the 12 subjects).

Additional analyses of these data are given in Figures 4.3-22 through 4.3-23 in terms of the time taken to recognize the targets as a function of SNR, target size, and target contrast.

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)

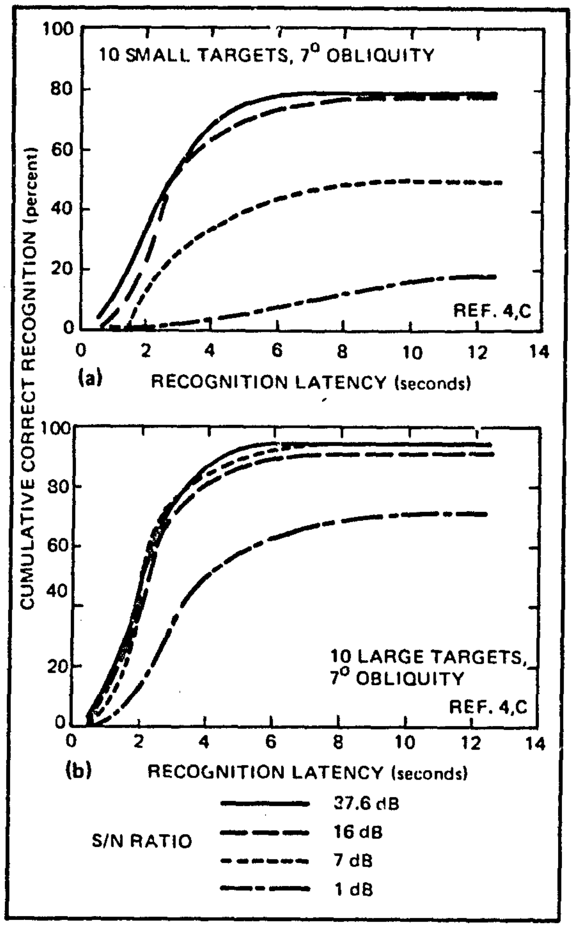


Figure 4.3-22. Time to Recognize Targets as a Function of Signal-to-Noise Ratio and Target Size. These charts show the results of a further analysis of the data given in Figure 4.3-20 for 20 of the 40 targets used for that figure (10 large and 10 small targets). The 20 targets are similar to those described in Figure 4.3-7. The performance measure analyzed was the time taken to recognize the target after it came into the field of view (recognition latency). The values given on the chart were defined as follows:

Recognition latency (seconds) = Duration from instant target enters FOV to instant of correct response

Each curve w[illegible] ...ased [illegible] responses (Ref. 4,C).

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)

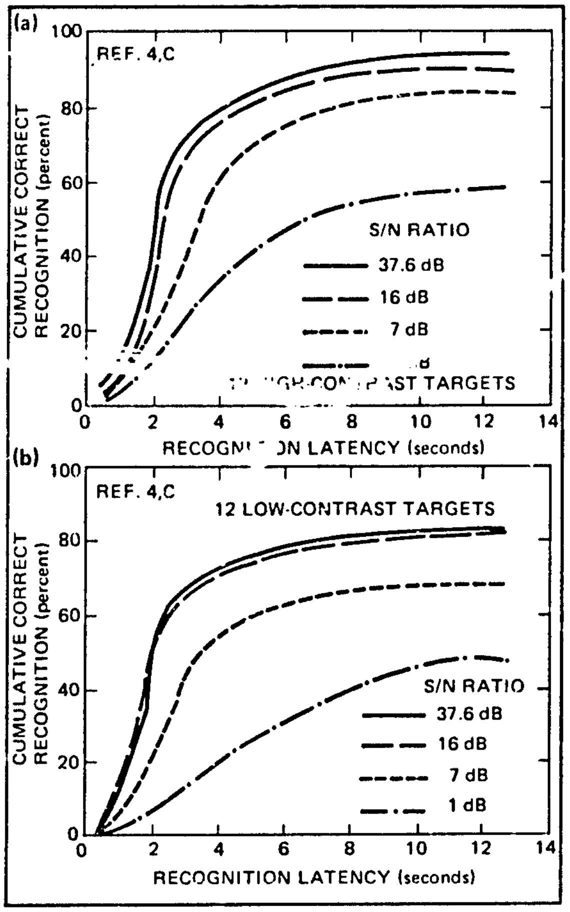


Figure 4.3-23. Target Recognition Time as a Function of Signal-to-Noise Ratio and Target Contrast. These charts show the results of a further analysis of the data given in Figure 4.3-21 for 24 of the 48 targets used for that figure (12 low-contrast targets and 12 high-contrast targets). The 24 targets are similar to those described in Figure 4.3-8.

The performance measure analyzed was the time taken to recognize a target after it had come into the field of view (recognition latency).

The values given on the chart were defined as follows:

Recognition latency (seconds) = Duration from instant target enters FOV to instant of correct response

Each curve was based on 108 responses (9 each from each of the 12 observers) (Ref. 4,C).

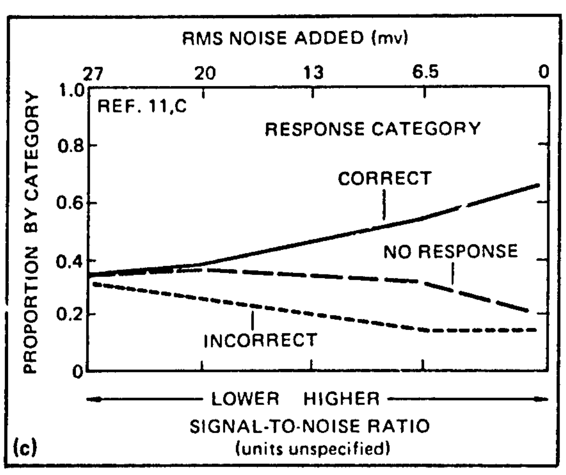


Figure 4.3-24. Effect of Noise on the Recognition of Targets Displayed on Cathode Ray Tubes. The results shown in this figure (Ref. 11,C) were obtained from a television presentation from previously obtained 35-mm film sequences simulating an aerial reconnaissance mission over a terrain model (see Figure 4.3-5 for a general description of the imagery preparation and target types (Ref. 4,C).

One target was presented at a time and was in the field of view of the monitor for approximately 45 seconds. The subjects knew the order in which the targets were to appear and were given a photo of each to use during the test. They were informed when one target had passed from the field of view so they could start searching for the next. The raster was divided into quarters and a response was scored correct if the observer reported the location of the target within the correct quarter of a frame. It was scored incorrect if the wrong quarter of the frame was designated or the target was out of the field of view when the report was given. If the target was missed, a "no response" score was given.

The data were reported in terms of rms noise volts. Since the peak video signal was not given, it was not possible to calculate the SNR. For the purposes of illustrating the results, the SNR has simply been illustrated as varying inversely with the rms noise voltage. A 43-cm (17-in) monitor was used, and the viewing distance was 1 meter (40 in). Target size and contrast on the monitor and monitor luminance values were not reported.

Ambient illumination was low, but not specifically reported.

Eleven subjects were used; each made one observation for each target at each SNR.

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)

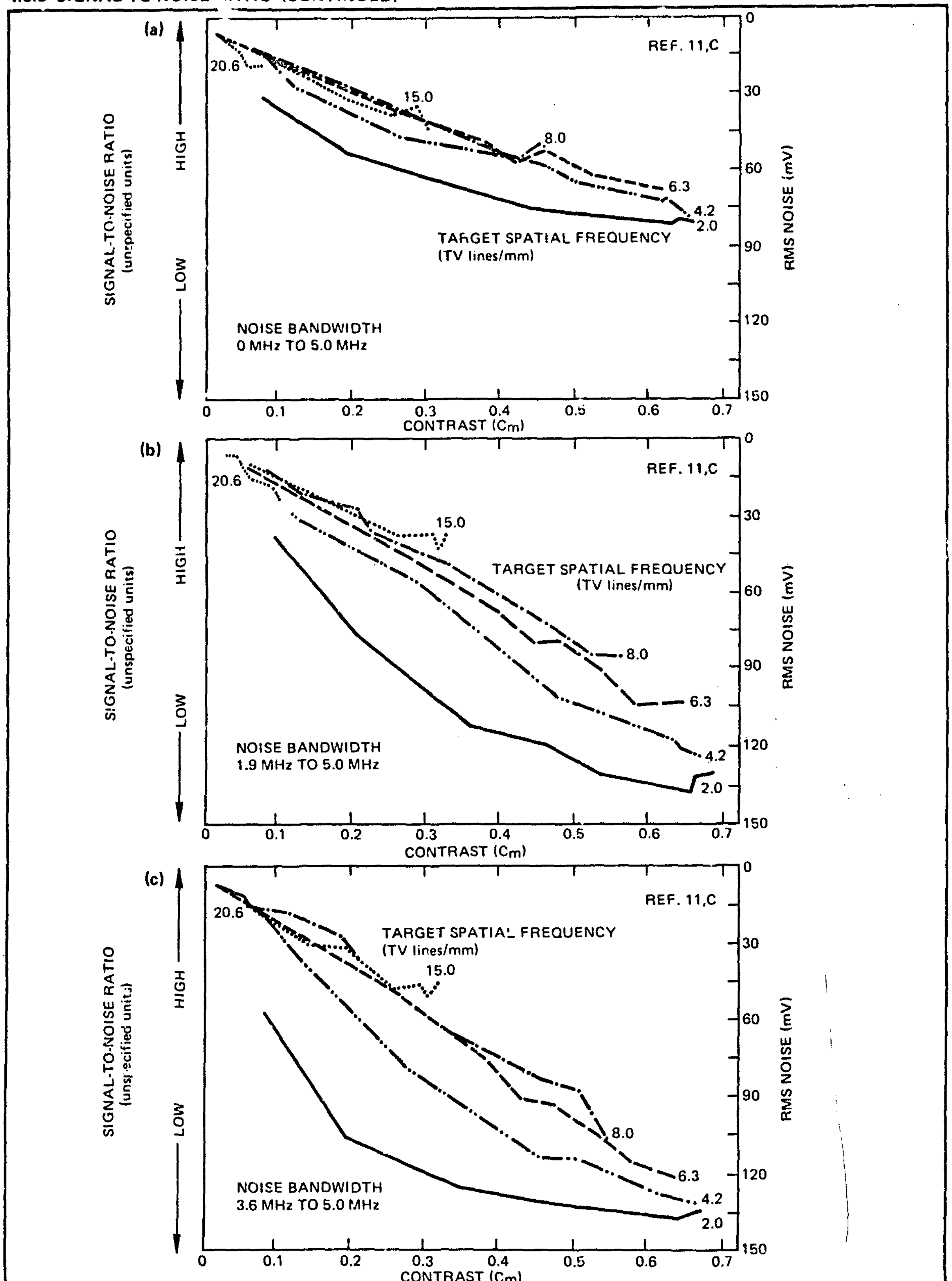


Figure 4.3-25. Effect of Noise Level and Noise Bandwidth on the Detection of Tri-Bar Target Elements

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)

(d)

TV LINES/ (cm)	BAR WIDTH (cm)	TV LINES/ IN	BAR WIDTH (in)	VISUAL ANGLE (arc min)	ESTIMATED* FREQUENCY (MHz)	NOISE BANDWIDTH (MHz) (not to scale) FIGURE (c)	(b)	(a)
2.0	0.50	5.1	0.20	17.2	0.63			0
4.2	0.23	10.7	0.093	8.0	1.3		1.9	
6.3	0.16	16.0	0.062	5.3	2.0			
8.0	0.12	20.4	0.049	4.2	2.5	3.6		
15.0	0.066	38.2	0.026	2.2	4.7			
20.6	0.048	52.3	0.019	1.6	6.4	5.0	5.0	5.0

*CALCULATED BY PRESENT AUTHOR, ESTIMATED 32 cm (12.5 in) HORIZONTAL RASTER DIMENSION.

(e)

TARGET SPATIAL FREQUENCY (TV lines/cm)	TARGET SIGNAL FREQUENCY (MHz)	RMS NOISE VOLTAGE FOR TARGET OF 0.6 C_m FIGURE A	B	C	INCREASE (percent) FIGURE A TO B	A TO C
2.0	0.63	79	135	137	71	73
8.0	2.5	66	82	105	24	59
15.0	4.7	45	45	49	0	9

Figure 4.3-25. Effect of Noise Level and Noise Bandwidth on the Detection of Tri-Bar Target Elements. These three graphs show the effect of noise level and noise bandwidth on the detection of the target elements in a square wave tri-bar target displayed on a CRT. Each curve gives the contrast (C_m) of the target on the display that was necessary to just permit perception of the three separate bars. The bars were displayed perpendicularly to the raster lines. The three graphs represent three different noise bandwidths. For 4.3-25(a) the bandwidth was 0 to 5 MHz; for (b) it was 1.9 MHz to 5.0 MHz; and for (c) it was 3.6 MHz to 5.0 MHz. The relationship of these bandwidths to the calculated target frequencies is given in (d). A 6.6-cm (17-in) diagonal CRT was used in the study, a 4.C-cm (12.5-in) raster width was assumed. The calculations to determine the bandwidth followed the model given in Figure 4.4-12.

The signal for the display was generated by a TV camera viewing specially prepared target material developed from the Air Force tri-bar target (Ref. 11,C). The target material consisted of single tri-bar elements from that target prepared in a number of spatial frequencies and contrasts. The observer's task was to report the noise level at which the bar structure of the target became visible.

Table 4.3-25(e) shows that the noise voltage at which the bar structure of the target remained visible increased 71 percent for the 2-TV-line/mm, 0.6-contrast (C_m) target when the lower end of the noise bandwidth was eliminated; for the 8-TV-line/mm target, the increase was 24 percent. Further reduction in bandwidth (part (c)) had little effect on the higher contrasts of the 2-TV-line/mm target, but the noise level for the 8-TV-line/mm target is increased 59 percent over what it was in part (a). The 15- and 20.6-TV-line/mm targets, which lie outside the bandwidth of the noise for all three graphs, remain substantially unchanged.

It is important to note that the lower contrast (C_m) 2-TV-line/mm targets continued to improve with reduced bandwidth, indicating that these are more sensitive to noise than their higher contrast equivalents.

The bandwidth and TV-line rating of the system could be set to several levels; 8 MHz with a 2:1 interlaced 525-TV-line format was used for the data shown here. The display was a 43-cm (17-in) CRT with a P4 phosphor. The luminance level for a "nearly white bar" was between 61.7 and 63.3 cd/m^2 (18 and 18.5 fL). The noise levels were reported in root-mean-square millivolts (mV$_{rms}$); lack of information on the peak signal strength precludes calculation of the SNR's.

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)

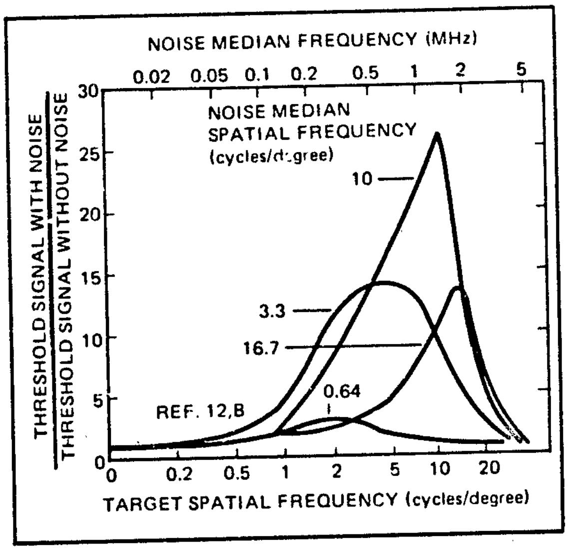


Figure 4.3-26. Effect of Narrow-Band Noise on Sine-Wave Target Visibility as a Function of the Median Frequency of the Noise for a CRT Display. The effect of narrow-band noise on the visiblity of sine-wave targets displayed on CRT's is strongly dependent upon the relationship between the *median frequency* of the noise and the spatial frequency of the target. The median frequency is that frequency which is halfway between the highest and lowest frequency of the noise; it is also sometimes referred to as the center frequency.

Tests were conducted using four *white noise* sources with 200-kHz bandwidths having median frequencies of 0.096 MHz, 0.5 MHz, 1.5 MHz, and 2.5 MHz. These frequencies corresponded to spatial frequencies of 0.64, 3.3, 6.7 and 10 cycles per degree, respectively. The effect of this noise on sine-wave target visibility was measured (12,B).

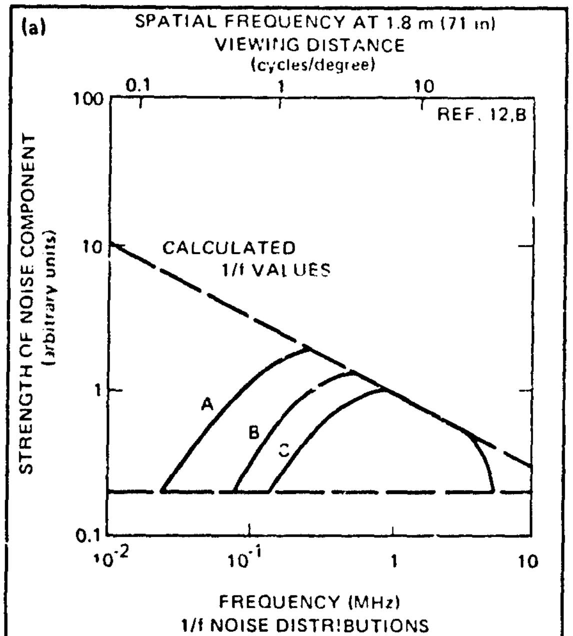
The performance measured was the ability to detect the "bar" structure in the sine-wave targets. The noise level was held constant (1 Vrms), and the results were reported in terms of the ratio tne rms signal strength required for detection with and without noise. With the exception of the target with the lowest spatial frequency, the disruption caused by the presence of the noise is greatest when the median signal frequency of the noise is at or near the signal frequency of the target.

Neither the luminance of the target surround nor the average luminance of the target was reported.

The system used to generate and display the signals had a 8.5-MHz bandwidth. The viewing distance was 1.8m (71 in), and six subjects were used. The number of observations per subject was not reported.

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)

(a)



CURVE	NOISE DISTRIBUTIONS USED IN TEST				
	LOW CUTOFF		HIGH CUTOFF		
	FREQ (KHz)	SPATIAL FREQ (cycles/degree)	FREQ (MHz)	SPATIAL FREQ (cycles/degree)	DISTRIBUTION
A	25	1.4	5	32.5	1/f
B	80	5.0	5	32.5	1/f
C	150	8.5	5	32.5	1/f
D	0	0	5	32.5	WHITE
E	NO ADDED NOISE —			—	—

(b)

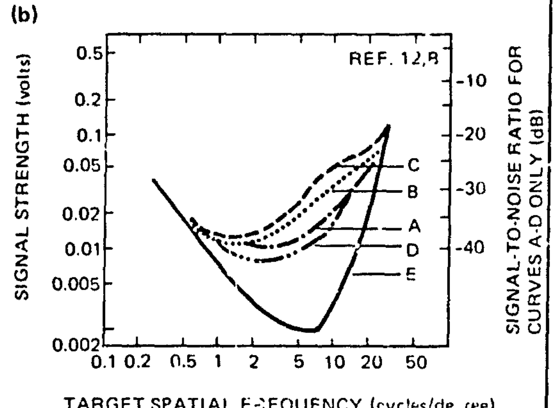
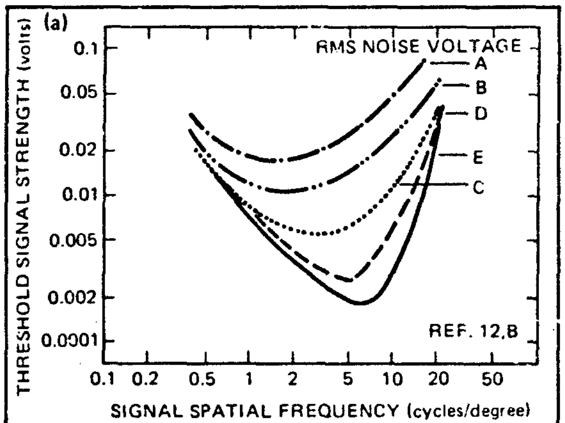


Figure 4.3-27. Effect of the Distribution of Signal Strength and the Bandwidth of Noise on Detection Thresholds for Sine-Wave Targets. The signal-to-noise ratios at which the "bar" structure in sine-wave targets was just detectable were determined for five noise conditions over target spatial frequencies ranging from 0.2 to 20 cycles/degree. In addition to the noise inherent in the system and broad-band (0 to 5 MHz) white noise, three noise sources with a 1/f signal-strength distribution were tested. The characteristics of these distributions and the cutoff frequencies for each are given in Figure 4.3-27(a) (Ref. 12,B). The effects of each of these three noise distributions and two others—a 0 to 5 MHz *white noise* distribution and the inherent noise of the system—were studied. The results are shown in part (b) of this figure. The signal voltage values for curves A through D were converted to signal-to-noise ratios and are shown on the right-hand vertical scale. These values do not apply to curve E, for which no rms voltage value of the noise was reported. For the other curves, the noise had an rms value of 1 volt.

The results for the study reported here indicate that for the 1/f distributions, as more energy becomes concentrated in the higher noise frequencies, it disrupts the visibility of targets whose signal frequencies lie near the median frequency of the noise.

Six subjects participated in the tests; "several" repetitions of the observations by each subject were made. The absolute luminance values and their modulations on the display were not reported for this test, but the average luminance value was kept constant throughout the test. The sine-wave signals and the noise were generated electronically and displayed on a CRT. The "luminance" of the testroom was reported as "much less" than that of the display.

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)



CURVE	NOISE VOLTAGE (rms)
A	1.8
B	1.2
C	0.6
D	0.3
E	NO ADDED NOISE

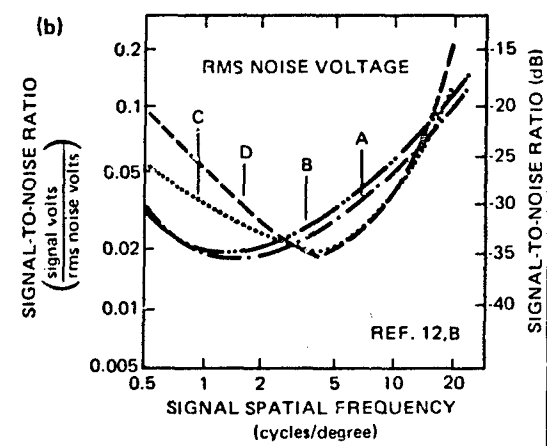
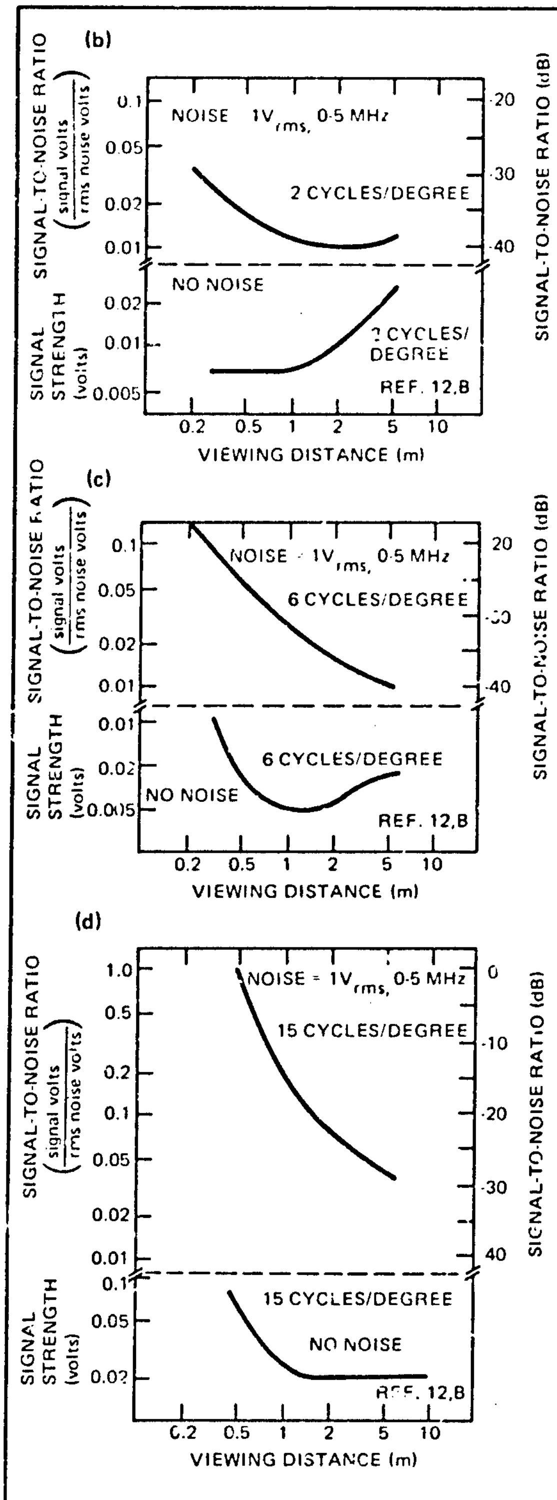


Figure 4.3-28. The Effect of the Strength of Broad-Band Noise on Sine-Wave Target Detectability. Broad-band white noise (0 to 5 MHz) at four levels, 0.3, 0.6, 1.2, and 1.8 volts rms, was introduced into a CRT display of a sine-wave-modulated bar pattern. The modulation of the signal for the pattern was adjusted to determine the point at which the bars in the target were just visible. The results reported by the authors (Ref. 12,B) are shown in Figure 4.3-28(a), where the change of the *peak-to-trough* voltage is shown rather than the rms voltage reported. Figure 4.3-28(b) shows the results replotted as signal-to-noise ratios for the four curves for which the rms noise voltage was given. Curve number E is for the test apparatus with no noise added.

There appears to be an interaction between the strength of broad-band noise and the spatial frequencies at which it was most disruptive to the detection of the bars—the stronger noise having more effect at lower frequencies than the weaker noise.

The apparatus and test conditions were the same as those described in Figure 4.3-26 except that only the broad-band (0 to 5 MHz) noise was used.

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)



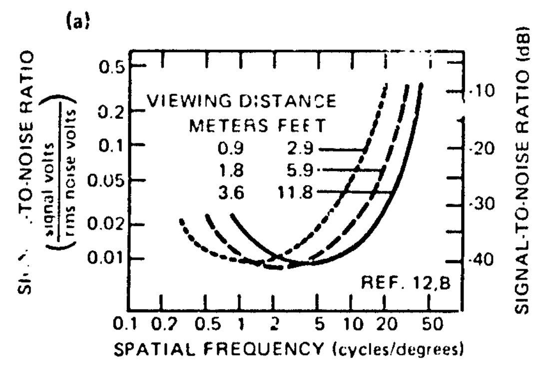
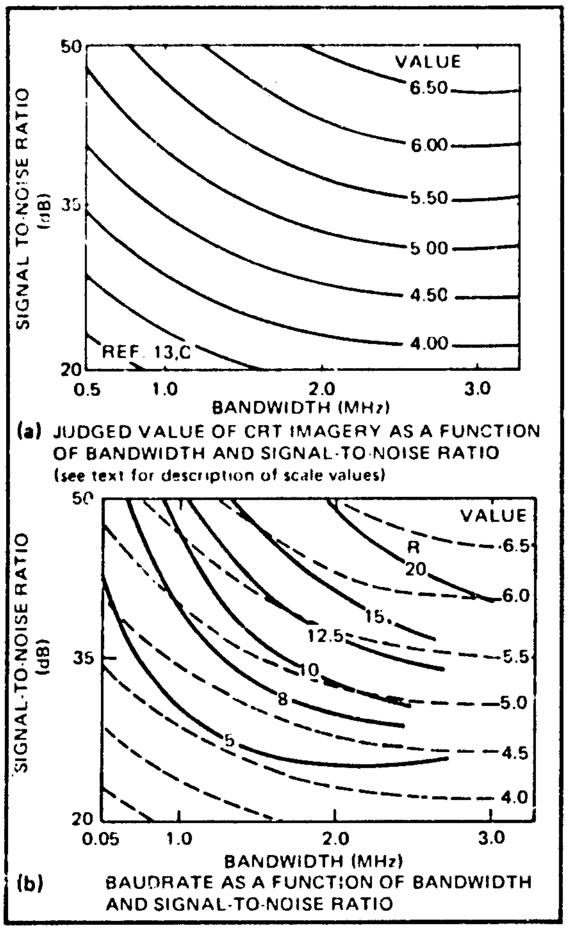


Figure 4.3-29. Effect of Viewing Distance and Target Spatial Frequency on Signal-to-Noise Detection Thresholds. The interactions between viewing distance and the threshold SNR for target detection are complex. In the study reported here, two sets of data are presented (Ref. 12,B). The first, Figure 4.3-29(a), at the top of this column, shows that with reference to the angle subtended at the eye, the spatial frequency that can be detected at a given SNR increases in proportion to viewing distance. Figures 4.3-29(b), (c), and (d) show how the SNR for detection increases as viewing distance increases. For comparative purposes, the threshold signal strengths for noise-free imagery are shown for each spatial frequency. It is clear that the noise is not just raising pre-existing thresholds.

The apparatus used in these studies was identical to that reported in Figure 4.3-26 with the exception that only a broad-band (0 to 5 MHz) signal was used.

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)



(a) JUDGED VALUE OF CRT IMAGERY AS A FUNCTION OF BANDWIDTH AND SIGNAL-TO-NOISE RATIO (see text for description of scale values)

(b) BAUDRATE AS A FUNCTION OF BANDWIDTH AND SIGNAL-TO-NOISE RATIO

Figure 4.3-30. Effect of Bandwidth and Signal-to-Noise Ratio on the Judged Quality of Television Pictures. Subjective quality judgments, based on the scale shown below, were made by 24 subjects for a televised still picture of two "attractive girls" swimming (Ref. 13,C). The picture was presented to each subject using all combinations of the following levels of bandwidth and SNR:

- Bandwidth: 0.5, 1.0, 2.0, and 3.0 MHz
- Signal-to-Noise Ratio: 20, 35, and 50 dB

The signal-to-noise ratio was defined as:

$$\text{SNR (dB)} = 20 \log \frac{\text{Peak signal voltage}}{\text{rms noise voltage}}$$

The noise was described only as wideband and generated by a commercially available random noise generator.

The rating scale used is shown below.

Scale Value	Picture Quality Description
7.	Excellent. The picture is of extremely high quality; it's as good as you could want one to be.
6.	Very good. The picture is of very high quality, providing enjoyable viewing.
5.	Fair. The picture is of fairly high quality.
4.	Marginal. The picture is not good and not bad.
3.	Poor. The picture is poor in quality and you wish you could improve it.
2.	Very poor. The picture is very poor but you could watch it if you really wanted to watch television.
1.	Unusable. The picture is so poor that you could not watch it.

The pictures were presented on a standard 525-TV-line NTSC system (bandwidth unspecified). The subjects viewed the monitor at 71 cm (28 in). Neither display contrast nor highlight luminance was reported. Because the tests were conducted in a semi-darkened room, ambient illumination was low.

The results shown in Figure 4.3-30(a) indicate the need for increasing the SNR as bandwidth is reduced, if subjective picture quality is to be maintained.

Figure 4.3-30(b) shows the same results with *baudrate* curves superimposed. The term "baudrate" refers to the rate at which binary bits are transmitted in a digital system. A baudrate of 1 indicates a transmission of one binary bit per second; the letter R before a baudrate number denotes the rate is in megabauds (1,000,000 bauds). The baudrate curves were calculated from the bandwidth and SNR values using the method described in Reference 14.

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)

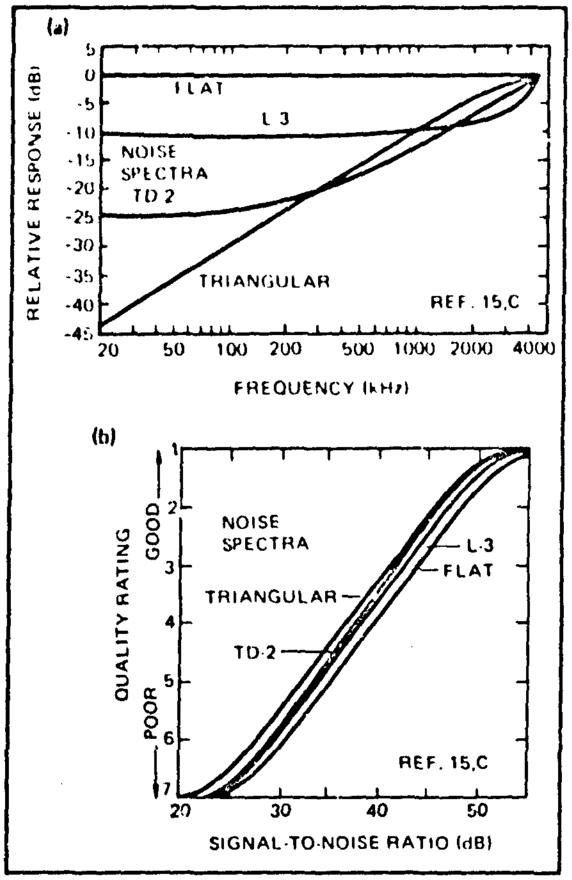


Figure 4.3-31. The Effect of Noise Spectra on Judgments of Picture Quality in NTSC Color Television Systems. Judgments of color television picture quality, using the scale shown below, were made by 10 observers for each of the four noise spectra plotted in Figure 4.3-31(a) (Ref. 15,C).

Scale Value	Judged Degradation
1.	Not perceptible
2.	Just perceptible
3.	Definitely perceptible, but only slight impairment to picture
4.	Impairment to picture, but not objectionable
5.	Somewhat objectionable
6.	Definitely objectionable
7.	Extremely objectionable

The L-3 noise spectrum is typical of the type found in coaxial cable systems. The TD-2 noise spectrum represents that found in TD-2 relay links for long-distance transmission. The flat spectrum and triangular spectrum are not common to broadcast systems but represent what is considered to be bounding conditions. The results (Figure 4.3-31(b)) indicate that for a given level of noise, the quality judgments improved as the low-frequency portions of the noise spectrum were reduced.

The pictures were of still scenes similar in content to those that might be found in commercial broadcasting. Highlight brightness was 86 cd/m^2 (25 fL), and the contrast ratio was between 70:1 and 80:1. The pictures were presented on a 525-TV-line NTSC color television system.

The subjects were seated at a distance from the monitor of 4 times the picture height. No room illumination was provided beyond that created by the monitor.

It must be remembered in interpreting the data in this chart that the judgments were made on the basis of quality for home entertainment, not information extraction. It also must be remembered that the testing was done on an NTSC system which, unlike most closed-circuit TV's, has separate luminance and chrominance signals.

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)

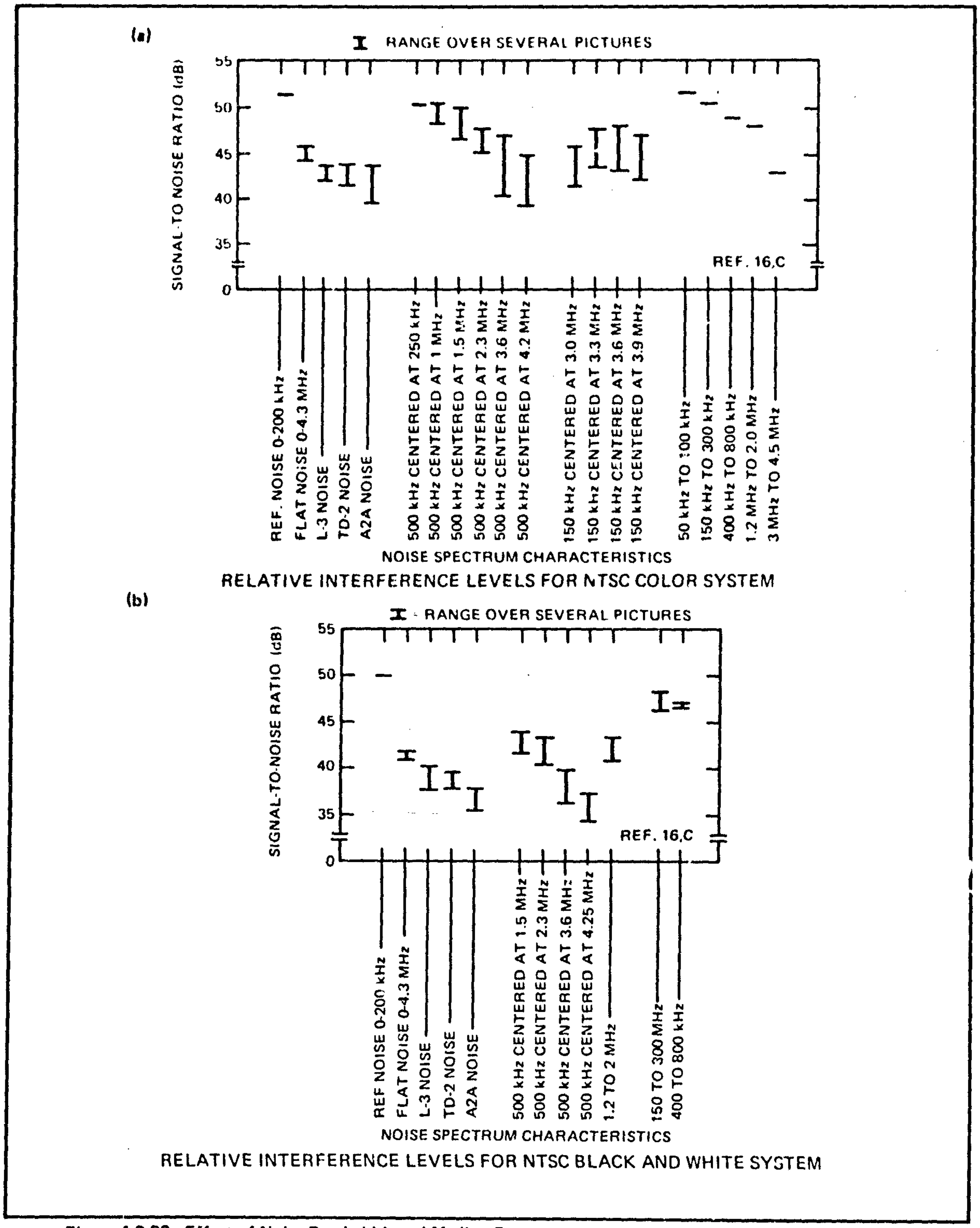


Figure 4.3-32. Effect of Noise Bandwidth and Median Frequency on Judged Picture Degradation for NTSC Color and Black and White Systems

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)

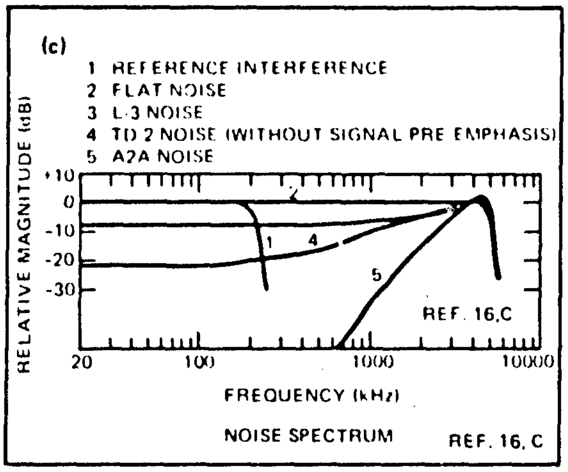


Figure 4.3-32. Effect of Noise Bandwidth and Median Frequency on Judged Picture Degradation for NTSC Color and Black and White Systems. An image containing a 0 to 200 kHz noise source 3 to 6 dB above the threshold for its detection was used as a reference against which images containing other noise spectra were compared. The signal-to-noise ratio in the comparison image was adjusted until the quality of the two images was judged equal. The SNR of the reference noise is plotted at the left of each graph. The range of SNR values which produced images judged to have equivalent quality is shown for each of the spectra tested. Spectra having lower SNR values for judged equality can be considered to be less disruptive than ones having high SNR's.

The spectra for the reference, flat, L-3, TD-2, and A2A noises are shown in part (c) of this figure.

The wide variability shown for the color system (Figure 4.3-32a) for noise located near 3.6 MHz is due to the fact that this is the frequency of the color *subcarrier* in the NTSC system. The adverse effect is greatest for saturated reds and blues.

For the black and white system, the narrow-band (500-kHz) signal had decreasingly disruptive effects as the median frequency moved up (Ref. 16,C).

The data shown for the first 11 noise spectra in Figure 4.3-32(a) are from 80 observations. For the others, an unreported number of observations was made. For the black and white data, each point represents 30 observations.

Still scenes common to broadcast television were used as test material. Viewing was from a distance equal to 4 times the picture height. The highlight luminances averaged about 27 cd/m^2 (8 fL) for the color pictures and 3.4 to 100 cd/m^2 (10 to 30 fL) for the black and white pictures. Each was presented on its own 21-inch monitor; the monitor for the black and white system employed a P4 phosphor.

It must be remembered in interpreting those results that the judgments were made on the basis of quality for entertainment, not information extraction. It also must be remembered that the testing was done on NTSC systems, and that for color, the luminance and chrominance signals are separate.

4.3.3 SIGNAL-TO-NOISE RATIO (CONTINUED)

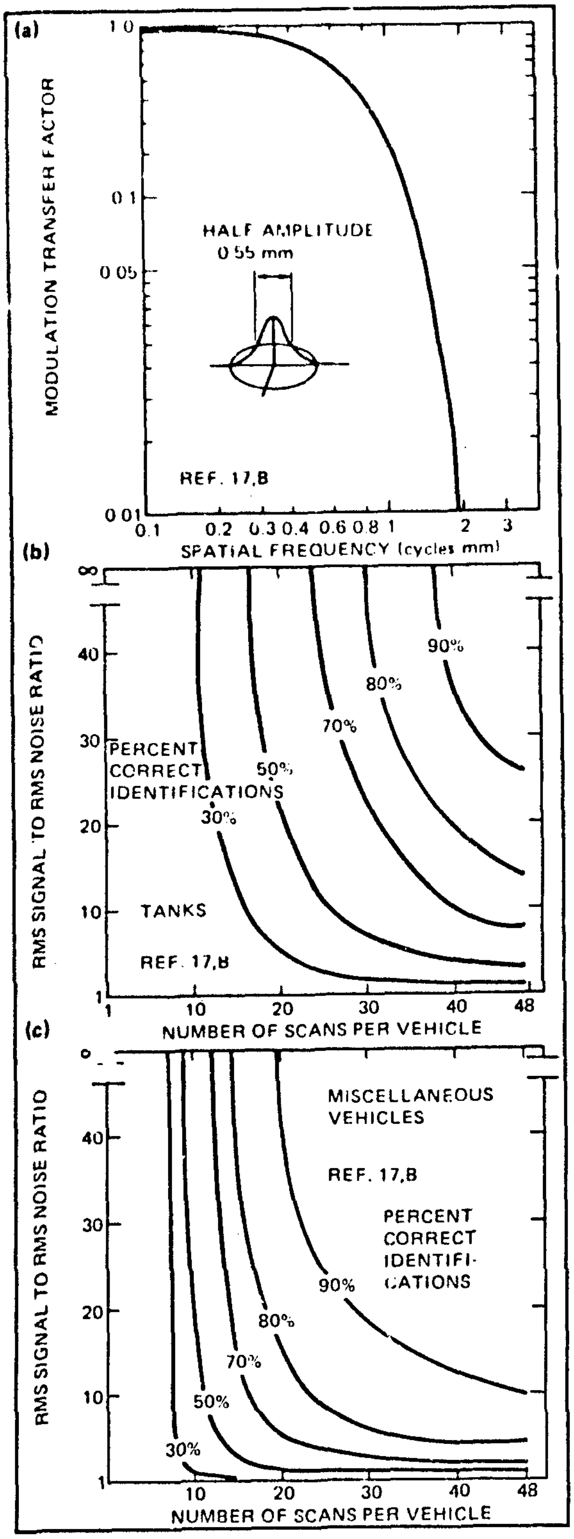


Figure 4.3-33. Effect of the Number of Scan Lines and Signal-to-Noise Ratio on Line-Scan Transparencies. Line-scan transparencies with six levels of SNR and three different numbers of scans per vehicle were tested. The test material was prepared from nadir photographs of models of military vehicles (Ref. 17,B). The term signal-to-noise ratio was defined by the authors as follows:

$$\frac{S}{N} = \left(\frac{\text{Variance of signal}}{\text{Variance of noise}}\right)^{1/2}$$

where:

$$\frac{S}{N} = \left[\frac{\overline{(T_s - \overline{T}_s)^2}}{\overline{(T_n - \overline{T}_n)^2}}\right]^{1/2} = \left[\frac{\overline{(T_s - \overline{T}_s)^2}}{\sigma_n^2}\right]^{1/2}$$

where:

T_s, T_n = instantaneous values of the signal and noise in transmittance with means of $\overline{T}_s$ and $\overline{T}_n$ respectively

σ_n = standard deviation of noise (rms noise) in transmittance

This, however, must not be confused with the definition of signal-to-noise ratio used for television (see Figure 4.1-15 and Ref. 18).

The line-scan imagery was generated using identical scanning and reconstruction spots of *Gaussian* distribution with a σ of 0.235 mm (0.009 in). The pictures were sampled at 0.55-mm (0.02-in) intervals. The *MTF* of the spots is shown in Figure 4.3-33(a). The *transmittance* range of the input imagery was *quantized* into 4096 levels (12 bits). The five signal-to-noise ratios were 3, 5, 10, 20, 30, and ∞. The ∞ case is presumed to have had no noise beyond that of the photographic grain, which would be visually unresolvable with unaided viewing. The number of scan lines per target was 16, 32, and 48. The two performance measures taken were classification and identification. The details of the test and scoring procedures were identical with those described in Figure 4.3-15. Fifty-four college students served as subjects for the study.

The vehicles were classified into two categories: tanks and miscellaneous vehicles. The results for the identification task, as shown in Figures 4.3-33(b) and 4.3-33(c), were different for the two classes. The authors attribute this to the greater heterogeneity of appearance among the vehicles in the "miscellaneous" class, which made them easier to distinguish from one another. No differences in the classification performance were found for any of the image conditions.

4.3.4 DISPLAY CONTRAST RATIO AND GRAY SHADES

Display contrast ratio (C_r) is the ratio between the areas of highest and lowest luminance of the display. The term is most often used in conjunction with CRT's. The ratio may run from approximately 5:1 to more than 100:1 depending upon the design of the tube, how it is operated, and the amount of ambient illumination reflected from the screen.

Figure 3.1-11 compares contrast ratio with other measures of contrast. Additional discussions on the influence of equipment considerations can be found in Sections 4.4.1 and 4.4.2.

Gray-scale steps or *gray levels* are patches of known reflectance or transmittance arranged in ascending and descending order on television test charts. Two types of chart are commonly used, one with equal linear steps and one with equal logarithmic steps which increase by a factor equal to the $\sqrt{2}$ between each step. By determining the highest and lowest step that can be distinguished, a notion of the *dynamic range* of the system can be obtained. The contrast-rendering capabilities of the system can be determined by observing the number of gray shades that can be distinguished and their placement along the scale. Such determinations, however, are not direct indications of the number of *quantized levels* which a digital system can display, as often the difference between two adjacent $\sqrt{2}$ steps is several times larger than the threshold for *just perceptible differences*.

Figure 4.3-34(a) illustrates that a high contrast ratio in a CRT does not necessarily mean that a large number of gray shades can be reproduced. If the luminance transfer through the system is nonlinear, then the differences between gray shades will be compressed in some areas and expanded in others. Such nonlinearities can result in a reduction of the total number of visible steps.

The data in this section indicate that obtaining a high-contrast ratio at the expense of gray shades hurts performance, particularly for more difficult targets (see Figures 4.3-35 and 4.3-36). If the observer has had direct visual access to the scene just prior to its being presented on the CRT, gray shades appear to increase in importance as image scale decreases (Figure 4.3-38).

4.3.4 DISPLAY CONTRAST RATIO AND GRAY SHADES (CONTINUED)

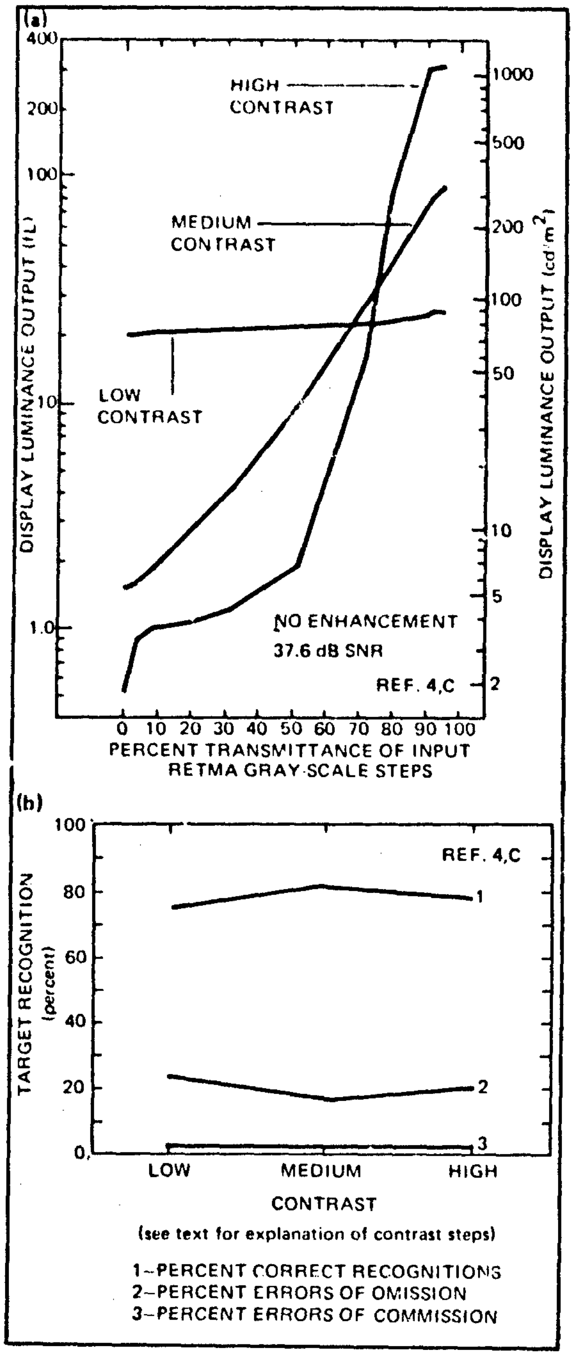


Figure 4.3-34. Target Recognition as a Function of Display Contrast Ratio. The experimental apparatus and imagery used in this study were the same as that described in Figure 4.3-5. A detailed description of the general test conditions can be found there. A subset of 48 targets out of the original 63 targets from that study were used. A 15-MHz bandwidth with 725 TV lines per frame was the only bandwidth/TV-line combination used. Three contrast ratio conditions were established by adjusting the response of the system operating at 37.6 dB SNR to the three curves shown in Figure 4.3-34. As the accompanying table shows, a high contrast ratio is not necessarily associated with the display of a larger number of gray shades. Under favorable SNR conditions (36.7 dB), the high contrast and low contrast conditions are only slightly different in the ability to produce gray shades, and the medium contrast condition is superior to them both; under unfavorable SNR conditions, all the contrast ratios (1 dB and 7 dB) are very similar in gray scale rendition. The accompanying table shows the luminances and display contrast ratios associated with each of the experimental conditions over which the data were collected. Details of the SNR conditions are given in Figure 4.3-34(c). The relationship between shades of gray and contrast ratio should also be noted. Both the low and high display-contrast-ratio conditions produce fewer visible shades of gray than the medium contrast condition. The table accompanying this figure illustrates how interactions between three experimental conditions (contrast ratio, image enhancement, and SNR) affected the visual stimulus produced by a CRT. The reduction in contrast caused by decreasing signal-to-noise ratios for the medium contrast and high contrast conditions is substantial and illustrates one reason for the decreasing performance as SNR decreases. (See Sections 3.1.3, 3.1.4, and 3.1.5 for data on visual performance as a function of contrast.)

The method for calculating the values for the three curves in Figure 4.3-34(b) was:

$$\text{Percent correct recognitions} = 100\left(\frac{\text{Number of correct responses}}{\text{Number of assigned targets}}\right)$$

$$\text{Percent omitted recognitions (Percent errors of omission)} = 100\left(\frac{\text{Number of omitted responses}}{\text{Number of assigned targets}}\right)$$

$$\text{Percent incorrect recognitions (Percent errors of commission)} = 100\left(\frac{\text{Number of incorrect responses}}{\text{Number of correct and incorrect responses}}\right)$$

The data for each point on the curve showing the percent of correct responses represent the average of 144 observations (12 each for the 12 subjects). Further analyses of this data by target size and contrast are given in Figures 4.3-35 and 4.3-36 (Ref. 4,C).

Image enhancement was accomplished by an edge sharpening technique that weighted the value of the second derivative of the video signal from that signal. The effects of this technique on performance are reported in Figure 4.3-52.

4.3.4 DISPLAY CONTRAST RATIO AND GRAY SHADES (CONTINUED)

(c) REF 4.C

EXPERIMENTAL CONDITIONS			DISPLAY PARAMETERS				
DISPLAY CONTRAST RATIO	IMAGE ENHANCEMENT	S/N RATIO (dB)	LOW LIGHT BRIGHTNESS (fL)	HIGH LIGHT BRIGHTNESS (fL)	DISPLAY CONTRAST RATIO	CONTRAST (C_m)	NUMBER OF GRAY SHADES
LOW	NONE	1	21.0	25.0	1.19	0.09	5
		7	20.0	25.0	1.25	0.11	6
		16	20.0	25.0	1.25	0.11	6
		37.6	20.0	25.0	1.25	0.11	7
	MEDIUM	1	21.0	24.0	1.14	0.07	6
		7	20.0	25.0	1.25	0.11	7
		16	20.0	25.0	1.25	0.11	7
		37.6	20.0	25.0	1.25	0.11	7
	HIGH	1	21.0	25.0	1.19	0.09	6
		7	20.5	25.0	1.22	0.10	6
		16	20.5	25.5	1.24	0.11	7
		37.6	20.5	27.0	1.31	0.14	9
MEDIUM	NONE	1	34.0	155.0	4.6	0.66	5
		7	8.5	95.0	11.2	0.84	6
		16	2.9	90.0	31.0	0.94	8
		37.6	1.5	90.0	60.0	0.97	11
	MEDIUM	1	54.0	165.0	3.1	0.51	5
		7	16.0	112.0	7.0	0.75	7
		16	5.7	96.0	16.8	0.90	10
		37.6	2.1	96.0	45.7	0.96	11
	HIGH	1	120.0	235.0	2.0	0.32	4
		7	65.0	147.0	2.3	0.39	6
		16	17.5	115.0	6.6	0.74	9
		37.6	3.4	107.0	31.5	0.94	11
HIGH	NONE	1	55.0	320.0	5.8	0.71	5
		7	2.9	310.0	107.0	0.99+	7
		16	0.8	300.0	378.0	0.99+	7
		37.6	0.5	300.0	600.0	0.99+	7
	MEDIUM	1	72.0	310.0	4.3	0.62	5
		7	19.0	340.0	17.9	0.89	7
		16	2.4	340.0	142.0	0.99+	7
		37.6	1.4	340.0	243.0	0.99+	7
	HIGH	1	120.0	300.0	2.5	0.42	5
		7	55.0	320.0	5.8	0.71	8
		16	14.0	340.0	24.3	0.92	8
		37.6	2.2	340.0	155.0	0.99+	8

Figure 4.3-34: Target Recognition as a Function of Display Contrast Ratio (Contrast ratios and gray shades as a function of experimental conditions)

4.3.4 DISPLAY CONTRAST RATIO AND GRAY SHADES (CONTINUED)

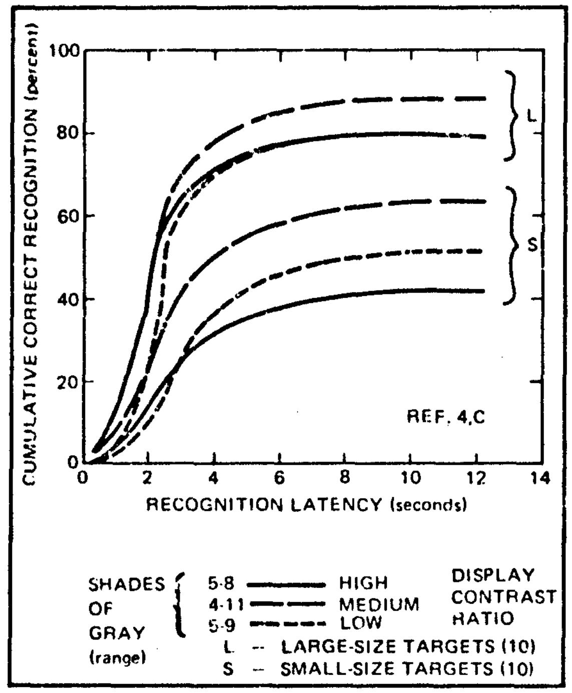


Figure 4.3-35.

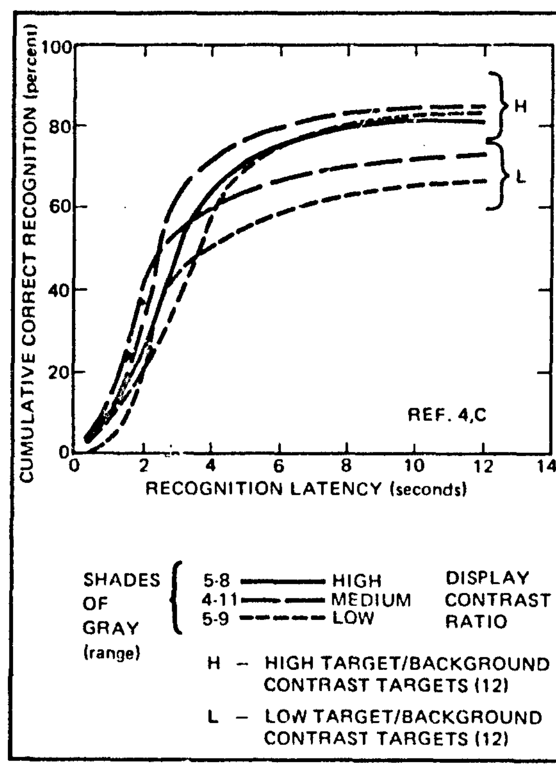


Figure 4.3-36.

4.3.4 DISPLAY CONTRAST RATIO AND GRAY SHADES (CONTINUED)

Figure 4.3-35. Time To Recognize Targets as a Function of Display Contrast Ratio and Target Size. These data are derived from further analysis of the information shown in Figure 4.3-34 for 20 of the 48 targets represented in that figure. The 20 targets were similar to those described in Figure 4.3-7. The performance measure used in the analysis for the present figure was the time from when the target entered the field of view until it was recognized. It was calculated as follows:

Recognition latency (seconds) = Duration from instant target enters FOV to instant of correct response

Each curve represents 120 observations (10 each by each of 12 observers). An estimate of the average number of gray shades for each contrast ratio was made from the data in Figure 4.3-34(c). The estimates were 6.8 for the high contrast condition, 7.8 for the medium contrast condition, and 6.6 for the low contrast condition. It must be remembered that the number of visible gray shades is only indirectly related to the number of visually discernable luminance steps

Figure 4.3-36. Time To Recognize Targets as a Function of Display Contrast Ratio and Target-to-Background Contrast. These data are a further analyses of the information shown in Figure 4.3-34. The performance measure used in the present figure was the time taken to recognize a target after it came into the field of view (recognition latency). This measure was as follows:

Recognition latency (seconds) = Duration from instant target enters FOV to instant of correct response

Some caution is needed in interpreting the differences in results between the two groups of target/background contrast data because the values used were those measured on the terrain model (see Figure 4.3-5) and not on the display.

Twenty-four of the 48 targets from the set used to develop the data in Figure 4.3-34 were used, and they were similar to those used in Figure 4.3-7.

The performance on the medium contrast condition, having an average of 7.8 shades of gray, is superior for both the high- and low-contrast targets (Ref. 4,C).

4.3.4 DISPLAY CONTRAST RATIO AND GRAY SHADES (CONTINUED)

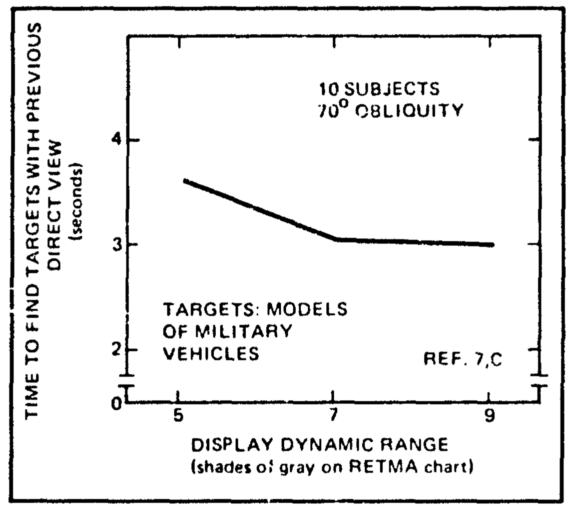


Figure 4.3-37.

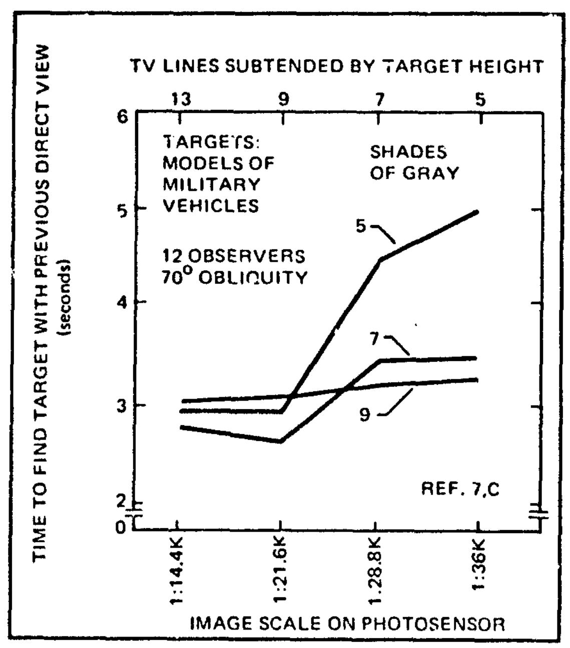


Figure 4.3-38.

4.3.4 DISPLAY CONTRAST RATIO AND GRAY SHADES (CONTINUED)

Figure 4.3-37. Time To Find Targets as a Function of Display Contrast Ratio (Shades of Gray). This chart was compiled from the same data used for Figure 4.3-14, but was analyzed to extract the effect of contrast ratio. The contrast ratio was changed by *clipping* the video signal to remove gray-scale information below preset levels and displaying the gray steps above those levels. Three conditions were studied in which the displayed gray levels were 5, 7, and 9 as measured by the log gray level scale on the RETMA chart (Ref. 7,C).

A precaution is necessary in interpreting this data. Gray levels were found to have an effect only when the observers had visual access to the targets just prior to their display on the CRT. Also, it must be remembered that the gray scale range is only indirectly related to the number of visually discriminable luminance levels in the display (Ref. 6; see Figure 4.3-10 for more information on the experimental conditions).

Figure 4.3-38. Time To Find Targets as a Function of Display Contrast Ratio (Shades of Gray), Image Scale on Photosensor and TV Lines Subtended by Target Height. This graph was compiled from the same data presented in Figures 4.3-11(a) and Figure 4.3-12(a) analyzed for the effects of display contrast ratio. A description of the study from which these data were collected can be found in Figure 4.3-10 (Ref. 7,C). As the scale of the imagery decreased, the importance of gray shades increased. A precaution is necessary in interpreting these data because the results apply only when the observer had visual access to the scene just prior to its being presented on the CRT. When no such prior access was available gray shades did not influence performance (Ref. 7,C).

4.3.4. DISPLAY CONTRAST RATIO AND GRAY SHADES (CONTINUED)

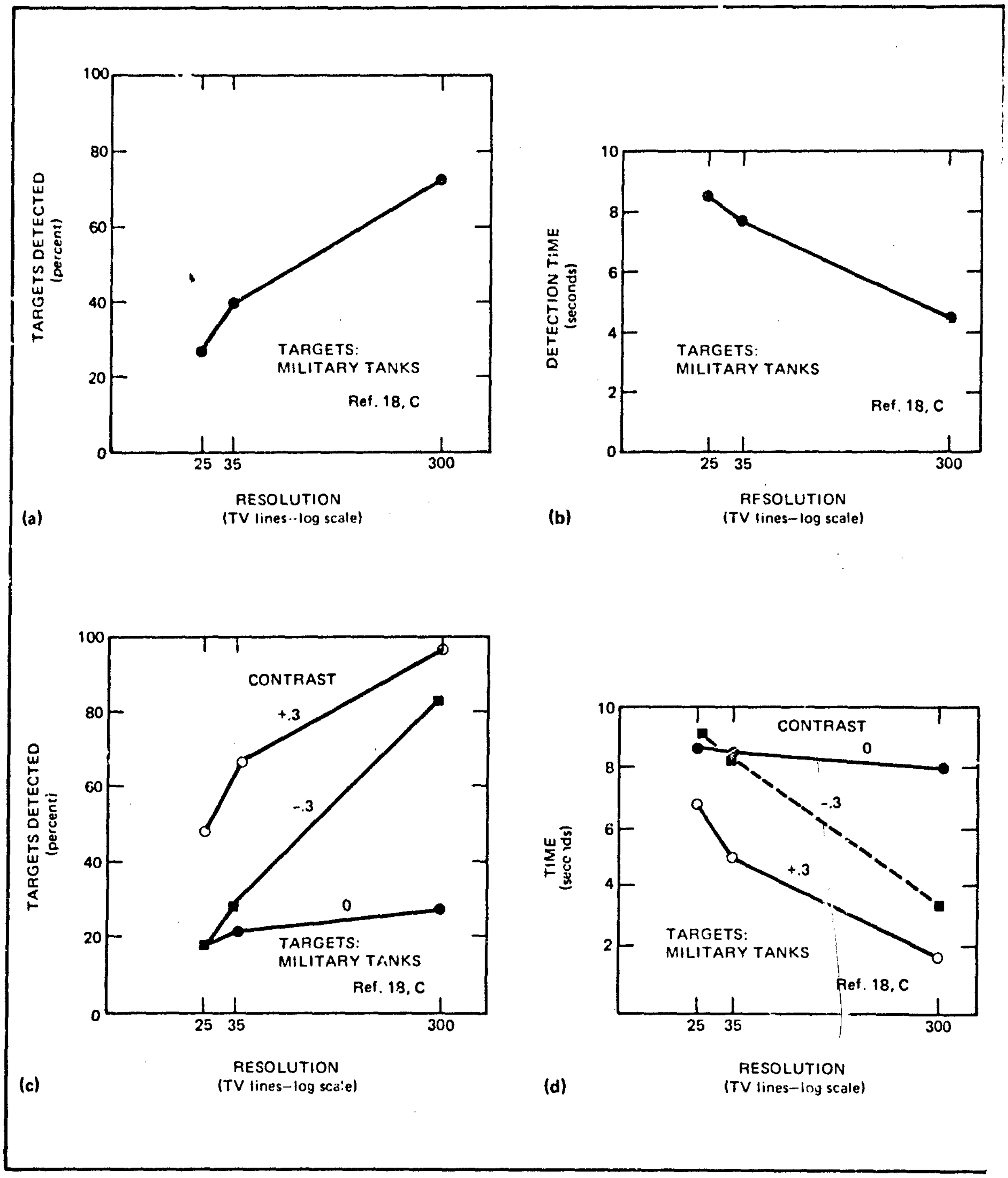


Figure 4.3-39. Detection of Tanks in TV Images as a Function of TV Resolution and Target Contrast

4.3.4 DISPLAY CONTRAST RATIO AND GRAY SHADES (CONTINUED)

Figure 4.3-39. Detection of Tanks in TV Images as a Function of TV Resolution and Target Contrast. In this study the TV resolution was changed by defocusing the lens of the TV camera. Three levels were used—25, 35, and 300 TV lines as measured on the RETMA resolution chart (Ref. 5). The targets (models of army tanks on a terrain model) were presented in a dynamic display simulating an overflight of the terrain model. Only one target at a time was presented, and each was in the field of view for 10 seconds. Three target-to-background contrasts were used: -0, -0.3, and +0.3. Contrast was defined as:

$$\frac{L_t - L_b}{L_b} \quad \text{where:}$$

L_t = target luminance
L_b = background luminance

Two measures of performance were taken: the percent of the targets detected and the time from the appearance of the target in the field of view until its detection. The overall results for these two measures are given in parts (a) and (b) of this figure. For the differences in contrast, the results showed that improved resolution had a greater effect on performance for the higher contrast targets and that it had the greatest effect on the target whose contrast was positive with respect to the background (Ref. 18,C).

The imagery was displayed on a NTSC-compatible color TV system (see Figure 4.1-11 for a brief description of this system). The targets were presented in both the black and white and color modes. The results shown here were averaged over both. (For an analyses of the differences in performance as a function of color versus black and white, see Figure 4.3-51.)

Of the 10 observers used, only 3 had had previous experience in target acquisition studies.

4.3.5 VISUAL CONTRAST DETECTION IN CRT IMAGERY

This section presents information on how the contrast detection limits of the visual system are affected by CRT characteristics. Figure 4.3-40 illustrates the maximum CRT performance levels that can be expected. The data were gathered in careful studies of the visual mechanism; the use of the CRT was incidental to the intent of the studies.

The second study reported in Figure 4.3-41 was conducted for the specific purpose of determining visual contrast thresholds for CRT displays. Comparison of the results is not a straightforward process because of the differences in the studies. However, the range of thresholds shown between the two figures is probably a reasonable estimate of the range that can be expected in operational settings. The performance achieved will depend greatly on the care with which the viewing situation is designed, the difficulty of the work being performed, and time pressures.

4.3.5 VISUAL CONTRAST DETECTION IN CRT IMAGERY (CONTINUED)

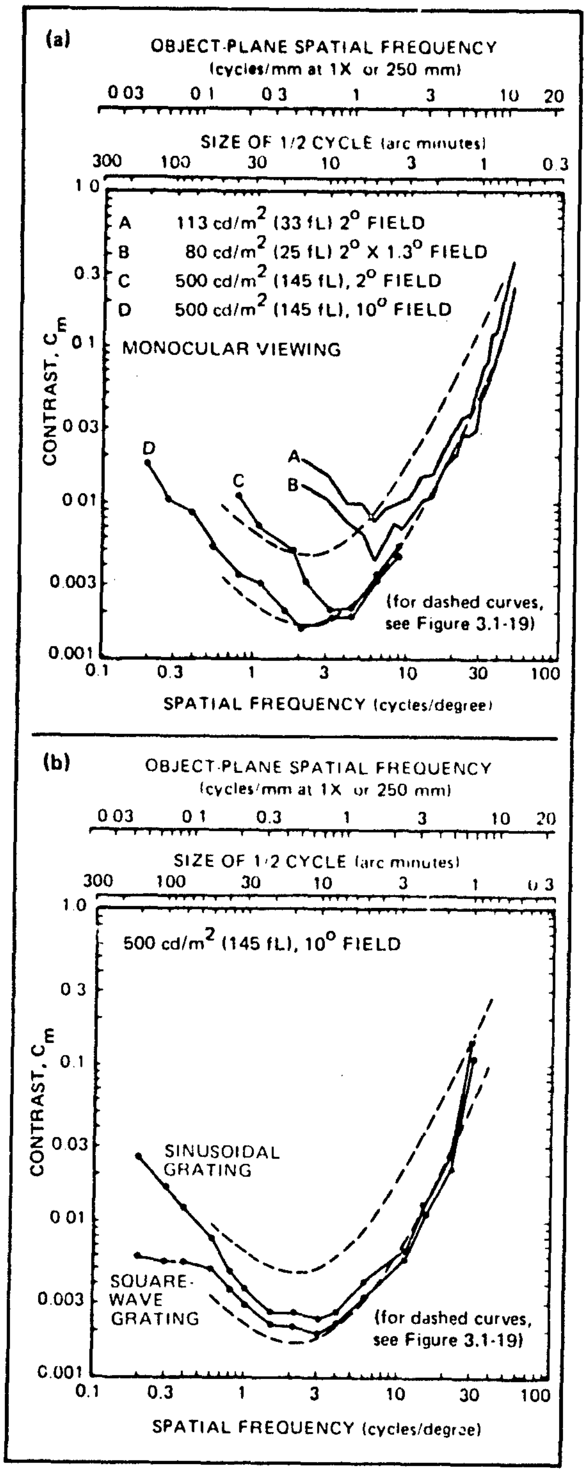


Figure 4.3-40. Minimum Detectable Contrast on CRT Displays. The data shown on these two graphs come from three different studies run under differing conditions by different authors (Ref. 19, 20, 21). They indicate trends rather than quantitatively comparable data.

The studies were run under conditions which maximized the contrast sensitivity of the eye. They indicate that under ideal viewing conditions, contrasts (C_m) of as low as 0.002 are detectable. In interpreting these results, consideration must be given to the fact that the test objects were represented in a field whose luminance was closely matched to the average luminance of the test object and that the visual task was simply one of detection. When large differences exist between the luminance of the target and that of the area surrounding it, the thresholds will be significantly higher (see Section 3.1.10 and Figure 3.2-12). Increasing the difficulty of the task from detection to identification or classification of the target will have a similar effect. The study reported in Figure 4.3-41 found contrast thresholds for the 95 percent level of detection much higher than those reported here. Comparison of the results is difficult because of the different nature of the targets involved, different thresholds reported, and likely differences in experimental design. Taken together, they probably represent the contrast detection range that can be expected for CRT viewing in the environment of the image interpreter. For more rigorous viewing environments, for instance in the presence of very high ambient illumination or of vibration, the thresholds will increase further.

The data shown in Figures 4.3-40(a) and 4.3-40(b) were derived as follows:

Figure 4.3-40(a)

Curve	Reference Figure
A	3.1-23
B	3.1-26(b)
C	3.1-29
D	3.1-29
E	3.1-29

Figure 4.3-40(b) 3.1-28

Further information on the conditions under which the data were collected are given in these earlier figures. A description of the dashed curves can be found in Figure 3.1-19.

4.3.5 VISUAL CONTRAST DETECTION IN CRT IMAGERY (CONTINUED)

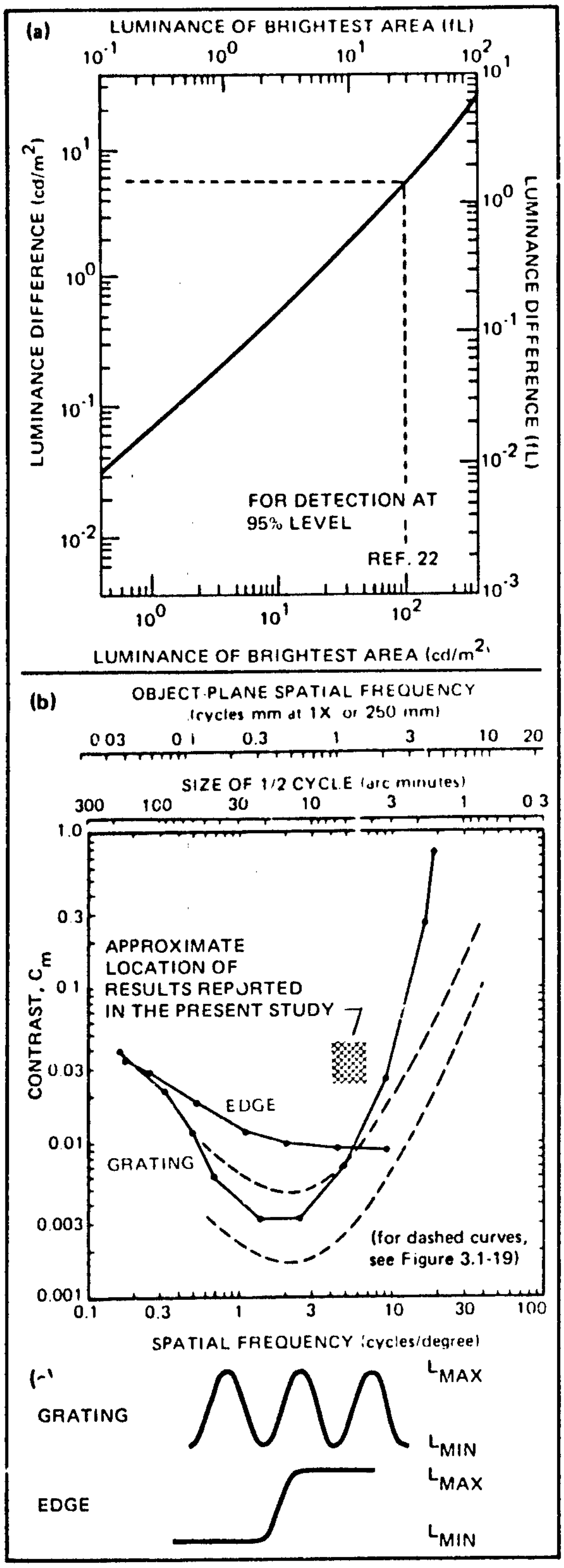


Figure 4.3-41. Contrast Detection Between Adjacent Areas on a CRT Display. A square area, subtending approximately 2 degrees of visual angle per side, was divided vertically into two areas approximately 1 degree wide and 2 degrees long. The luminance of one area was held constant and that of the other was adjusted to determine the difference necessary for detection 95 percent of the time (Ref. 22).

The area of the CRT which lay outside of the 2X2-degree test area was masked off.

The results indicate that contrasts (C_m) between 0.026 and 0.044 were needed to ensure that the luminance difference between the two sides of the rectangle could be detected 95 percent of the time under the conditions of this test. Contrast (C_m) can be calculated from Figure 4.3-41(a) as follows:

From Figure 3.1-10:

$$C_m = \frac{\text{Higher luminance - lower luminance}}{\text{Higher luminance + lower luminance}}$$

From Figure 4.3-41(a), at 100 cd/m^2 (29 fL), the luminance difference needed to be detectable at the 95-percent threshold is approximately 5.5 cd/m^2 (1.6 fL). If 100 cd/m^2 (29 fL) is taken as the higher luminance, then 100-5.5 or 94.5 cd/m^2 (27.6 fL) will be the lower and:

$$C_m = \frac{100 - 94.5}{100 + 94.5} = \frac{5.5}{194.5}$$

$$C_m = 0.03$$

These numbers are much higher than those reported for the detection of cyclical targets in Figure 4.3-40. The visual tasks were quite different. The targets in the earlier figure were cyclical and the detection threshold was set at 50 percent. For the present study, the target was a divided rectangle, with a single edge separating the two luminances. Figure 4.3-41(b) shows that the detection of such an edge depends upon the slope of the transition between the two luminances. The data in Figures 4.4-24 and 4.4-25 show that because of internal reflections in the face of the CRT, the luminance gradient between the two areas may be 4 to 6 mm (0.16 to 0.24 in) wide before the brightness drops to 10 percent of its maximum value. This distance is equivalent to 4.5 to 7 arc minutes for the viewing distance used to collect the data for Figure 4.3-41(a). Figure 4.3-41(b) shows a 50-percent contrast detection threshold of between 0.008 and 0.009 for such an edge in non-CRT displays. Thus it would appear that the 95-percent contrast threshold reported in the present study is 3 to 4 times that for the 50-percent threshold for non-CRT displays.

The spatial frequency of the edge target was taken as the spatial frequency of a grating with an equal luminance gradient. Figure 4.3-41 (c) shows, to scale, the luminance distribution of two targets with numerically equal modulation and spatial frequency.

The relative contribution of the differences in thresholds, viewing conditions, and display apparatus to the discrepancies between the results cannot be determined from existing data.

4.3.6 QUANTIZING LEVELS

Quantizing refers to the process of dividing the range over which the image signal strength varies into a number of discrete steps. The number of steps is usually some multiple of 2 (2, 4, 8, 16, etc.). The number of steps used is designated by the power to which 2 must be raised to produce the desired number; the powers are referred to in binary terminology as the number of bits. Since $2^3 = 8$, an image whose signal strength range has been divided into eight steps is said to have a quantized level of 3, or 3 bits. In practice, much higher levels of quantization are used, 5 to 8 being common (32 to 256 steps). (See Figure 4.1-5 and 4.4-13).

No studies could be found dealing with image interpretation performance on CRT's as a function of quantizing level. Two studies using subjective assessments of CRT image quality are included (Figures 4.3-42 and 4.3-43).

In an interpreter performance study using transparencies, the number of quantizing levels required to reach a given performance level was found to be inversely related to the number of scan lines subtended by the target. However, from the standpoint of total systems requirements, fewer total bits of information (horizontal resolution x vertical resolution x quantizing levels) were needed for the lower number of scan lines. It must be noted, though, that the performance levels above 80 percent were achieved only with the higher line-number conditions (Figure 4.3-44).

4.3.6 QUANTIZING LEVELS (CONTINUED)

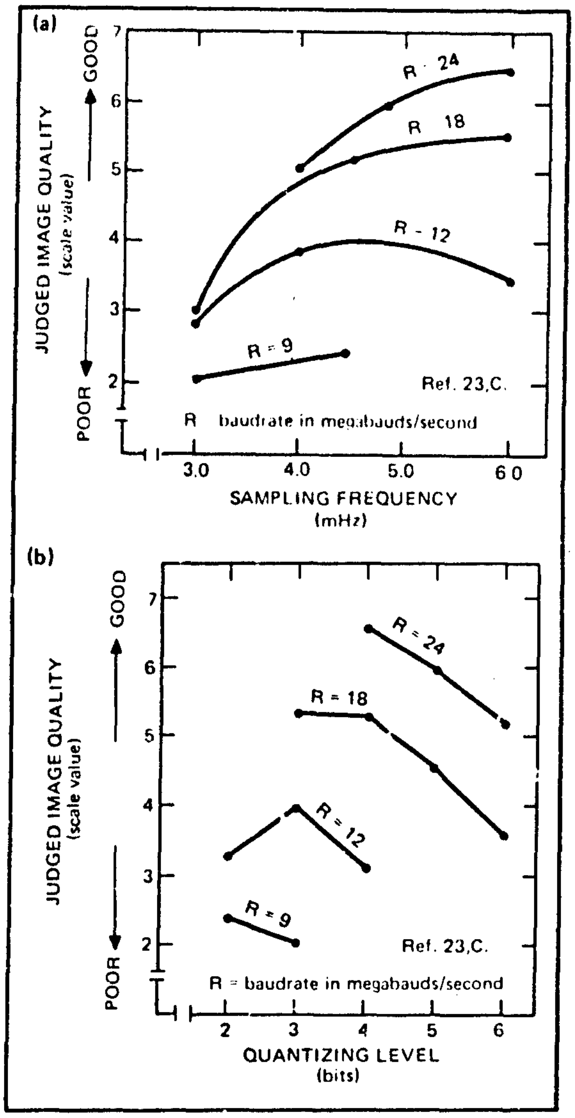


Figure 4.3-42. Relative Value of Sample Frequency and Quantizing Levels in Differential Pulse Code Modulated (DPCM) Systems. In *pulse code modulation* (PCM) and *differential pulse code modulation* (DPCM) systems, the available bandwidth must be partitioned between the frequency with which a signal is sampled and the number of levels to which the amplitude of the signal is quantized. In terms of imaging systems, the sampling frequency determines the spatial resolution of the system and the levels of encoding determine the number of contrast steps for the luminance signal. See Figures 4.1-5 and 4.4-13 for discussions of quantizing, PCM, and DPCM. In discussing these systems the terms *baud* and *baud rate* are used to denote a single pulse and the rate at which these pulses are processed. A 1-megabaud system is one whose bandwidth will handle 1-million signal pulses a second. Such a system is said to have a baudrate of R = 1, R being used to designate the number of megabauds.

In the study reported here, image quality was judged for photographs prepared from 12 combinations of sampling rate and quantizing level. These 12 combinations were divided among four baudrates as shown below:

Baudrate (R)	Quantizing Levels (bits)	Sampling Frequency (MHz)
9	2	4.5
	3	3.0
12	2	6.0
	3	4.0
	4	3.0
18	3	6.0
	4	4.5
	5	3.6
	6	3.0
24	4	6.0
	5	4.8
	6	4.0

The rating scale used was:

Scale value	Judged image quality
7	Excellent
6	Very Good
5	Good
4	Fair
3	Passable
2	Poor
1	Unusable

Two scenes were used to prepare the sampled imagery. One was a portrait of a girl and the second was a very high oblique photograph of a college campus.

Part (a) of this figure shows the results of the quality ratings for each baudrate. For the three higher baudrates it appears that the judged image quality has reached or is approaching a maximum value as a function of sampling frequency. The fact that these curves, in general, show increasing quality as a function of increasing sampling frequency means that for a given baudrate, as spatial frequency is given up for increased quantizing levels, the judged quality must decrease. This decrease is shown in part (b) of this figure in which the data from part (a) is replotted as a function of quantizing levels (Ref. 23,C).

The limitations of applying this data to interpretation situations must be recognized. First, the extent to which the quality judgment data reflects potential interpretation performance is not known; second, applying the results outside the studied range of baudrates, quantizing levels, and sampling frequencies should only be done with caution.

The imagery was presented on a black and white television monitor viewed at a distance equal to 6 times the picture height. The monitor had a contrast ratio of 50:1 and the testing took place in a dimly lighted room. Nine observers were used and all made three judgments at each of the combinations of quantizing level/sampling frequency for each scene, for a total of 72 judgments per observer.

4.3.6 QUANTIZING LEVELS (CONTINUED)

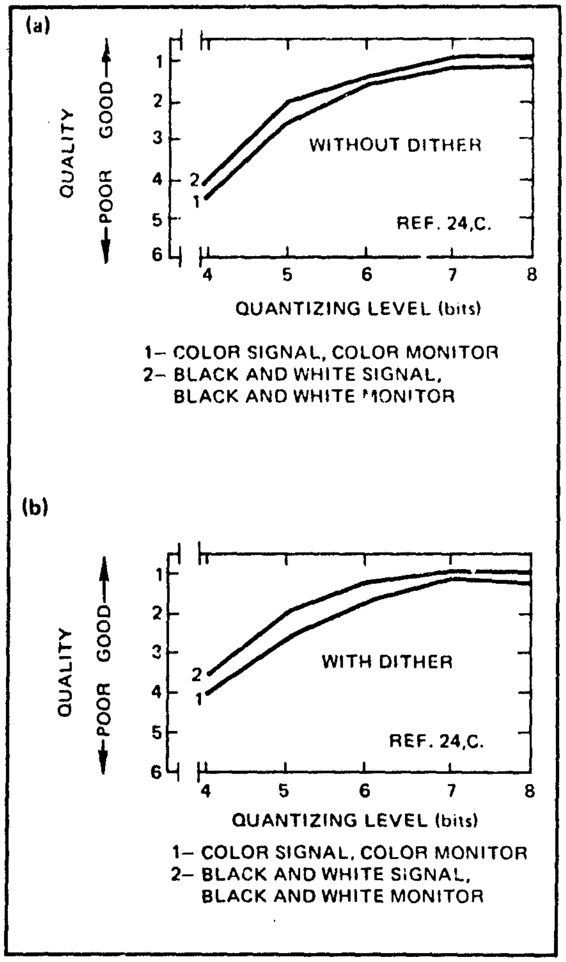


Figure 4.3-43. Effect of Quantizing Levels and Dither on Subjective Judgments of CRT Picture Quality. The quality of pictures of ordinary scenes presented on CRTs was judged as a function of the following factors:

1) Level of quantizing

2) Color or black and white CRT

3) Presence or absence of combined *dither* and noise

The levels of quantization and the number of steps these represent are given below:

Quantizing level	Number of steps
4	16
5	32
6	64
7	128
8	256

4.3.6 QUANTIZING LEVELS (CONTINUED)

Dither, as used in quantizing, is the addition of a high-frequency, low-amplitude noise or square-wave pulse to the signal being quantized. This has the effect of "blurring" the edges of the displayed image, and for low levels of quantization where pictures tend to look "blocky," the subjective quality is improved. The scale used to judge the picture quality was:

Scale value	Judged degradation
1	Imperceptible
2	Just perceptible
3	Definitely perceptible but not distrubing
4	Somewhat objectionable
5	Definitely objectionable
6	Unusable

The results indicate that, as expected, dither was helpful at the lowest quantizing level (4 bits) but had little or no effect at levels above that. The black and white pictures were more acceptable at every quantizing level than the color pictures. At 6 bits for both color and black and white, the average judgment (from seven observers) was that the effects of quantization lay somewhere between imperceptible and just perceptible.

In interpreting these results, it must be remembered that the pictures were being judged for quality as it relates to home entertainment requirements, not from the standpoint of information extraction.

The quantizing was done on standard NTSC *composite* video signals. The system had a 4.4-MHz video bandwidth at the -3 dB level and a SNR or 44 dB. SNR was defined as peak-to-peak signal/rms noise. The highlight luminance was 65 cd/m^2 (19 fL). The ambient illumination came from "softly illuminated" gray walls. Seven subjects (engineers) served as observers, and each made one judgment under every condition; therefore each data point is the average of seven judgments (Ref. 26,C).

A description of the quantizing process can be found in Figures 4.1-5 and 4.4-13.

4.3.6 QUANTIZING LEVELS (CONTINUED)

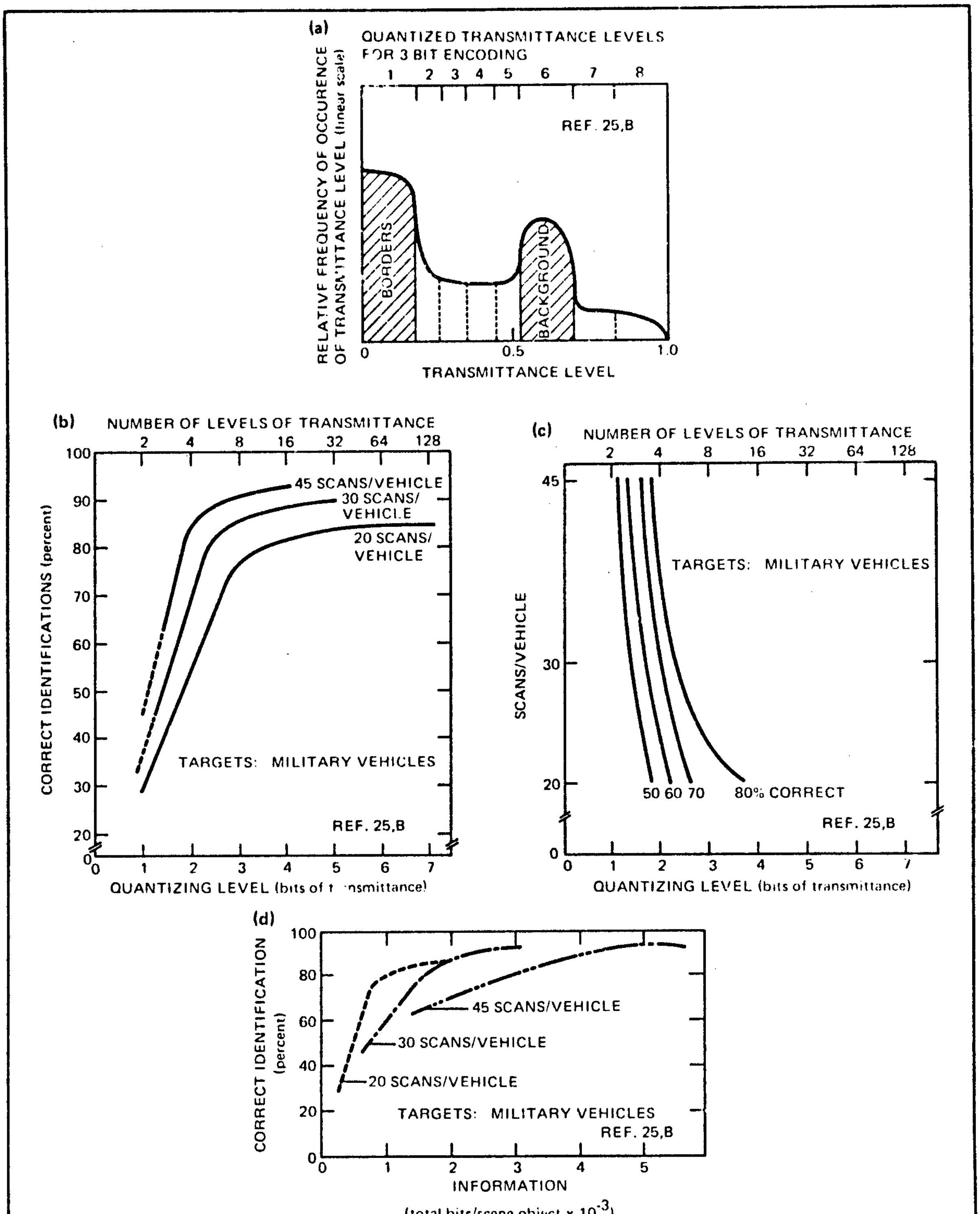


Figure 4.3-44. Effect of Quantizing Levels and Number of Scan Lines on Vehicle Identification From Spot-Scan Transparencies

4.3.6 QUANTIZING LEVELS (CONTINUED)

Figure 4.3-44. Effect of Quantizing Levels and Number of Scan Lines on Vehicle Identification From Spot-Scan Transparencies. Spot scan transparencies were prepared from nadir photographs of scale models of military vehicles. Seven *quantizing* levels, 1, 2, 3, 4, 5, 6, and 7 bits (2, 4, 8, 16, 32, 64, and 128 levels), and three different number of scans per vehicle, 20, 30, and 45, were used. A complete set of transparencies was prepared; i.e., for each quantizing level, all three line scan levels were used (Ref. 25,B).

A Gaussian spot with a 2σ diameter of 0.55 mm (0.022 in) was used both to sample the photographs and print the transparencies. The spot spacings for sampling and printing were also identical (0.54 mm, 0.021 in). The spacing between scan lines was equal to the spot spacing, making the sample spacing equal in both the horizontal and vertical dimensions. Since the spot size and spacing remained the same for all three scan-line-per-target conditions, the scale of the targets was in the same ratio as the number of lines.

Except for the 1-bit and 2-bit levels, quantizing was nonlinear and was carried out as shown in Figure 4.3-44(a). The example shown is for 3-bit encoding (8 levels). The *transmittance histogram* was divided into equal areas under the curve; i.e., equal probability of occurrence, except for the background and border areas, to which one gray level each was assigned. Note that this results in a nonlinear assignment of transmittance levels.

Each transparency contained images of 25 vehicle models. Performance was measured in percent of vehicles that were properly identified. Scale models of the vehicles were on display during the test. Viewing distance, visual angles subtended by the targets, their contrast, and luminance levels were not reported. Figure 4.3-44(b) shows performance as a function of quantizing levels for each scan-line-per-vehicle level. Figure 4.3-44(c) shows the same data plotted as a function of performance level. Figure 4.3-44(d) shows the results plotted for each scan-line condition as a function of the total number of bits per vehicle. The total number of bits per vehicle was defined as follows:

$$\text{Bits/vehicle} = N_p$$

where:

N = sampling elements/vehicle
p = bits of transmittance associated with each sampling element.

Since the number of sampling elements is equal to the square of the sampling parameter (scans/vehicle)

$$N = (\text{scans/vehicle})^2$$

The number of sampling elements/vehicle is proportional to the size of the scene object, which varied somewhat among vehicle models. At the lowest value of the sampling parameter (20 scans/vehicle), there were approximately 244 sampling elements over the image of the smallest vehicle and about 315 sampling elements over the largest. The abscissa in the figure reproduced here as 4.3-44(d) was scaled to correspond to an average of 280 sampling elements for this case.

The results indicate that for a given performance level the number of quantizing levels is inversley related to the number of scan lines per vehicle. However, information requirements in terms of total bits per scene are directly related to the number of scan lines per vehicle at a given performance level. A description of quantizing can be found in Figures 4.1-5 and 4.4-13. Spot shape is described in Figure 4.1-9, and a study on the effects of spot shape on image quality is reported in Figures 4.3-56 and 4.3-57.

4.3.7 IMAGE MOTION

While several of the studies reported in Section 4.3.1 involved moving images, none investigated the effects of the motion itself. Many studies have been done on the effects of image motion in other types of displays (see Section 3.10), but none involved the use of a television camera or CRT.

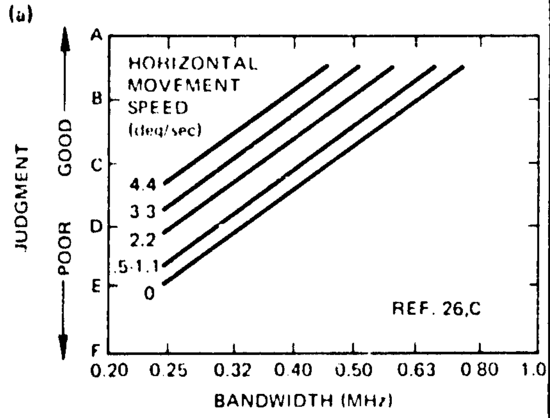
Both TV cameras and CRT's have characteristics that degrade the quality of moving images. In the case of the camera, both the frame time and residual image left after each scan, called *lag*, contribute to the degradation. In CRT's the phosphor persistence is the source of the degradation.

Four studies are reported in this section. The first involves judged quality comparisons between two moving images of different resolution. The second is a performance study that shows interactions between the scan lines per target and target orientation, as a function of image velocity. The third is a performance study in which the target motion was erratic in the manner that would be expected in images from guided weapons being affected by atmospheric turbulance. The fourth concerns the effect of combined horizontal and vertical jitter on image quality judgements.

Data concerning the influence of image motion on the resolution of a TV camera are reported in Figure 4.4-24.

4.3.7 IMAGE MOTION (CONTINUED)

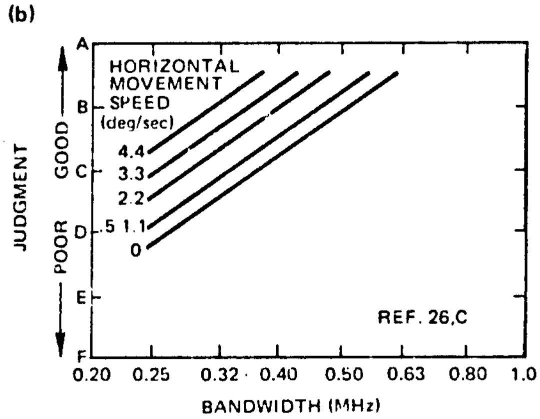
(a)



TARGET WITH MANY HIGH-CONTRAST EDGES

BANDWIDTH REDUCTIONS CAUSING JUST PERCEPTIBLE IMAGE DEGRADATION				
IMAGE MOTION		BANDWIDTH		
VISUAL ANGLE (deg/sec)	FRAME WIDTHS/ SEC	TEST SCENE (MHz)	COMPARISON SCENE (MHz)	PERCENT REDUCTION (test comparison)
0	0	1.0	0.63	37
~0.5-1.1	0.23-0.45	1.0	0.56	44
2.2	0.27	1.0	0.48	52
3.3	0.41	1.0	0.42	58
4.4	0.54	1.0	0.37	63

(b)



TARGET WITH FEW HIGH-CONTRAST EDGES

Figure 4.3-45. Relationship Between Bandwidth, Image Motion, and Judged Image Quality. A series of comparisons were made between two images of a moving object presented sequentially on a CRT. One image, the test scene, was transmitted at the fixed bandwidth common to all tests (1 MHz); the other, the comparison scene, was transmitted with various amounts of bandwidth reduction keeping the number of TV lines constant (Ref. 26,C). As a result, a reduction in bandwidth reduced the resolution in the horizontal direction only. (See Figure 4.1-6 for discussion of relationship between horizontal resolution and bandwidth.) The observers were asked to compare the quality of the second image with that of the first, and to rate the degradation caused by the bandwidth reduction on the six-point scale shown below.

Scale value	Judged degradation
A	Not perceptible
B	Just perceptible
C	Definitely perceptible but not disturbing
D	Somewhat objectionable
E	Definitely objectionable
F	Extremely objectionable

Tests were conducted on two targets, one with a large number of high-contrast edges (a series of vertical strips) and one with very few high contrast edges (a tuppence). The targets moved in the horizontal direction only.

The results show the relative lack of sensitivity of moving images to bandwidth reduction. The table, taken from Figure 4.3-45(a), shows that while a 37-percent reduction in bandwidth produced a just-perceptible degradation for an image with no motion, a 62-percent reduction was needed to produce the same effect between two images moving at the rate of 0.54 picture-widths/second. It is important to remember, when interpreting these results, that the comparisons were made between two images moving at the same speed and do not represent a direct measure of the loss of resolution caused by the motion. The latter data would be obtained by comparing a moving test image with a still comparison image.

A comparison of the two graphs in this figure shows that while the smaller absolute bandwidth shifts are required for the picture with fewer high-contrast edges (Figure 4.3-45(b), the range of shifts induced by motion is similar.

A 271-l V-line system with a 30-Hz frame rate and a line interlace ratio of 2:1 was used for the tests. The subjects sat at a distance of 0.9m (36 in) from the display, where the raster subtended a visual angle of 8 degrees.

4.3.7. IMAGE MOTION (CONTINUED)

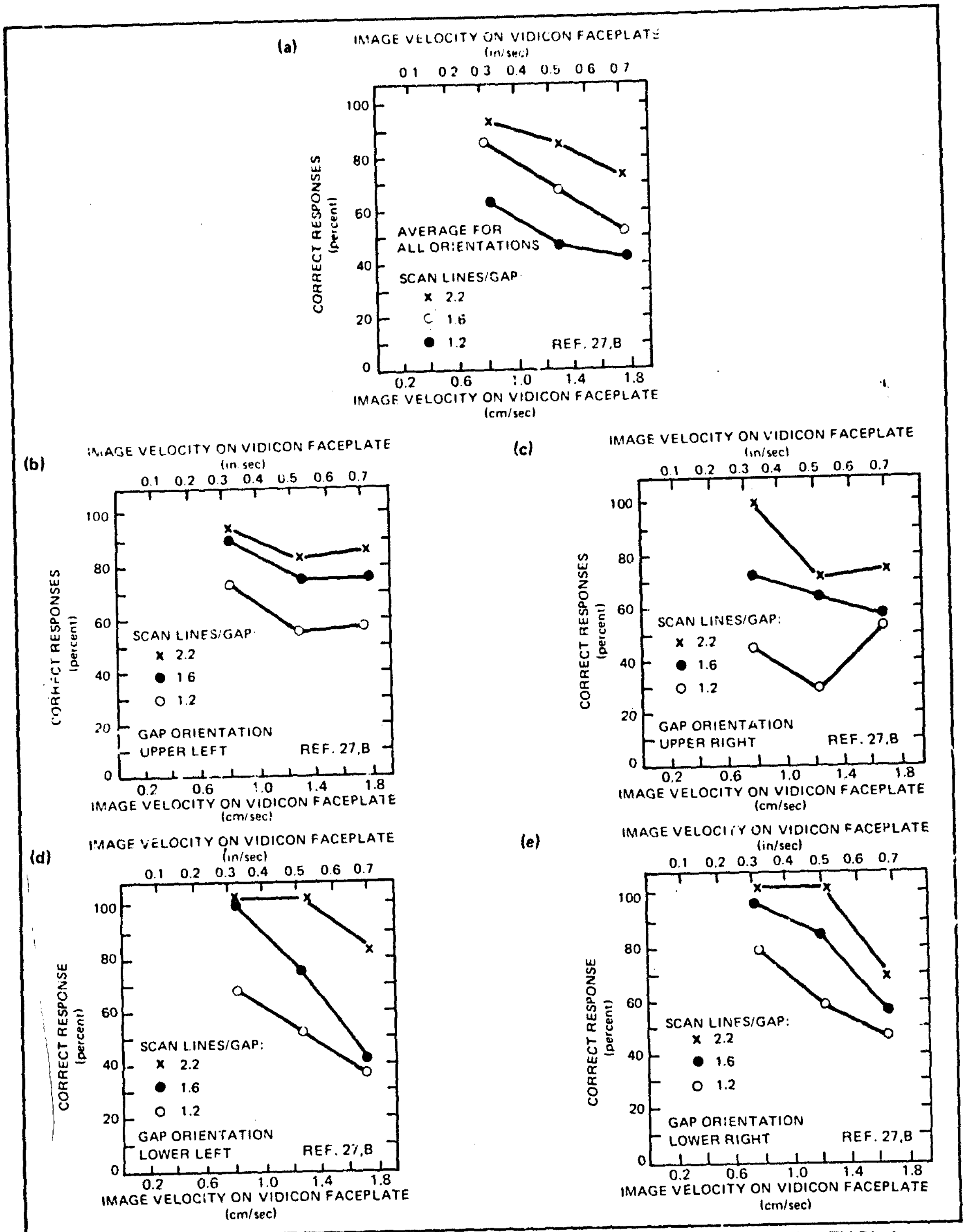


Figure 4.3-46. The Effect of Image Motion on the Detection of the Orientation of a Landolt Ring in a TV Display (continued)

4.3.7. IMAGE MOTION (CONTINUED)

Figure 4.3-46. The Effect of Image Motion on the Detection of the Orientation of a Landolt Ring in a TV Display. A *Landolt ring* is a frequently used target for testing visual performance. It is a broken ring in which the gap is equal to the width of the line. In visual acuity tests, the ring is rotated and the observer is asked to report its orientation (e.g., the gap at the top, bottom, left side, etc.). In the study reported in this figure, a Landolt ring moved across the monitor of a closed circuit television system at various rates. The ability to detect the orientation of the ring was measured as a function of image velocity and the number of scan lines per gap width. Part (a) of this figure shows the results as a function of gap size and rate of motion averaged across all orientations used in the study (upper left, upper right, lower left and lower right). Parts (b) through (e) show the effects of gap orientation (Ref. 27,B).

The data were collected on a 525-TV-line system with a bandwidth of 10 MHz and a SNR greater than 30 dB. The raster had a 2:1 interlace with a field rate of 60 Hz and a frame rate of 30 Hz. Ambient illumination on the faceplate was less than 32 lux (3 fc).

The results are averaged for four studies using from 5 to 12 subjects.

4.3.7. IMAGE MOTION (CONTINUED)

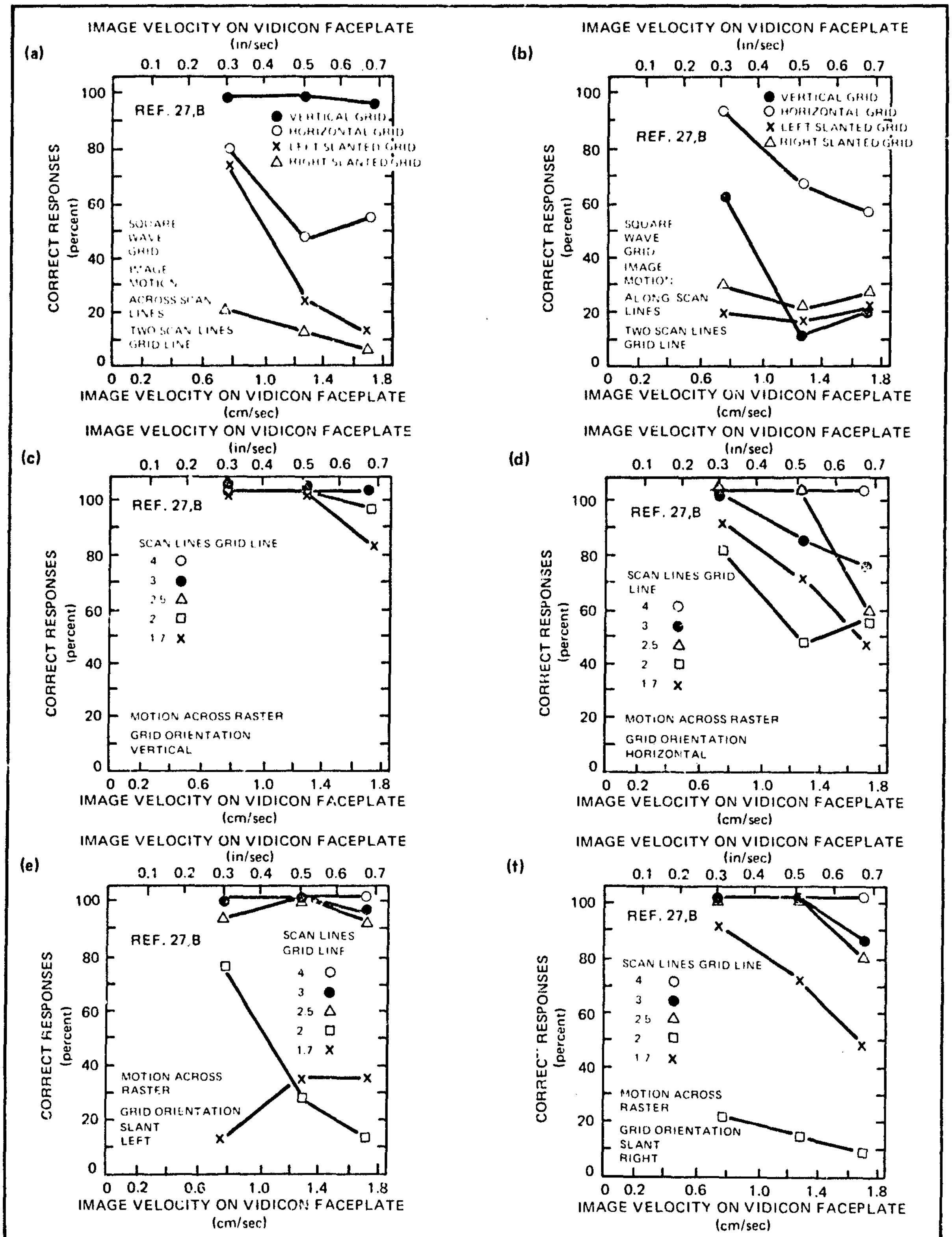


Figure 4.3-47. The Effect of Image Motion on the Detection of the Orientation of a Square Wave Grating Displayed on a CRT

4.3.7. IMAGE MOTION (CONTINUED)

Figure 4.3-47. The Effect of Image Motion on the Detection of the Orientation of a Square-Wave Grating Displayed on a CRT. A square-wave grating was moved across the TV display generated by a closed-circuit television system. The observer's task was to report the orientation of the grid.

Performance was measured as a function of grid orientation, direction of travel (along or across the scan lines), and velocity.

Four grid orientations were used: vertical, horizontal, slanted 45 degrees to the left, and slanted 45 degrees to the right. The results indicate a strong interaction between the orientation of the grid pattern and the direction of motion. This is shown by the changes in performance for a given grid orientation between part (a) of this figure, which shows performance for movement across the scan lines, and part (b), which shows performance for movement along the scan lines. Parts (c) through (f) show performance as a function of grid orientation, number of scans per grid, and image velocity for movement across the scan lines. The effect of grid orientation on performance reflects the effects of the one-dimensional sampling process of line scan systems (Ref. 27,B).

As image velocity increases, the time the target is visible on the display is reduced. The times in this experiment were 1.2 seconds for the lowest velocity and 0.6 second for the highest. These time differences must be taken into consideration in interpreting the results shown here. That is, the lowest performance scores were associated with the shortest times as well as the highest velocity.

The experimental apparatus used was the same as that described in Figure 4.3-46. The results were averaged over two studies, which used 5 and 6 subjects respectively.

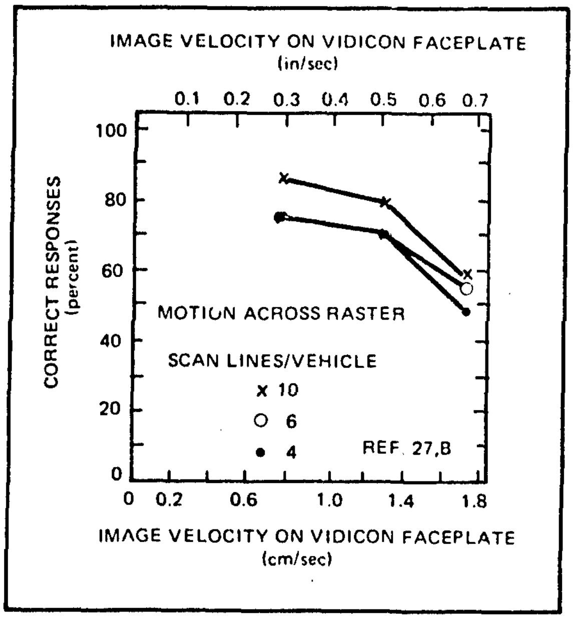


Figure 4.3-48. The Effect of Image Motion on the Identification of Vehicles Displayed on a CRT. The ability of observers to distinguish between TV images of model military vehicles and objects closely resembling the vehicles was tested as a function of image velocity and number of scan lines across the vehicles.

The results are shown in the accompanying graph. In interpreting the results, the same precaution must be taken as with Figures 4.3-46 and 4.3-47. That is, as image velocity increases, the time that the target is visible on the display decreases. For this study these times were 1.2 seconds for the lowest velocity and 0.6 second for the highest (Ref. 27,B).

The experimental apparatus was the same as described in Figure 4.3-46. Six subjects were used and each subject made 72 observations.

4.3.7 IMAGE MOTION (CONTINUED)

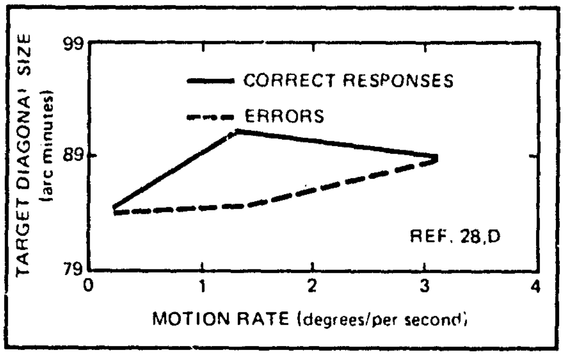
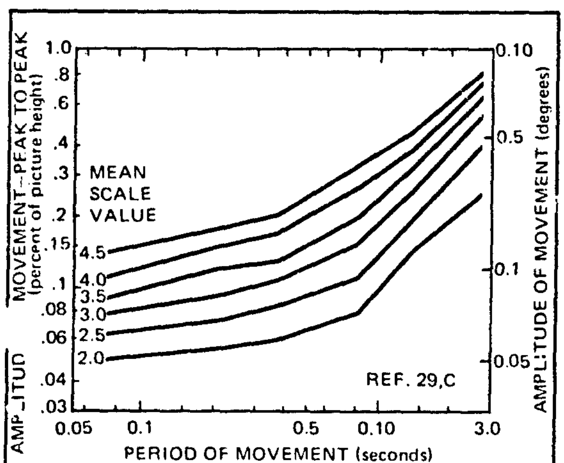


Figure 4.3-49. Effect of Image Motion in CRT on Target Detection Performance. These results are from the same study reported in Figure 4.3-55. The target motion simulated the movement caused by atmospheric turbulence acting on a TV guided weapon closing in on a target. The effect of such motion is that the target moves about in an unpredictable fashion. In this study the target was always within the field of view. The average rates of the motion, representing three conditions of turbulence, were 0.25, 1.33, and 3.25 degrees per second. The maximum rates were approximately 3 times these numbers.

The authors speculate that the reason the visual angle for correct detections did not increase between the 1.33- and 3.25-degree-per-second conditions is that the subjects learned that the relative motion increased as the missile neared the target; as a result, they made their decisions that the target had been detected earlier in the flight. In each case the accuracy of the decision was checked by requiring the subject to place a cursor around the target area (Ref. 28,D).

Additional information on the study conditions can be found in Figure 4.3-55.



SUBJECTIVE RANKING OF IMAGE UNSTEADINESS IN TELEVISION PICTURES

Figure 4.3-50. Effect of Image Unsteadiness on Judgment of CRT Picture Quality. Scenes typical of those found in commercial TV were caused to exhibit unsteadiness in both horizontal and vertical axes while being displayed on a CRT. A group of 20 observers rated the image quality from the standpoint of its acceptability based on its appearance (Ref. 29,C). The rating scale used was as follows:

Scale value	Judged image degradation
1	Imperceptible
2	Just perceptible
3	Definitely perceptible but not disturbing
4	Somewhat objectionable
5	Definitely objectionable
6	Unusable

The results shown here are for still scenes. It was reported that for scenes with movement in them, more unsteadiness could be tolerated. Both the period and amplitude of the unsteadiness contributed to the rating. The observers sat at a distance of approximately 6 times the vertical picture height from the display. The amplitude of movement, along with this approximate viewing distance, was used in the present report to calculate the values for the visual angle of the movement shown on the right-hand ordinate.

A description of the viewing system was not given, but since the authors were British, it might be assumed that it was a standard British 625-TV-line system with 2:1 interlace and a 1/25-second frame time. Highlight luminance was not reported. Ambient illumination was at a "typical" room level.

4.3.8 COLOR CRT DISPLAYS

The use of color CRT's for image interpretation work, particularly in the area of *gray scale color coding* for image manipulation purposes, is increasing rapidly. Unfortunately very few image interpretation studies have been conducted using these devices. One study is reported here which compares performance on color and black and white TV imagery for the identification of military vehicles. Figure 4.3-43 gives the results of a comparison between color and black and white judged image quality for quantized imagery as a function of TV line dither.

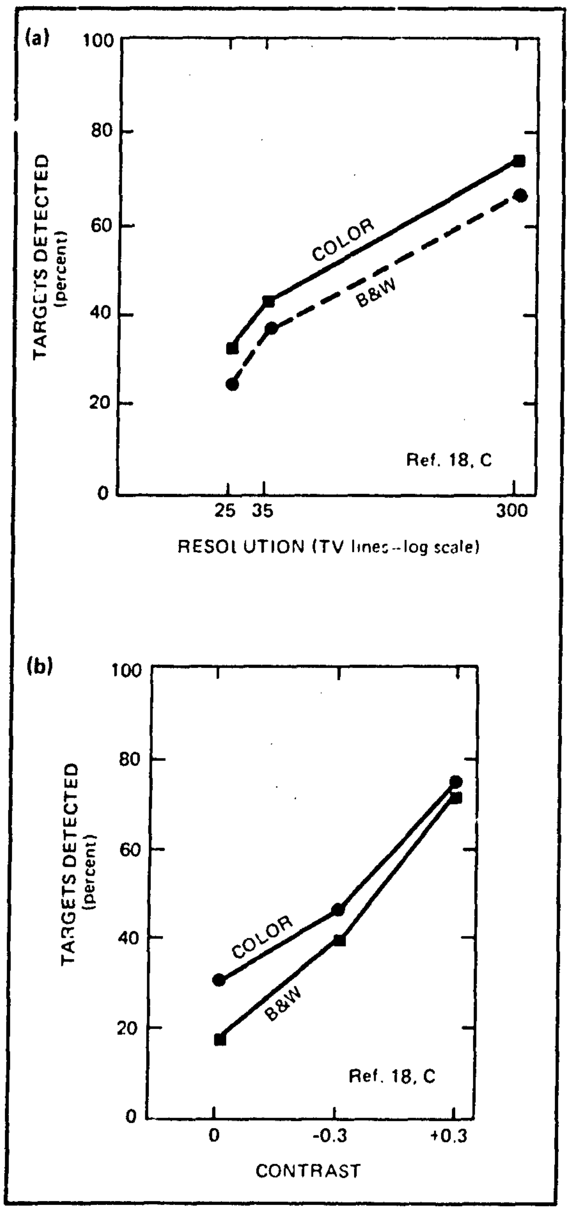


Figure 4.3-51. Detection of Tanks on Color Versus Black and White Television. Models of military vehicles (tanks) painted either brown, green, or gray were mounted on a terrain model in such a manner that three values of target-to-background luminance contrast were obtained, 0, -0.3, and +0.3. Contrast was defined as $\frac{L_t - L_b}{L_b}$ where L_t is the target luminance and L_b is the background luminance. Two background colors were used, green and brown. In addition to target color, target-to-background luminance contrast, and background color, three levels of resolution were used: 25, 35, and 300 TV lines. The differences in resolution were measured on a RETMA chart (Ref. 5) and obtained by defocusing the TV camera lens. The same monitor was used for presenting the color and black and white targets. The targets were viewed at a 12 degree obliquity (from nadir). The camera moved over the display model at a constant rate and the targets were in the field of view for 10 seconds. Only one target was presented at a time, and each subtended a visual angle of 25 arc minutes. Performance was measured as the percentage of targets detected.

The results indicated that the color presentation was superior to the black and white one except for the positive contrast condition, where they were equal (Ref. 18,C).

Caution must be used in generalizing these results to all black and white versus color TV presentations. Because of the aperture mask and phosphor matrix on color monitors, the black and white image displayed on a color CRT has somewhat different characteristics than the image for the same signal presented on a high-quality black and white monitor. The TV system was a 525-TV-line NTSC unit (see Figure 4.1-11). The phosphors had the following tristimulus values:

	X	Y
Red	0.654	0.335
Green	0.290	0.600
Blue	0.150	0.065

(See Section 5.2.1.3 for a description of the tristimulus method of specifying chromaticity.) The color temperature of the white signal was set at 6500°K.

Ten observers were used in the study, only three of whom had previous experience in target acquisition studies.

4.3.9 EDGE SHARPENING

Edge sharpening is an image manipulation technique for increasing the luminance gradient between two areas in an image. The purpose is to improve the visual perception of details in the imagery. In the study reported here, the sharpening was done on the video signal by taking the *second derivative* of that signal and subtracting it from the signal. The formula used was:

$$e_i = e_0 - (d^2e/dt^2)$$

where

e_i = the edge-sharpened signal and

e_0 = the original signal

The results of the study indicate that the technique impaired performance at low SNR's and improved it at high SNR's (Ref. 4.C).

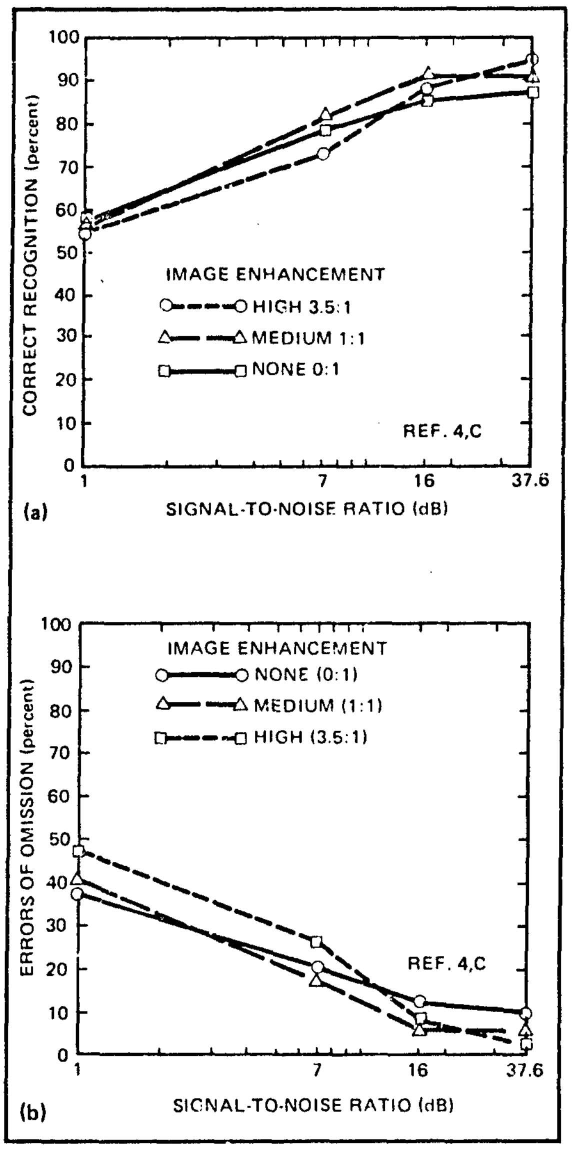


Figure 4.3-52. Effect of Edge Sharpening on Target Recognition Performance for Images Displayed on a CRT. The data presented here are from the same study as those shown in Figure 4.3-5 (Ref. 4,C), and have been replotted to show the effect of the edge sharpening technique employed. The data for the percent of correct recognitions are shown in part (a) and for errors of omission in part (b). The edge sharpening was accomplished by subtracting the second derivative from the video signal as follows:

$$e_i = e_o - (d^2e/dt^2)$$

where

e_i = the edge sharpened signal

e_o = the original video signal

There enhancement levels were tested—none, 1:1, and 3.5:1—where the ratio was applied as a multiplier to the derivative before subtraction. The results showed an interaction between the level of enhancement and SNR, with the high enhancement levels producing the poorest performance and most errors of omission at the lowest SNR and the best performance and lowest errors of omission at the highest SNR (Ref. 4,C). Details of the equipment, procedures, and subjects used in this study can be found in Figures 4.3-5 and 4.3-34.

4.3.10 VIEWING DISTANCE

Figure 4.3-28 showed how viewing distance and SNR interacted to influence target detection thresholds for sine-wave targets. Preferred distances for casual viewing purposes have been investigated and were found to be a function of picture height. The values fall in a range from 4 to 8 times the picture height for standard broadcast systems.

The distance is influenced by the TV line number of the system. Shorter viewing distances are preferred for systems of higher line number. This suggests that the visibility of the raster plays a role in determining how far from the monitor the casual observer wants to sit. The visibility of the line structure in CRT displays introduces considerations beyond those presented in Section 3.6. The nature of the noise in the CRT display is also an influencing factor (see Figure 4.3-29).

In the study reported in Figure 4.3-55, it was found that changing the visual size of the display by changing its distance from the observer did not affect the number of TV lines per target required for recognition over a range of 23 cm to 4 cm (9.2 to 33.3 in).

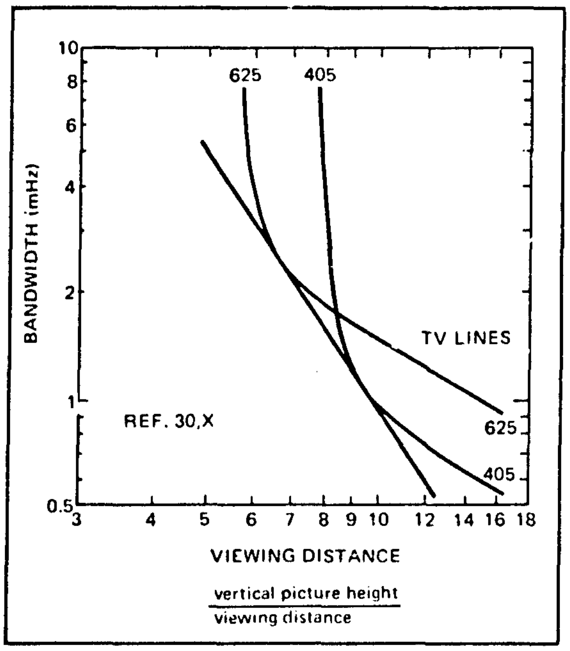


Figure 4.3-53. Relationship Between CRT Resolution, Picture Size, and Preferred Viewing Distance. In many of the studies reported in this section, the viewing distance is given as a function of picture height. The usual distance is 4 to 8 times the picture height (for a picture whose height is 35.5 cm (14 in), the viewing distance would be 1.4m (55 in) to 2.8m (110 in). These values have been established from studies such as the one reported in this figure (Ref. 30,X).

In this study, nine observers were allowed to choose the distance from which they wished to observe pictures of 405 TV lines and 625 TV lines presented at bandwidths of 7 MHz, 3 MHz, 1.5 MHz, and 0.75 MHz (Ref. 29). The results indicate, not surprisingly, that preferred viewing distance decreases as resolution increases. From the standpoint of transfer of information from the CRT to the observer, the viewing distance is of great importance. If the distance is so great that the smallest displayed element is below the resolution limit of the visual system, information will be lost. For a 525-line NTSC system, the displayed resolution, after taking the Kell factor into consideration, is about 343 TV lines (171 cycles; see Figure 4.1.6). For a tube with a picture height of 35.5 cm (14 in), a single line (½ cycle) will subtend 1 arc minute at approximately 57 inches, or 4.1 times the picture height. Viewing from a distance equal to 8 times the picture height would mean that 1 arc minute would subtend approximately two TV lines, and information would be lost in high frequency, low contrast targets. The optimum viewing distance for information extraction as a function of TV parameters has not been tested

Nine observers were used in this study, and each made four observations under eight conditions of bandwidth and TV line number. Smooth curves were fit to the data, as shown. The straight tangent to the two curves at their inflection points is the extrapolated locus of the inflection points for systems of other TV line numbers.

4.3.11 DISPLAY SIZE

The basic considerations for selecting a display size given in Section 3.5 are valid for CRT's provided that proper attention is given to the visibility of the scan lines. Since the number of scan lines per raster height is constant for a given system, increasing the physical size of the CRT will increase the size of the scan lines also. At some point the individual lines will subtend visual angles large enough to make the line structure highly visible and annoying. The visual angle can be reduced in such cases by increasing the viewing distance to the display, but since the larger displays are more expensive, this solution is not economical. A discussion of some of the factors affecting the visibility of th scan lines can be found in Figures 4.4-16 and 4.4-18.

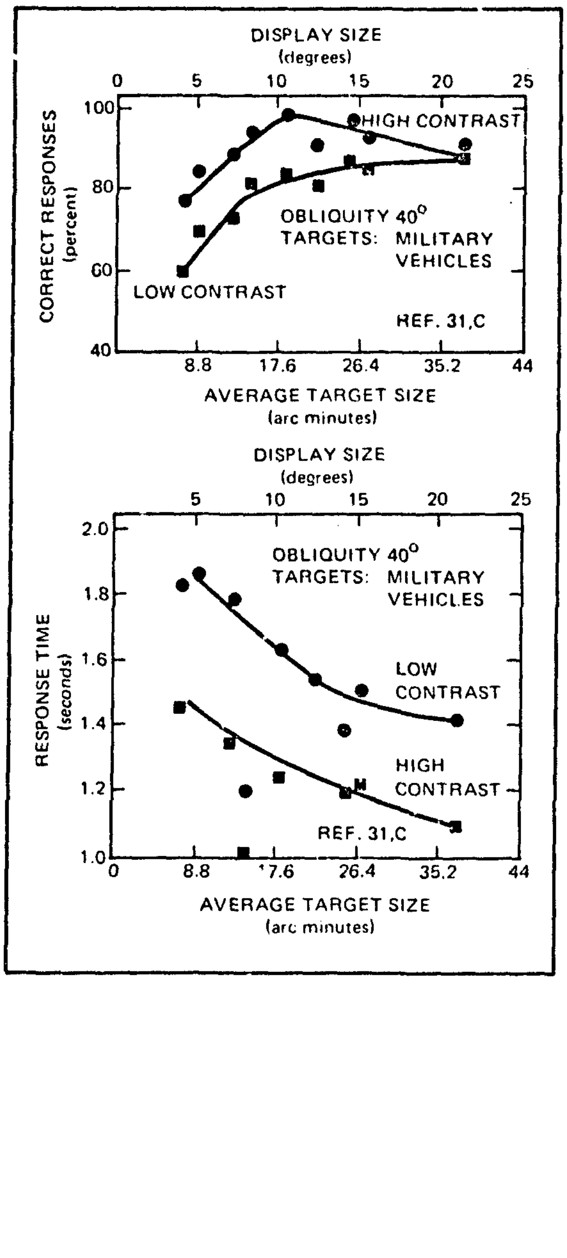


Figure 4.3-54. Effect of Target Size and Contrast on Target Detection Accuracy and Time. In the experiment reported here, the field of view with respect to the target area was held constant and the display size was varied by decreasing the scale of the image, with the smaller scale images occupying only part of the raster. The number of TV lines on both the camera and display remained constant, so the changes in scale were accompanied by equivalent changes in the number of lines subtended by the targets. This meant that the resolution increased with increasing display size. In terms of the average number of TV lines per target, the resolution varied from 7 to 26.2. The results indicated that there was no change in target detection performance as a function of resolution. The authors attributed this to the fact that the lowest resolution was adquate for the target detection task used (Ref. 31,C).

The visual angle subtended by the displays and that of the targets within them were varied by varying the viewing distance to the display. The changes in performance that were observed as a function of changes in visual angle are shown in part (a) of this figure for target detection performance and, in part (b) for the amount of time used to find the target. The figures given for the visual angles subtended by the target are approximate because oblique imagery was used, causing the scale to increase from the top to the bottom of the image. The numbers reported are the average scale values.

The test material was prepared from photographs of models of four types of military vehicles. The vehicles were located on a terrain model, and only one vehicle appeared in each photograph. Two levels of target contrast were used, an olive drab vehicle located on a sandy background and a flat black vehicle located on a foliage background. The search time was limited to 3 seconds per scene.

Three sets of six subjects were used, whose backgrounds ranged from office workers to Marine Corps aviators. Each subject had 216 trials consisting of 1 trial on each 24 scenes for nine resolution-scale combinations.

A 1,035-TV-line, 2:1 interlaced system was used with a 60-Hz field rate and 30-Hz frame rate. The SNR was reported as 40 dB minimum. System bandwidth was 25 MHz. Ambient illumination was less than 6.8 cd/m^2 (2 fL) on the face of the CRT. Average raster luminance, highlight luminance, and target contrast were not reported.

4.3.11. DISPLAY SIZE (CONTINUED)

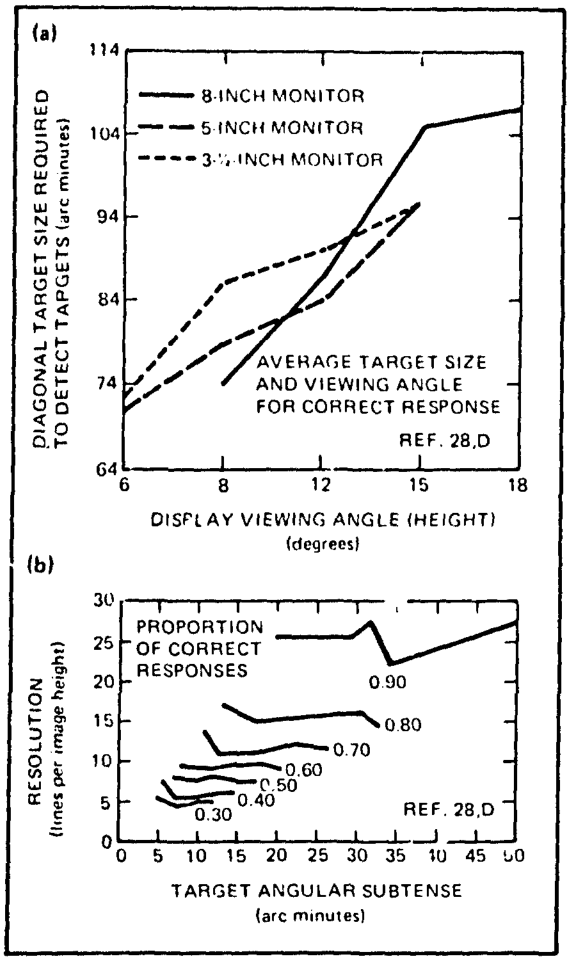


Figure 4.3-55. Effect of Display Size and Image Size on Target Detection in CRT Imagery. In the study reported here, it was found that the visual angle required to detect a target increased with increases in the visual angle subtended by the display (TV monitor) (Ref. 28,D). The increase was almost directly proportional to the tangent of the angle subtended by the vertical dimension of the monitor. Part (a) of this figure shows this relationship as a function of visual angle subtended by the monitor and the visual angle required for target detection. The display size was varied by using different size monitors and viewing distances. No difference in performance was found as a function of the physical size of the monitor. Part (b) shows the probability of detection as a function of visual angle and TV lines per target. These results suggest that the number of lines per target rather than the visual angle was the major factor in target detection in this study.

The subjects' task in this study was to detect a target in a dynamic display. The display simulated a forward-looking TV system in a TV guided weapon that was flying directly toward the target. The target moved around within the field of view in a manner similar to the motion that would be produced by atmospheric turbulence. Three levels of motion were used, the average rates of which were: 0.25, 1.33, and 3.25 degrees of visual angle per second. The effects of this motion on target detection performance are shown in Figure 4.3-49. The simulated attacks were prepared by using a zoom lens on a television camera and transparencies prepared from aerial photographs of actual targets. The targets included such items as a factory, several bridges, antiaircraft guns, an aircraft, barges, and oil tanks. The obliquities varied and were not reported.

The camera and all of the monitors were 525-TV-line, 2:1 interlace systems. Highlight brightness varied between monitors from 166 cd/m^2 (48.5 fL) to 218 cd/m^2 (63.8 fL) as measured on step 1 of the RETMA chart (Ref. 5). Resolution measured in the center of the display varied from 250 TV lines horizontal and 300 TV lines vertical for the smallest monitor to 325 TV lines horizontal and 400 vertical for the largest. The length of the trials varied from 20 to 140 seconds, with a mean of 69 seconds.

Sixteen military and civilian personnel served as subjects. Each subject was given 64 trials, with the targets and conditions balanced across all subjects.

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4.3.12 SPOT SPPEAD FUNCTION

In optical line-scan image generators, the spread function of the printing spot can be varied by placing appropriately shaped filters in the optical train. The shape of the spread function can be manipulated to provide different distributions of the overlap between adjacent lines or spots. The distribution of the overlap effects both the appearance of the imagery and the amount of resolution and contrast loss created by the blending of the signals from adjacent lines or spots at their points of contact. In the study reported here, nine different point spread functions were judged on two criteria:

- Information content
- Ability to maintain information content when spot position errors are introduced by the printing

A *quadratic interpolator* was found best for imagery with no printing errors. A *linear interpolator* was slightly better than the quadratic interpolator in the presence of *jitter* and *banding* errors.

Descriptions of the interpolation functions can be found in Figure 4.3-56.

Data on the judged information content in the presence of these errors are reported in Section 4.3.13, Figure 4.3-57.

4.3.12 SPOT SPREAD FUNCTION (CONTINUED)

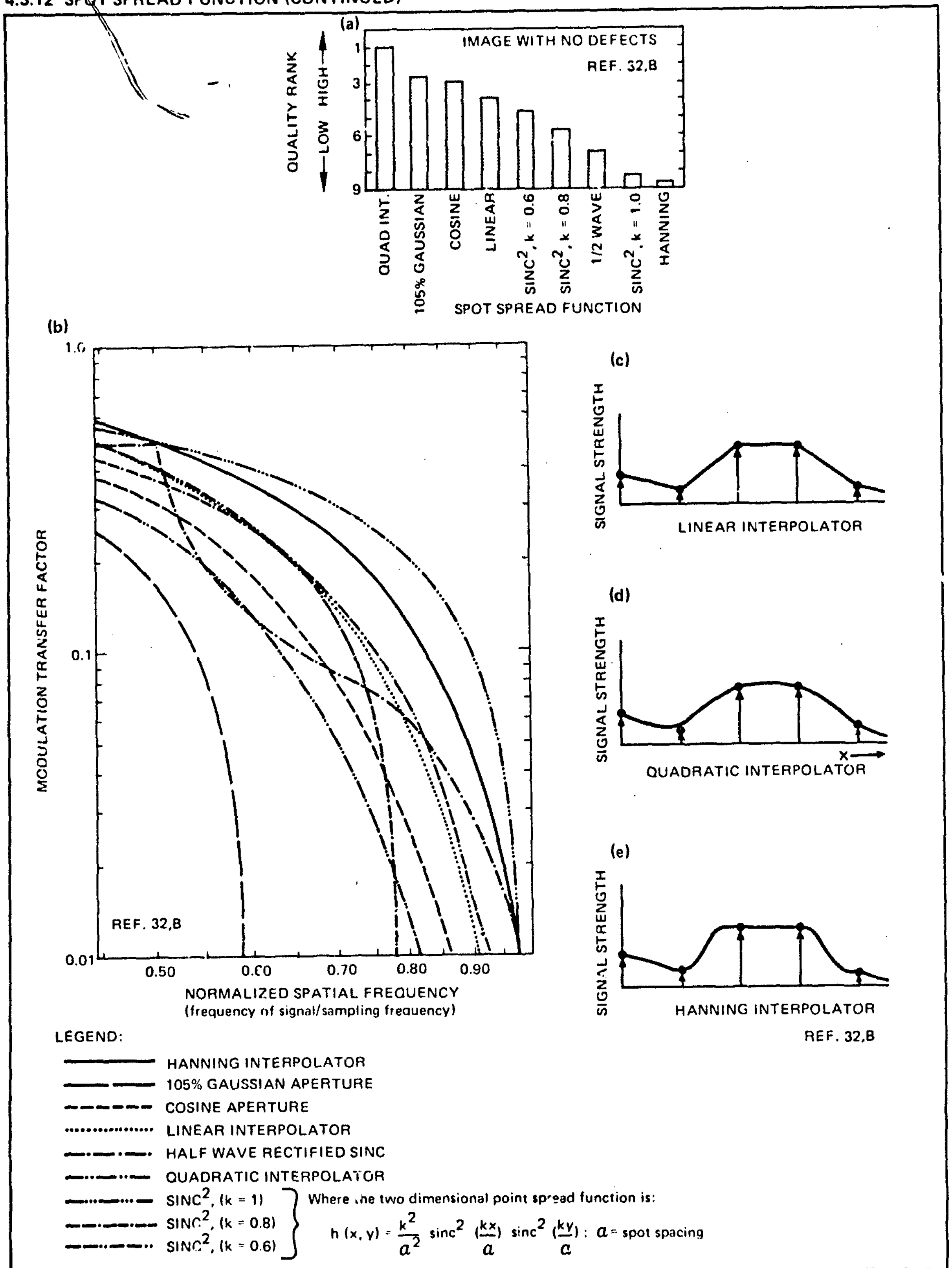


Figure 4.3-56. Judged Quality of Spot Scan Transparencies as a Function of Spot Spread Function

4.3.12 SPOT SPREAD FUNCTION (CONTINUED)

Figure 4.3-56. Judged Quality of Spot Scan Transparencies as a Function of Spot-Spread Function. Nine different *spot-spread functions* were used to reproduce a digitized aerial scene containing several types of targets (Ref. 32,B). (See Figure 4.1-10 for a discussion of spot shape.)

The imagery was prepared on a *line-scan image generator*, with operating principles similar to those described in Figure 4.1-16.

The digitized input image was sampled in two dimensions, so it was printed a spot at a time. (See Figure 4.1-4 for a discussion of *two-dimensional* sampling.) The resulting transparencies were judged for their information content by three observers familiar with image quality research. Emphasis was placed on judging for information content, not pleasing appearance. The observers were allowed to use any viewing distance they wished, and tube magnifiers were available if they wished to use them. The contrast and density of the imagery were not reported.

In performing the quality judgments, each subject viewed the transparencies for all nine spot functions at one time. They were ranked from 1 for the best to 9 for the worst.

The spread functions used are listed below:

- Linear interpolator
- Quadratic interpolator
- Cosine
- 105-percent Gaussian
- Sinc^2, k = 0.6
- Sinc^2, k = 0.8
- Sinc^2, k = 1.0
- Half-wave rectified sinc
- Hanning interpolator

Where the two-dimensional point-spread function is:

$$h(x,y) = \frac{k^2}{a^2}\,\text{sinc}^2\left(\frac{kx}{a}\right)\text{sinc}^2\left(\frac{ky}{a}\right)$$

and a = spot spacing.

One-dimensional representations of the manner in which the three interpolation functions distribute signal strength between adjacent spots are shown in parts (c), (d), and (e) of this figure. In practice the distribution is in two dimensions. The linear interpolator makes the luminance distribution between neighboring pixels a straight-line function, the quadratic interpolator fits a parabolic function across three successive pixels, and the Hanning interpolator fits a raised cosine function between neighboring pixels.

More information on the nature of these functions can be found in the reference entry in this book, a detailed discussion of their properties can be found in the reference itself (Ref. 32,B). The results of the ranking are shown in part (a) of this figure for "error free" imagery. Figure 4.3-57 and 4.3-58 shows the differential effects on the rankings caused by errors in the position of spots that occur during exposure. The high-frequency region of the modulation transfer frunctions for each is shown in part (b).

4.3-13 IMAGE DEFECTS

For the purposes of this section, image defects are degradations in image quality caused by improper operation of equipment or by transmission difficulties.

The data on line-scan transparencies are treated first in this section, as they come from the same study as the data in Figure 4.3-56.

No interpreter performance data could be found that related to image defects. All of the data for CRT displays in this section come from broadcast television image quality studies and are based on the NTSC system. For the data on color television defects, this distinction is important because in the NTSC system the luminance and chrominance signals are separate, and in closed-circuit or computer-driven color systems, each color is frequently independently transmitted, in which case no luminance signal is present.

The defects covered in this section are as follows:

	Figure
For line-scan transparencies	
• Cyclic banding	4.3-57
• Jitter	4.3-57
For CRT displays	
• Echo	4.3-58
• Differential delay between luminance and chrominance signals	4.3-59
• Differential gain and differential distortion between the luminance and chrominance signals	4.3-59

No data from either performance or image quality judgement studies could be found dealing with the image anomalies created by the sampling process (*for instance aliasing*). These phenomena have been of much theoretical interest but their effects on interpreter performance apparently have not been systematically investigated.

4.3.13 IMAGE DEFECTS (CONTINUED)

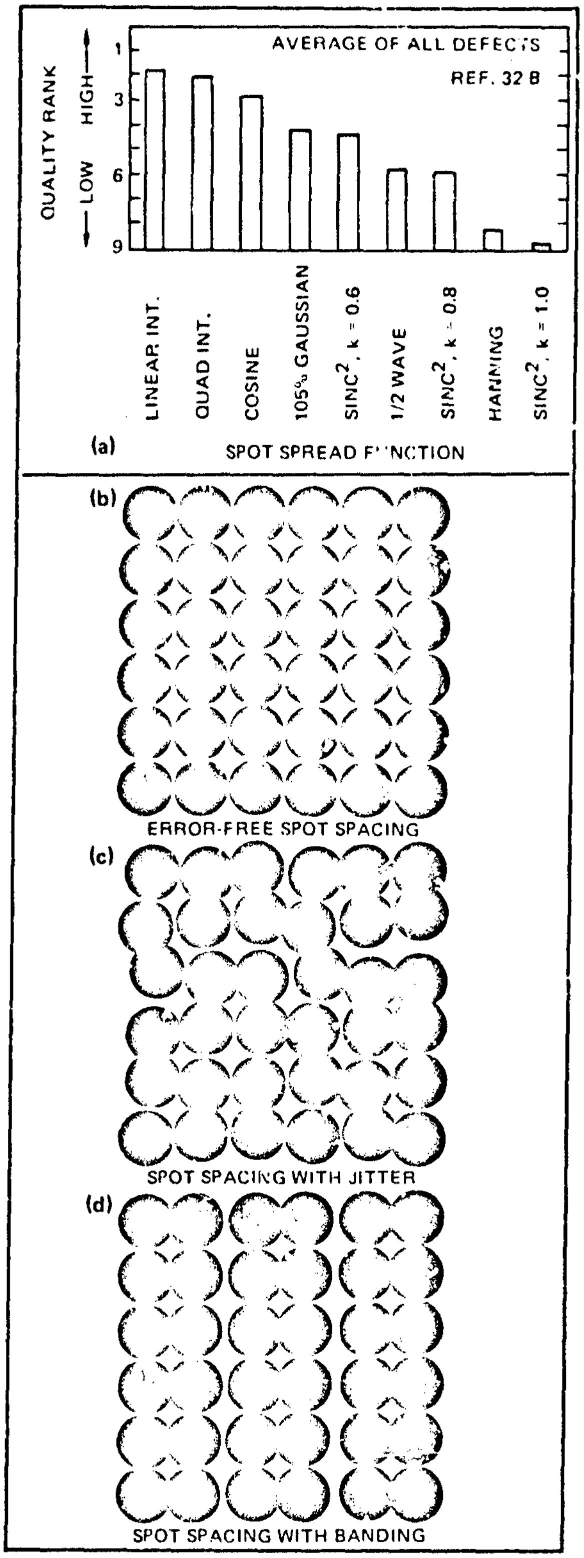


Figure 4.3-57. Effects of Jitter and Banding on Spot Scan Transparencies. The nine point-spread functions reported in Figure 4.3-56 were used to make transparencies in which errors in the positions of the dots were introduced. This was done in order to test the influence of such errors on the quality of the image produced by each type of function (Ref. 32,B). The images were ranked on their information content in the manner described in Figure 4.3-56, with a rank of 1 assigned to the best image and 9 to the poorest.

Four transparencies containing errors were made for each point-spread function. Three contained *cyclic banding* errors of 2, 5, and 8 percent, respectively, of the nominal sample spacing. The fourth contained *jitter* for which the errors in location had a Guassian distribution with a standard deviation of 0.026 space.

Banding is caused by systematic errors of position perpendicular to the direction of scan; it can be cyclic; i.e., repetitive over some distance on the imagery; or it can be localized, occurring in one particular area. It is generally caused by inaccuracies in the lead screw mechanism that advances the scanning spot from one line to the next.

A random inaccuracy in the placement of a single spot is caused by small errors in the position control mechanisms of the device. Jitter errors can be in either the horizontal or vertical dimension of the image.

Figure 4.3-57(b) illustrates a matrix of dots with no errors. Figure 4.3-57(c) illustrates the result of jitter, and Figure 4.3-57(d) the result of cyclic banding.

For the chart in this figure, the average of the judgments for all errors is shown. The order of the rankings changed somewhat from that for the error-free imagery shown in Figure 4.3-56. Figure 4.3-58 gives the results (individually) for the two types of error for each point-spread function.

4.3.13 IMAGE DEFECTS (CONTINUED)

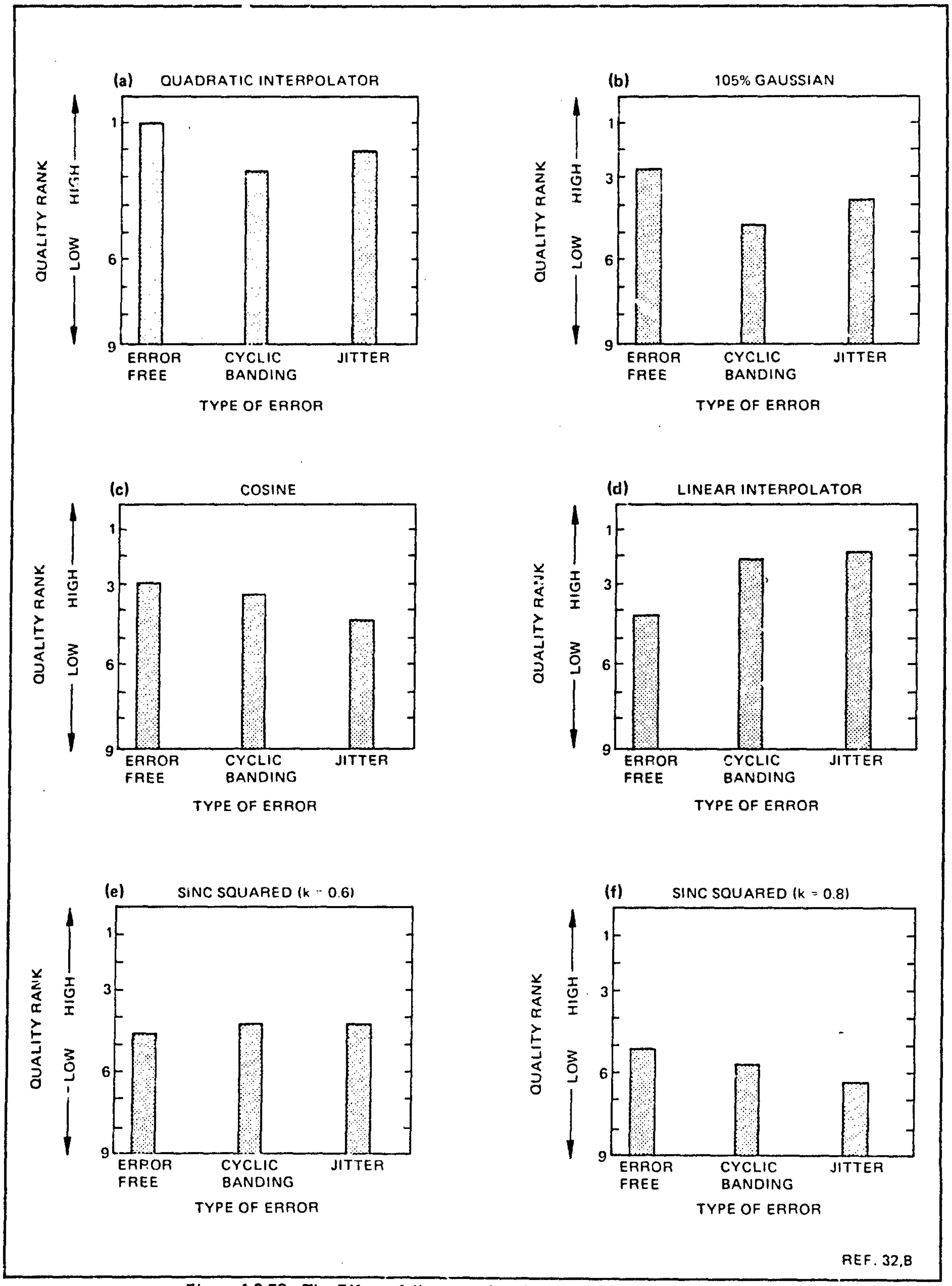


Figure 4.3-58. The Effect of Jitter and Bonding on Point-Scan Transparencies

4.3.13 IMAGE DEFECTS (CONTINUED)

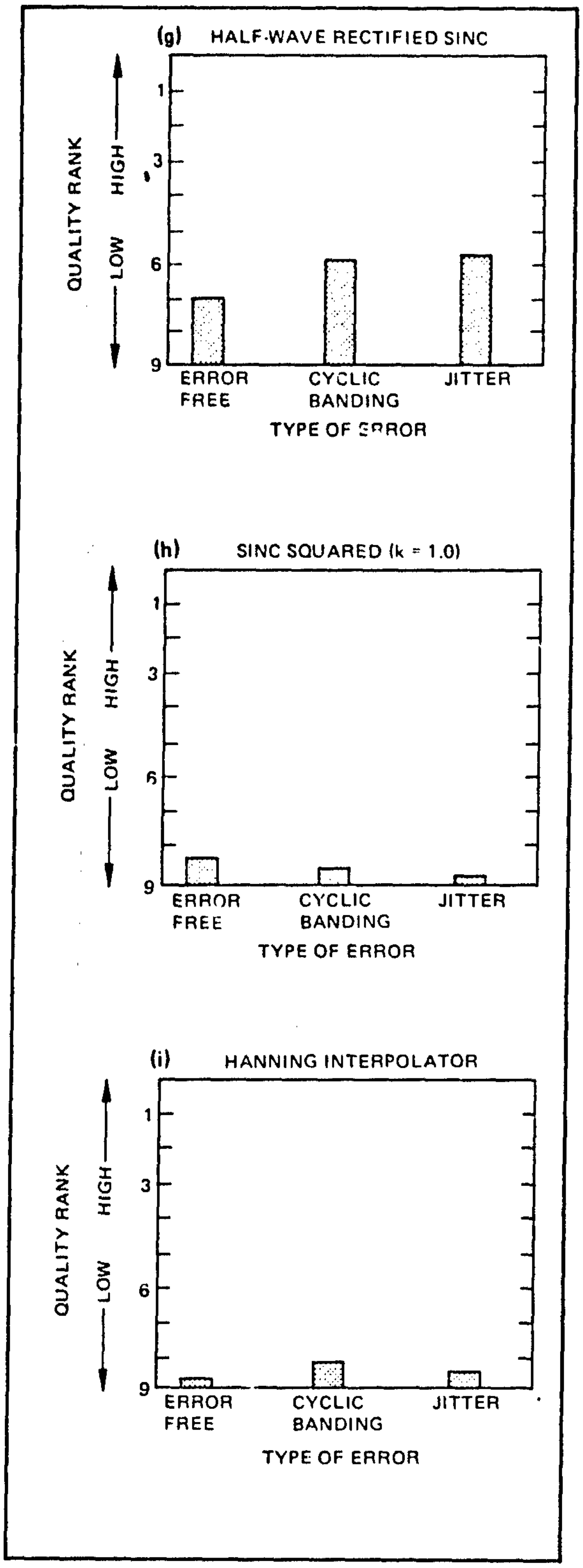


Figure 4.3-58. The Effect of Jitter and Banding on Point-Scan Transparencies. This shows the rankings of transparencies that contain the errors described in Figure 4.3-57 (Ref. 32,B). The effects of two kinds of errors, jitter and cyclic banding, are presented separately for each type of point-spread function. For jitter, the dot position error was Gaussian in distribution with a standard deviation of 0.026 space. The cyclic banding was at three levels, 2 percent, 5 percent, and 8 percent of the spot spacing. A further description of these errors can be found in the referenced figure.

The point-spread functions are presented in order by their rankings on the error-free imagery, as follows:

Function	Figure
Quadratic interpolator	a
105% Gaussian	b
Cosine	c
Linear interpolator	d
Sinc^2, k = 0.6	e
Sinc^2, k = 0.8	f
Half-wave rectified sinc	g
Sinc^2, k = 1.0	h
Hanning interpolator	i

In parts e, f and h, k is a constant used as shown in the formulas in Figure 4.3-56.

4.3.13 IMAGE DEFECTS (CONTINUED)

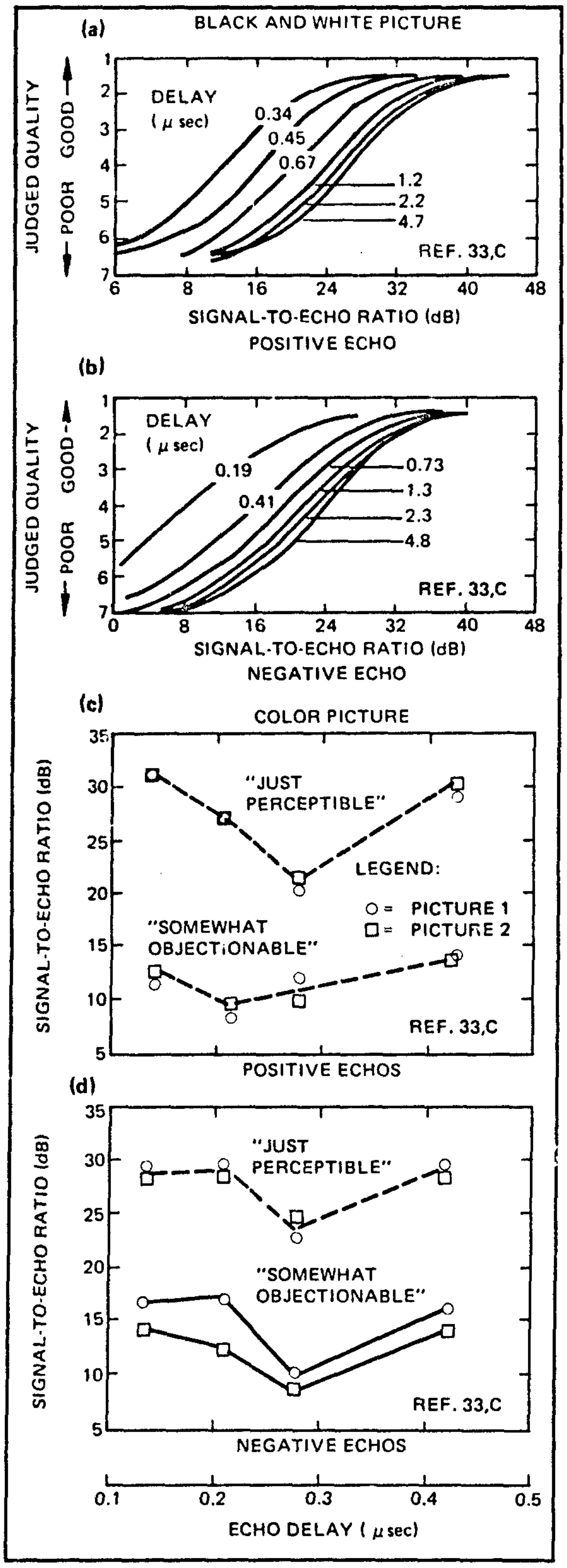


Figure 4.3-59. Effect of Echo Time on the Judged Quality of NTSC Black and White and Color Pictures. An *echo* in television terminology refers to a signal that has been reflected during transmission, with the result that it arrives at a different time from the main signal, and appears on the monitor as a *ghost image*. The echo can either lead or lag the main signal; if it leads, the ghost image appears to the left of the picture; if it lags, it appears to the right. It can have either a positive or negative contrast with respect to the picture.

The results shown here are for subjective evaluations of the impairment in picture quality caused by lagging echoes of both negative and positive contrast. The time delay and contrast of the echo were varied from one test session to another and covered a wide range of values (Ref. 33, C). The results were reported in decibels as the ratio of the signal strength to the echo strength. The method of calculation was not reported. A seven-point rating scale was used to judge the pictures:

Scale value	Judged degradation
1	Not perceptible
2	Just perceptible
3	Definitely perceptible, but only slight impairment to picture
4	Impairment to picture, but not objectionable
5	Somewhat objectionable
6	Definitely objectionable
7	Extremely objectionable

Pictures typical of the type found in broadcast television were used as test scenes.

In interpreting the results for these figures, it is useful to remember that the active portion of each scan line is approximately 52.6 μsec in duration for a 525-TV-line NTSC system (see Figure 4.1-8), so a 1-μsec delay displaces the echo a distance equal to approximately 1.9 percent of the picture width for a 50-cm (19.6-in) horizontal picture; this amounts to about 1 cm (0.4 in).

The curves in Figure 4.3-59(a) and (b) indicate that longer delay times are more deleterious to picture quality than very short delay times; however, the authors report that "strong close-in echoes of high amplitude can mutilate the picture. These stronger echoes were not tested.

The color data were highly dependent upon the nature of the test picture and for some pictures behaved erratically as a function of delay times, apparently having a particularly sensitive spot near 0.2 to 0.3 μsec, as shown in Figure 4.3-59(b). The curves for the two images in the case of the negative echoes illustrate that different pictures will respond differently to echoes.

The TV system used for the tests was a 525-line NTSC system. The highlight brightness for the black and white pictures ranged from 86 cd/m^2 (25 fL) to 54 cd/m^2 (15 fL). For the color pictures, the values ranged from 51 cd/m^2 to 69 cd/m^2 (15 fL to 20 fL). Contrast ratios

(Continued)

4.3.13 IMAGE DEFECTS (CONTINUED)

ranged from 71 to 100 for the black and white pictures and from 60 to 133 for the color pictures.

Ten observers were used, and each made 162 observations, two for each test condition. The observers were seated a distance equal to 4 times the picture height from the monitor. No room illumination was provided other than that from the monitor.

It must be remembered in interpreting these results that the pictures were judged on the basis of their quality for home entertainment purposes, not information extraction purposes, and that they, unlike most closed-circuit TV systems, have separate luminance and chrominance signals.

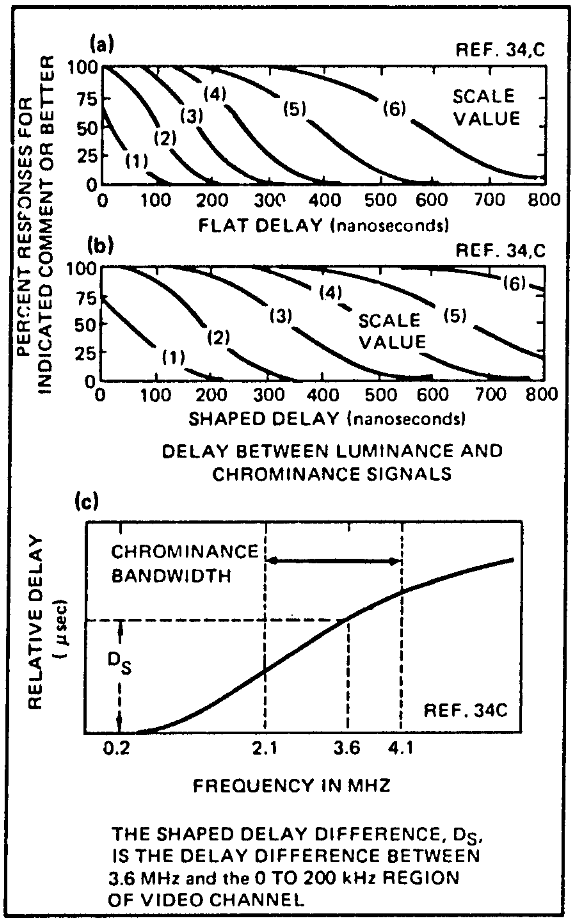


Figure 4.3-60. Effects of Differential Delay in the Luminance and Chrominance Signals in an NTSC Color Television System. The *luminance* and *chrominance* signals in an NTSC color television system carry, respectively, the brightness and color information for the picture (see Figure 4.1-11 for additional discussion). There are several places in the processing and transmitting operations which can cause a differential delay between these signals. When this happens, the visual effect is a color "smear" or color fringing caused by a lateral shift of the color signal. The color shift can be to the right or left of the objects in the scene.

Two types of delay were tested here—a flat delay and a shaped delay. In a flat delay, the entire chrominance signal range is displaced a given amount from the luminance signal; in a shaped delay, D_s, the higher frequencies are displaced more than the lower (Ref. 34, C). (See Figure 4.3-60(c) for a graphic representation and definition of the way the delay is measured.)

The effect on image quality was measured on a seven-point scale:

Scale value	Judged degradation
1	Not perceptible
2	Just perceptible
3	Definitely perceptible, but only slight impairment to picture
4	Impairment to picture, but not objectionable
5	Somewhat objectionable
6	Definitely objectionable
7	Extremely objectionable

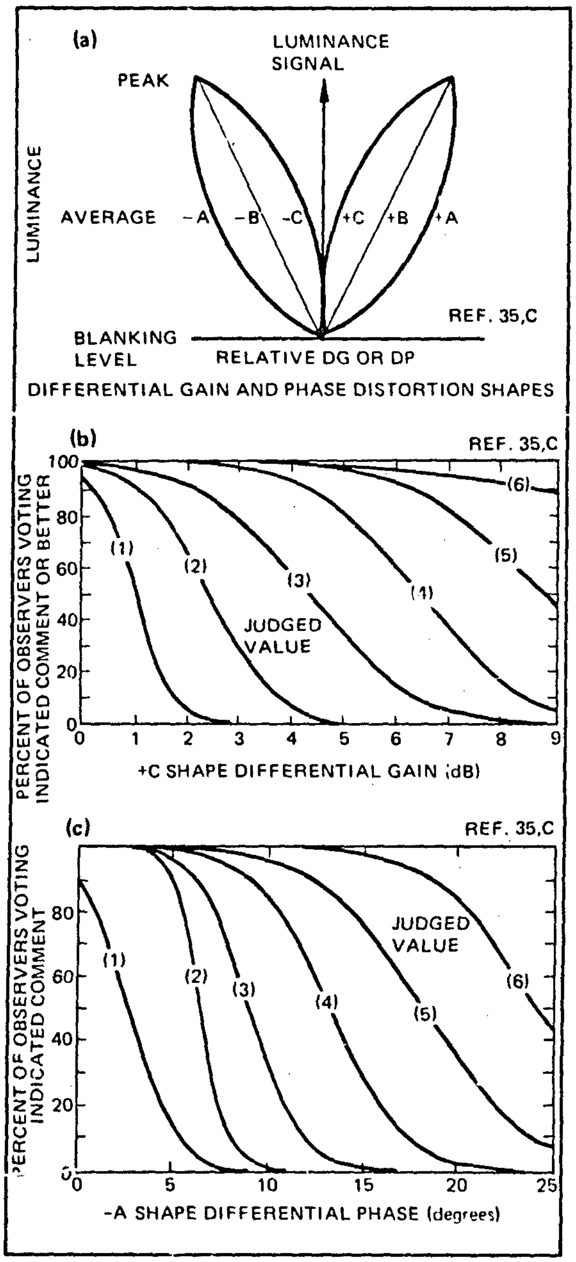
Twelve tests were performed, six each for the flat and shaped delays. A wide range of delay times was used, from zero to 600 *nanoseconds* (ns) for the flat delay and zero to over 1000 ns for the shaped delay. As described in Figure 4.3-59, a 1000 nanosecond (1 μsec) delay causes a displacement of approximately 0.19 percent in the horizontal position of the picture, or 1 mm (0.04 in) for a picture with a horizontal dimension of 50 cm (19.6 in).

As shown by the graphs, the flat delay caused greater picture impairment than the shaped delay. (At 100 ns, over 80 percent of the observations were of a quality 2 or better for the shaped delay while only 50 percent reached that level for a flat delay of the same length. (Continued)

4.3.13 IMAGE DEFECTS (CONTINUED)

The extent of the effect was found to be dependent upon the picture content. (Pictures typical of the type usually found in broadcast television were employed.) The difference in average values between the most sensitive and least sensitive picture was 59 ns for the flat delay and 49 ns for the shaped delay.

The color shift is most noticeable around vertical edges of highly saturated color areas adjacent to areas of low saturation that are relatively free of high frequency detail.



The basic television system and the viewing conditions were the same as those reported for Figure 4.3-59. Ten observers were used, and each made three judgments for every test condition.

In interpreting these results, it must be remembered that they were obtained on an NTSC color system. Most closed-circuit television systems do not have separate luminance and chrominance signals. Also it must be remembered that the pictures were judged for quality for home entertainment purposes, not information extraction purposes.

Figure 4.3-61. Effects of Differential Gain and Differential Phase in NTSC Color Television Pictures. Subjective evaluations were made of color television pictures that had been degraded by varying amounts of *differential gain* (DG) and *differential phase* (DP) Ref. 35,C). Differential gain causes a shift in the *saturation* of colors displayed in the picture, and DP causes a change in hue. Both terms, DG and DP, refer to the relationship that the chrominance signal bears to the luminance signal. They refer to shift that may take place in either the phase or amplitude of the chrominance signal as a function of changes in the amplitude of the luminance signal. To determine DG, the output amplitude of a chrominance signal of constant input strength is measured for two different strengths of the luminance signal. The DG can be expressed in decibels as:

$$\text{DG dB} = 20 \log \frac{A_{c_1}}{A_{c_2}}$$

where A_{c_1} = The amplitude of the chrominance signal for one strength of the luminance signal, and

A_{c_2} = The amplitude of the chrominance signal at the other strength of the luminance signal.

Differential phase is determined by measuring any phase shifts that occur in the chrominance signal at two levels of signal strength for the luminance signal. It is expressed in degrees.

Both the DG and DP can take either negative or positive values, with differing effects on the judged quality of the picture. Positive DG causes an increase in color saturation and negative DG causes a decrease. Positive DP causes a hue shift in flesh tones toward magenta and a negative DP causes a shift toward green. **(Continued)**

4.3.13 IMAGE DEFECTS (CONTINUED)

In addition to being either positive or negative, DG and DP may also be linear or nonlinear. Figure 4.3-61(a) gives the general nature of the polarity and shape of the DG and DP conditions tested. Data are shown in Figure 4.3-61(b) and (c) for the worst condition for each: +C shape for DG and the -A shape for DP. The test pictures were from the standard set of still scenes developed to test the quality of entertainment television.
The effects of the distortions on the picture were rated with the following scale:

Judgment scale value	Description
1	Not perceptible
2	Just perceptible
3	Definitely perceptible, but only slight impairment to picture
4	Impairment to picture, but not objectionable
5	Somewhat objectionable
6	Definitely objectionable
7	Extremely objectionable

Each of the positive DG shapes showed more degradation than the corresponding negative shape, indicating a loss of saturation was more tolerable than a gain. Each of the negative DP shapes showed more degradation than the positive, indicating that a shift toward green in the flesh tones was more acceptable than a shift toward the magenta.

Tests were also run on pictures with combined DG and DP, and their combined effect lowered the judged values considerably below those for either alone at a given level. Limited tests were run on a black and white monitor; it was found to be much more resistant to changes in DG and DP than the color monitor.

Ten observers participated in the test, and every test condition was presented to each observer twice. The viewing distance was 4 times the picture height. The Highlight luminance was 51 cd/m^2 (15 fL) for the color monitor, with a contrast ratio of 75:1. For the black and white monitor, the highlight luminance was 86 cd/m^2 (25 fL) and the contrast ratio was 50:1. No room illumination was used other than that generated by the monitor.

It must be remembered in interpreting these results that they were obtained on an NTSC system. Most closed-circuit systems do not have separate luminance and chrominance channels. Also it must be remembered that the pictures were judged for entertainment purposes, not information extraction purposes.

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The functions are described by the authors as follows:

The parameter "a" will denote the sample element spacing. As imaged on the film plane, the sample spacing is 0.548 mm. The sample element spacing projected back onto the mask plane is 9.56 x 0.548 = 5.24 mm, where 9.56 is the reconstruction optics demagnification factor.

All of the intensity point spread functions h(x,y) described are normalized so that the volume under the point spread function is equal to unity. This normalizes the transfer functions to unity at zero spatial frequency.

Quadratic Interpolator

The two dimensional point spread function for the non-integrated mask is given by:

$$h(x,y) = \frac{1}{a^2}\left[\frac{3}{4} - \left(\frac{x}{a}\right)^2\right]\left[\frac{3}{4} - \left(\frac{y}{a}\right)^2\right], \quad |x|;|y| \leq \frac{a}{2}$$

$$h(x,y) = \frac{1}{2a^2}\left[\frac{3}{2} - \frac{|x|}{a}\right]^2 \left[\frac{3}{4} - \left(\frac{y}{a}\right)^2\right],$$

$$a/2 < |x| \leq 3a/2$$

$$|y| \leq a/2$$

$$h(x,y) = \frac{1}{2a^2}\left[\frac{3}{4} - \left(\frac{x}{a}\right)^2\right]\left[\frac{3}{2} - \frac{|y|}{a}\right]^2, \quad |x| \leq a/2, \quad a/2 < |y| \leq 3a/2$$

$$h(x,y) = \frac{1}{4a^2}\left(\frac{3}{2} - \frac{|x|}{a}\right)^2 \left(\frac{3}{2} - \frac{|y|}{a}\right)^2, \quad \frac{a}{2} < |x| \leq \frac{3a}{2}, \quad \frac{a}{2} < |y| \leq \frac{3a}{2}$$

$$h(x,y) = 0, \quad |x|, |y| > \frac{3a}{2}$$

The point spread function is separable; in either the x or y direction, it is a parabola of height 3/4a and an extent of 3a.

The MTF is given by:

$$H(f_x, f_y) = \text{sinc}^3(af_x)\,\text{sinc}^3(af_y)$$

Note that this function is not band-limited.

105 Percent Gaussian Aperture Distribution Function

The desired MTF was best fitted in the sense of least squares to a Gaussian function, where the standard deviation σ_f derived from the fitted Gaussian MTF satisfies:

$$\sigma_f = 0.362\, f_s$$

where the sampling frequency $f_s \cong 1/a = 1/0.548$ mm = 1.82 cycles/mm in the film plane.

Thus $\sigma_f = 0.66$ cycles/mm.

For a Gaussian MTF, it is well-known that the point spread function is Gaussian and that σ_s, the standard deviation in the spatial domain, is equal to $1/2\pi\sigma_f$ where σ_f is the standard deviation in the spatial frequency domain. Thus $\sigma_s = 0.242$ mm in the film plane.

The 105 percent Gaussian aperture distribution MTF goes to zero at $0.95\, f_s$.

Cosine Aperture Distribution Function

By means of a Fast Fourier Transform computer program, the point spread function h(x,y) was obtained from the MTF data. The point spread function is separable.

Linear Interpolator Function

The two-dimensional point spread function of the linear interpolator for the nonintegrated mode is given by:

$$h(x,y) = \frac{1}{a^2}\left[1 - \frac{|x|}{a}\right]\left[1 - \frac{|y|}{a}\right] \quad |x|, |y| \leq a$$

$$= 0 \quad |x|, |y| > a$$

The point spread function is separable; in either the x or y direction, it is a triangle of height 1/a and with a full extent of 2a. Note that the function is linear in x and in y, but quadratic along the diagonals.

The modulation transfer function (MTF) is given by:

$$H(f_x, f_y) = \text{sinc}^2(af_x)\,\text{sinc}^2(af_y)$$

where

$$\text{sinc}(f_x) \equiv \frac{\sin(\pi f_x)}{\pi f_x}$$

Note that $H(f_x, f_y)$ is not band-limited.

Sine-Squared Functions

The two-dimensional point spread function is given by:

$$h(x, y) = \frac{k^2}{a^2} \; \mathrm{sinc}^2 \left(\frac{kx}{a}\right) \mathrm{sinc}^2 \left(\frac{ky}{a}\right)$$

A family of point spread functions was considered where the parameter k took on the values 1.0, 0.8, and 0.6. The point spread function is separable; in either direction, it consists of a sinc-squared function of height k/a. Since the spatial extents of the point spread functions are infinite, it was necessary in the mask fabrication process to truncate. Truncation was made to occur at a natural zero of the function to minimize the effects of artifacting. The point spread function has natural zeros at y = ma/k, where m is an integer. To satisfy the optical uniformity constraint, two was the largest value of m which could be chosen. The extent of the truncated function is, therefore, 4a/k. For k - 1, 0.8, and 0.6, the mask spatial extents are: 20.96 mm, 26.2 mm, and 34.9 mm in the mask plane. Some amount of truncation was experienced at the extremities of the k - 0.6 mask.

The MTF is given by:

$$H(f_x, f_y) = \begin{cases} \left[1 - \frac{a}{k}|f_x|\right]\left[1 - \frac{a}{k}|f_y|\right], & |f_x| < k/a; \quad |f_y| < k/a \\ 0, & |f_x| > k/a; \quad |f_y| > k/a \end{cases}$$

Rectified Sinc Function

The point spread function h(x,y) was obtained from a desired MTF by a Fast Fourier Transform program. (The upper end of the MTF is shown in figure 4.3-56(b).)

Hanning Function

The two-dimensional point spread function for this nonintegrated mask if given by:

$$h(x, y) = \begin{cases} \frac{1}{4a^2}\left[1 + \cos \frac{\pi x}{a}\right]\left[1 + \cos \frac{\pi y}{a}\right] & |x|, \; |y| < a \\ 0, \quad |x|, \; |y| > a \end{cases}$$

The point spread function is separable; and in either the x or y directions, it is a raised cosine function of height 1/a and extent 2a.

The modulation transfer function is given by:

$$H(f_x, f_y) = \frac{\mathrm{sinc}\;(2\,af_x) \;\; \mathrm{sinc}\;(2\,af_y)}{\left[1 - (2\,af_x)^2\right]\left[1 - (2\,af_y)^2\right]}$$

Note that this function is not band-limited. Let $f_s = 1/a$.

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4.4 ELECTRO-OPTICAL DISPLAY CHARACTERISTICS

4.4.1 CRT Luminance

4.4.2 Resolution and Modulation Transfer in Cathode Ray Tubes

This section is intended to give the electro-optical display system designer or purchaser a better understanding of the way in which equipment and operating features affect the visual quality of the images produced by CRT's.

Some understanding of the way in which equipment features interact in producing the CRT image is valuable. This is because changes in one feature that appear to have desirable effects on image quality may, through interaction with other features, lose their effectiveness, or actually result in decreased quality.

For instance, increasing the maximum beam current will result in increased display luminance. Data in Section 3.2 indicate that visual performance tends to improve with increasing luminance, up to very high values. However in CRT displays, other factors must be taken into consideration. For instance, increasing the beam current results in larger spot diameters. These larger spot diameters will result in losses in both resolution and contrast in the image. The increase in beam diameter can be corrected, up to a point, by changes in the focusing circuit.

However, the light from the phosphor which is reflected within the faceplate will increase with increasing luminance. This light, striking the phosphor in areas of low image luminance, will cause a loss of contrast (see Figure 4.4-25). Thus, the potential for increased visual performance through the increased luminance may be more than offset by losses in contrast caused by the internally scattered light.

Section 4.4.1 deals with equipment characteristics and the important interactions among these characteristics which affect the perception of luminance in the display. Section 4.4.2 deals with resolution and modulation transfer. These two topics are treated together for two reasons. First, they interact to establish visual perceptibility in black and white imagery. This relationship is discussed in detail in Sections 3.1 and 3.2. Second, they are strongly interdependent with regard to the equipment features which produce the CRT image.

4.4.1 CRT LUMINANCE

The major factors contributing to CRT luminance are presented in this section. Both black and white and color systems are discussed. The importance of the application for the interactions among the equipment parameters and between the equipment parameters and the visual system cannot be overemphasized. None of the individual items discussed in this section act independently of the others. Of equal importance is their influence on the visual and equipment performance topics covered in later sections, particularly resolution and contrast reproduction. Wherever possible, these interrelations have been pointed out, and cross references given to the appropriate sections or figures. In addition to the characteristics covered in this section, many other factors affect CRT luminance. Among these are the method of phosphor preparation, phosphor crystal size, method of application to the tube face, and treatment during the coating process. Sources for information on these topics can be found in Ref. 1. Unfortunately a comprehensive treatment of the areas covered here would require space which is considerably beyond that available in a book such as this. Therefore an attempt has been made to alert the designer of interpretation systems to the major characteristics of the system which influence CRT luminance and provide some quantified examples for each topic covered, so he may determine which, if any are critical to his application.

Because of the loss of contrast caused by scattered light within the phosphor and CRT faceplate, which could act as a veiling luminance, very high CRT luminance is undesirable. However when the scattered light can be controlled, such as with a fiber optic faceplate, the restriction does not apply.

Four different measures of CRT brightness are covered.

- Peak luminance - The luminance at the center of the scanning spot, where the current density is greatest in the electron beam.
- Average spot luminance - The luminance of the spot averaged over the area of the spot. Since the luminous output of a spot follows a Gaussian spread function, decreasing away from the center, the value which the average spot brightness assumes will depend on the definition of spot size (see Figure 4.1-9).
- Line luminance - The luminance of the line averaged over its area. Since the spread function of the line is Gaussian, the line brightness will depend upon the definition of a line, in the same way that spot brightness depends upon definition of the spot.
- Raster luminance - The luminance of an extended area on the face of the CRT.

4.4.1 CRT LUMINANCE (CONTINUED)

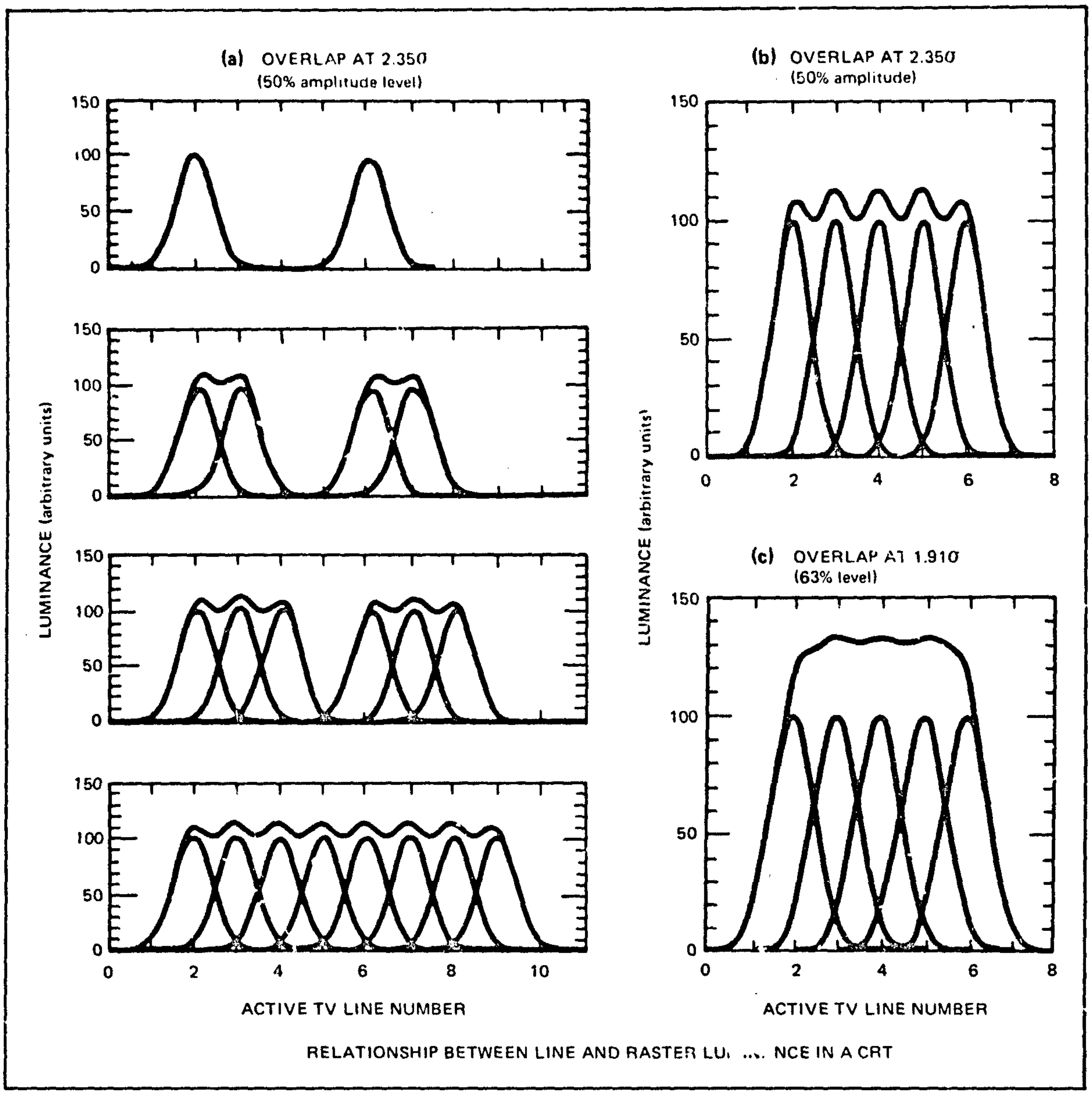


Figure 4.4-1. CRT Luminance as a Function of Line Spacing for CRT's Without Shadow Masks. (Continued)

4.4.1 CRT LUMINANCE (CONTINUED)

Figure 4.4-1. CRT Luminance as a Function of Line Spacing for CRT's Without Shadow Masks. In considering the effects of line spacing on CRT luminance, particularly for tubes without shadow masks, it is necessary to take into account the visual effect created by the overlapping spread functions of adjacent lines. (Figure 4.1-9 discusses the relationship between the spot spread function and line spacing.) When adjacent lines are written within the integrating time of the eye (this time depends upon a number of conditions, a single figure is likely to be misleading, but for normal CRT viewing conditions 0.1 second is a reasonable number), the luminances in the overlapping portions of the two lines produce a visual sensation equal to the sum of the two individual luminances (Ref. 2). This effect is illustrated in the accompanying illustration. In (a) the visual effect produced by scan lines spaced 2.35 σ apart is shown. At 2.35σ the lines overlap at the 50-percent intensity level of the spread function. The top illustration shows that lines number 2 and number 6 of the raster have been written. They are spaced 4x2.35σ or 9.42σ apart and their amplitudes at the point of overlap (4.71σ) are so low that they are considered to produce no brightness sensation. The second illustration in (a) shows the effect of writing lines 3 and 7. Since they overlap at the 50-percent intensity level with lines 2 and 6 respectively, the luminance at that point is perceived as equal to 100 percent of the peak luminance of the individual lines. The overlap at the line spacing interval (2.35σ) causes a luminance increment of approximately 6 percent to the peak luminance of the individual lines. The subsequent illustrations in (a) show the effect of completing a raster of nine lines.

If the raster is viewed from a short distance, the *ripple* of the combined luminances will be detected. If the raster is viewed from a distance great enough so that the ripple is below the limit of visual resolution, the perceived luminance will be the average luminance of the ripple.

Parts (b) and (c) illustrate the change in ripple and in average luminance caused by decreasing the line spacing from 2.35σ to 1.19σ. The vertical scale has been expanded so that the ripple of the 1.91σ spacing can be seen.

The ratio of the line spacing to the standard deviation of the spot is called the *pitch* of the raster. The pitch of a raster whose lines are spaced 2.34σ apart is 2.34; for lines spaced 1.91σ apart, the pitch of the raster is 1.91. The relation between pitch and the modulation of the ripple is shown in Figure 4.4-16.

4.4.1 CRT LUMINANCE (CONTINUED)

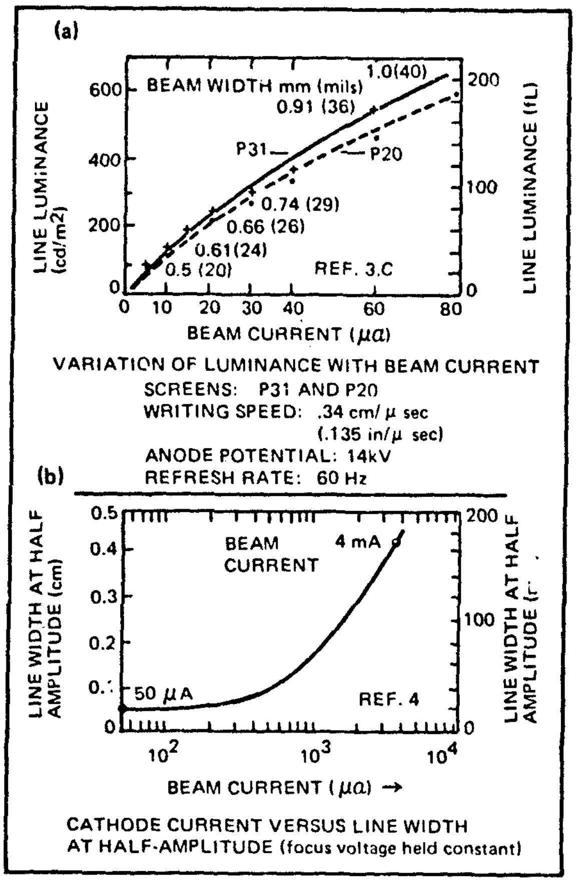
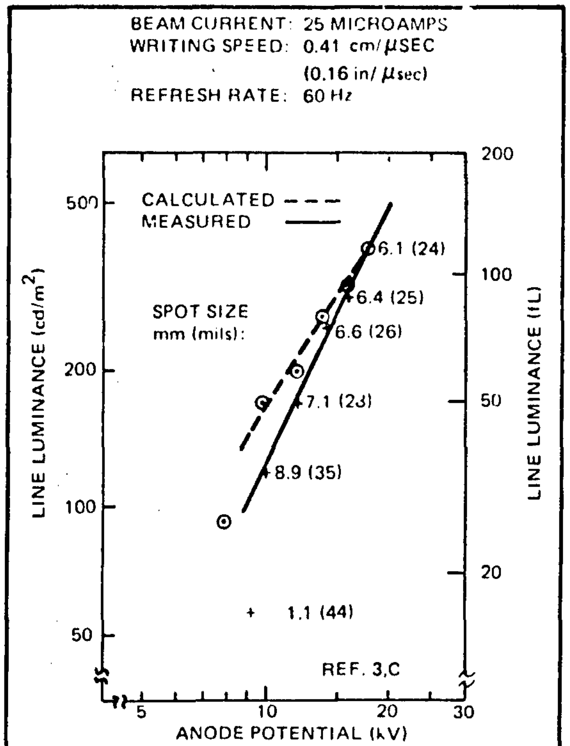


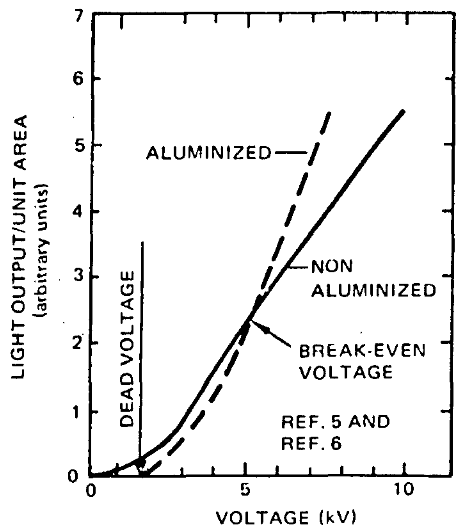
Figure 4.4-2. Effect of Beam Current on Line Luminance for Two Black and White Phosphors. The relationship between line luminance and beam current is fundamental to the image forming process in CRT's (see Figure 4.1-2). The curves in (a) (Ref. 3,C) show a nonlinear relationship between beam current and luminance for the P20 and P31 phosphors and are typical of those found for other phosphors (see Figure 4.4-9).

The increase in spot size (a) and, consequently line width (b) (Ref. 4) as beam current increases is caused by defocusing of the beam that accompanies the increased current. This change in spot size affects resolution and contrast transfer in both the horizontal and vertical directions (see Figures 4.1-3 and 4.4-15) as well as the ripple amplitude (Figure 4.4-16).

4.4.1 CRT LUMINANCE (CONTINUED)



(a) BRIGHTNESS AS A FUNCTION OF ACCELERATING VOLTAGE FOR A P31 PHOSPHOR



(b) BRIGHTNESS-VOLTAGE CURVE

Figure 4.4-3. CRT Line Luminance as a Function of Anode Potential. Increasing the anode potential increases the speed with which the electrons in the electron beam strike the phosphor in a CRT. For a given beam current (25 microamperes for the case shown), the increase in luminance is approximately a direct function of the square of the increase in anode potential (Ref. 3,C). The changes in spot size indicated in the figure are caused by the improved focus that can be achieved with increased anode potential. The dashed line in (a) represents luminance values that have been calculated for a constant diameter spot size (0.61 mm, 24 mils).

The changing spot size will affect the contrast transfer and resolution characteristics. See Figures 4.1-3 and 4.4-15.

As indicated in (b), at the low end of the voltage range the nonlinearity of the relationship between luminance and the anode potential becomes accentuated. The voltage that is obtained by extending the nearly linear portion of the curve to the zero luminance level is called the *dead voltage* (Ref. 5).

The application of aluminized backing on CRT phosphors to control secondary emissions and stray light within the tube reduces the effectiveness of the low anode potentials. For an aluminized backing 0.1 µm (0.004 mils) thick, the light production of the aluminized and nonaluminized phosphors are equal at about 5 kV (Ref. 6). The voltage at which this equality is reached is known as the *break-even voltage*.

4.4.1 CRT LUMINANCE (CONTINUED)

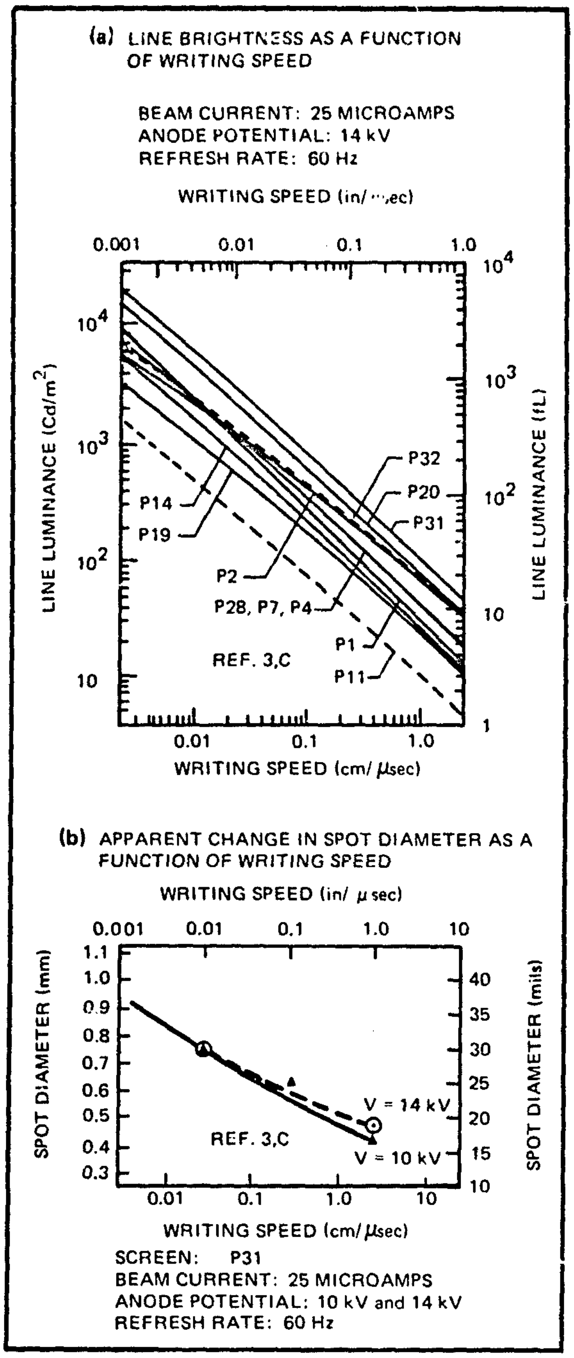


Figure 4.4-4. CRT Line Luminance as a Function of Writing Speed. For a given beam current, anode potential, and spot size, the luminance of an individual line depends upon the *writing speed* of the electron beam, which is the speed of the electron beam as it travels over the surface of the phosphor. Writing speed depends on the number of TV lines, interlace order, frame rate, and CRT size. For a 525-TV-line NTSC system (2:1 interlace with a 30-Hz frame rate), which has a 25-cm (9.8-in) horizontal raster, the beam must travel the length of the raster in approximately 52.6 microseconds (see Figure 4.1-8 for the derivation of this time). Thus:

$$\text{Writing Speed} = \frac{25\text{ cm}}{52.6\mu\text{sec}} = 0.475\text{ cm}/\mu\text{sec}$$

$$= 0.187\text{ in}/\mu\text{sec}$$

Writing speeds of up to 2.54 cm/μsec (1 in/μsec) are sometimes used in high line-number, noninterlaced systems.

The loss in luminance is due to the reduction in the *dwell time* for the electron beam (Ref. 3,C). Dwell time is the time the beam spends on a given spot on the phosphor. Since the luminance is determined by the number of electrons striking the phosphor, as well as their energy, as the writing speed increases, dwell time decreases. By reducing the dwell time, fewer electrons are delivered to a given spot on each passage of the beam, with the result that luminance is lowered (a).

At very slow writing speeds, the relationship between luminance and writing speed will become increasingly nonlinear because of *saturation* effects. That is, the phosphor will be emitting close to the maximum amount of light it can, so the addition of more energy from the electron beam does not produce an accompanying increase in luminance. The change in spot size as a function of writing speed (b) will affect horizontal and vertical resolution and contrast (see Figure 4.1-3 and Figure 4.4-15). The change in spot size will also affect ripple modulation (Figure 4.4-16).

4.4.1 CRT LUMINANCE (CONTINUED)

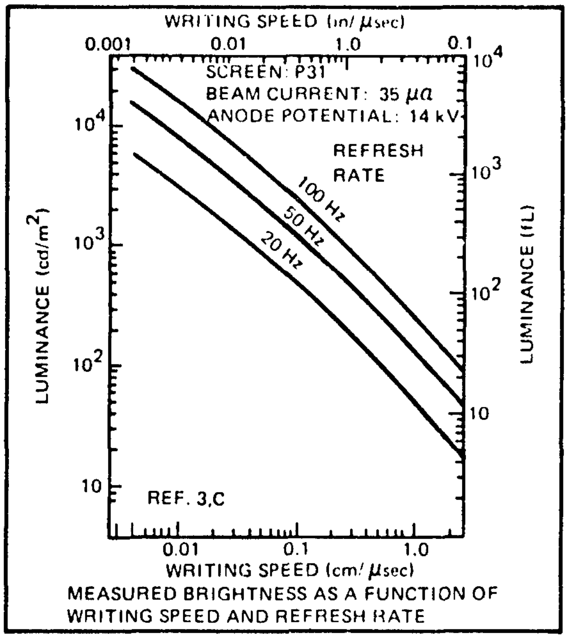


Figure 4.4-5. CRT Line Luminance as a Function of Combined Writing Speed and Refresh Rate. The combined effect of writing speed and refresh rate on CRT line luminance is shown here for a single phosphor (P31). The relationships are nearly linear over the ranges studied (Ref. 3,C).

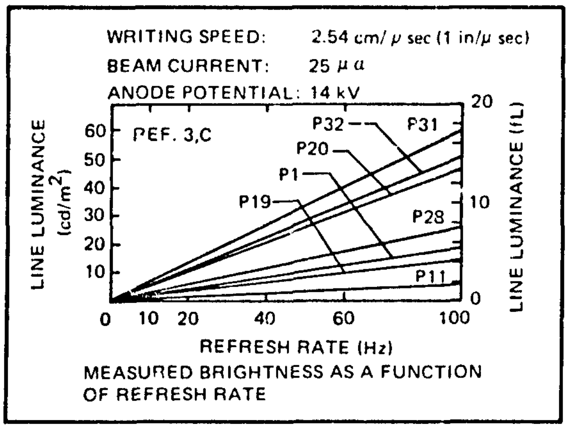


Figure 4.4-6. CRT Line Luminance as a Function of Refresh Rate. Refresh rate is the rate at which the electron beam in the CRT returns to a given spot on the phosphor. It is nominally taken to be the same as the frame rate. As shown in the accompanying graph, increases in refresh rate increase line luminance (Ref. 3,C). Each phosphor tested had a unique rate. The linear relationship may not hold for very high refresh rates that have time periods approaching the persistence times of the phosphor.

Since the refresh rate is determined by the frame period, an increase in the refresh rate for a given system must be accompanied either by an increase in bandwidth or reduction in resolution (see Figure 4.4-12).

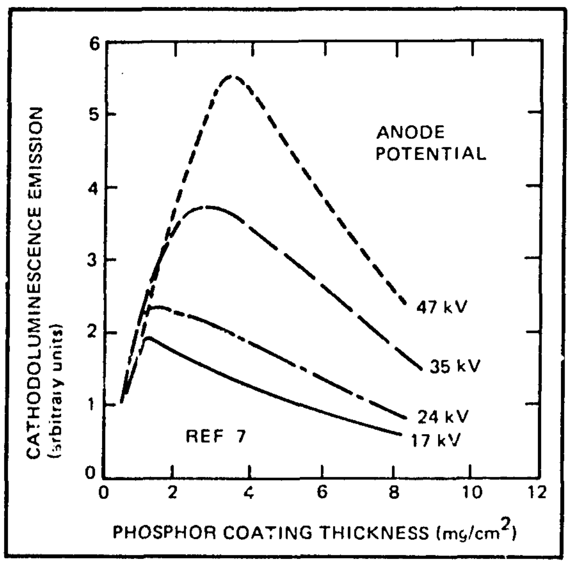


Figure 4.4-7. Effect of Phosphor Thickness on CRT Luminance. Phosphor thickness is measured by the number of milligrams (mg) of phosphor that are applied to each square centimeter of the CRT face. The curves reproduced in this figure indicate that there is an optimum coating density for each expected use in terms of anode potential. The light production of the phosphor coating falls off rapidly on either side of this value (Ref. 7). The phosphor used in this study was similar to the P11. The beam current was kept constant at 20 μa/cm².

Electron beams striking the faceplate at high energies (which are created by high anode potentials) generate X-rays. For a discussion of allowable X-radiation limits, see Section 6.8.2.

4.4.1 CRT LUMINANCE (CONTINUED)

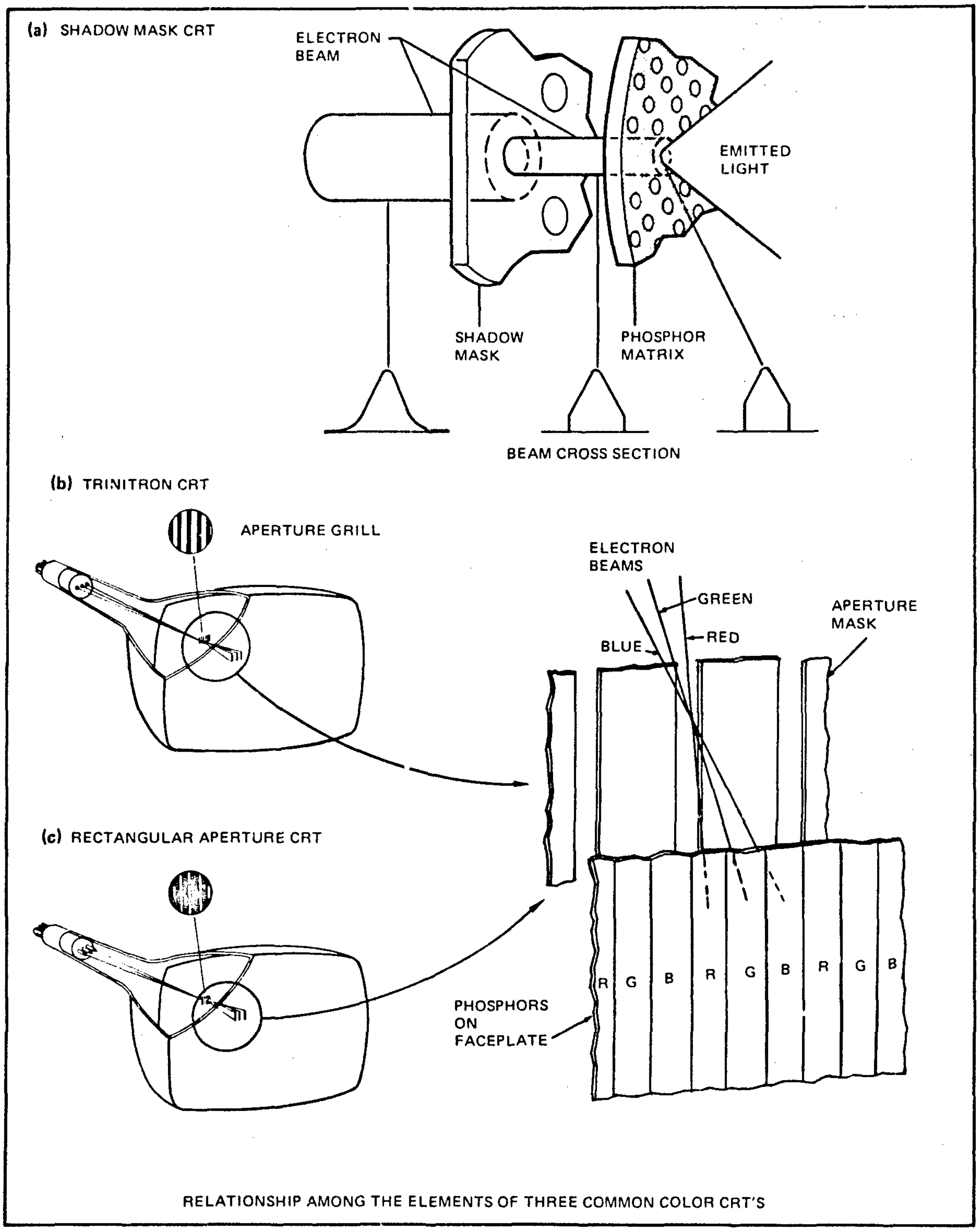


Figure 4.4-8. Effect of Aperature Masks and Phosphor Matrix on CRT Luminance. (Continued)

4.4.1 CRT LUMINANCE (CONTINUED)

Figure 4.4-8. Effect of Aperture Masks and Phosphor Matrix on CRT Luminance. The shadow mask, in conjunction with the phosphor dot matrix found in some color CRT tubes, affects the luminance of the display in three ways. First, because of the discrete nature of the phosphor dot matrix, only about 50 percent of the total area of the tube is capable of producing light (Ref. 8). At normal viewing distances where visual integration takes place over an area larger than the individual dots, the luminance of the display is reduced in direct proportion to the ratio of the luminous area to the nonluminous area. Second, both the shadow mask and the areas of the matrix surrounding each phosphor dot restrict the edges of the electron beam so that little overlap between scan lines takes place; therefore, the additive effect described in Figure 4.4-1 is greatly diminished. The third, compensating factor is that because its edges are cut off, the beam diameter can be increased, permitting the use of a higher beam current. Thus, the central portion of the beam has a higher energy than that of a beam used for comparable line spacing in a tube without a shadow mask.

Two other techniques in addition to the shadow mask that have been developed for preventing the beam for one color from hitting the phosphor for another color are the trinitron and the rectangular aperture. These both use physical barriers to the electron beam which are placed between the electron gun and the phosphor screen. The trinitron, shown at (b) uses a series of slots instead of circular holes, and the rectangular aperture, shown at (c), uses rectangular openings. The phosphor for these tubes is applied in stripes rather than dots.

Both permit a larger percentage of the tube area to be covered with phosphor and permit more efficient electron optics, which result in increased luminance (Ref. 9). They also allow visual integration of the luminance created by the overlapping scan lines. As a result, there is a greater increase of luminance possible with these tubes than with the shadow mask. The luminance reported for the three types of tubes is listed below (Ref. 10).

Aperture type	Luminance cd/m^2	fL
Trinitron	343	100
Rectangular	188	55
Shadow Mask	172	50

4.4.1 CRT LUMINANCE (CONTINUED)

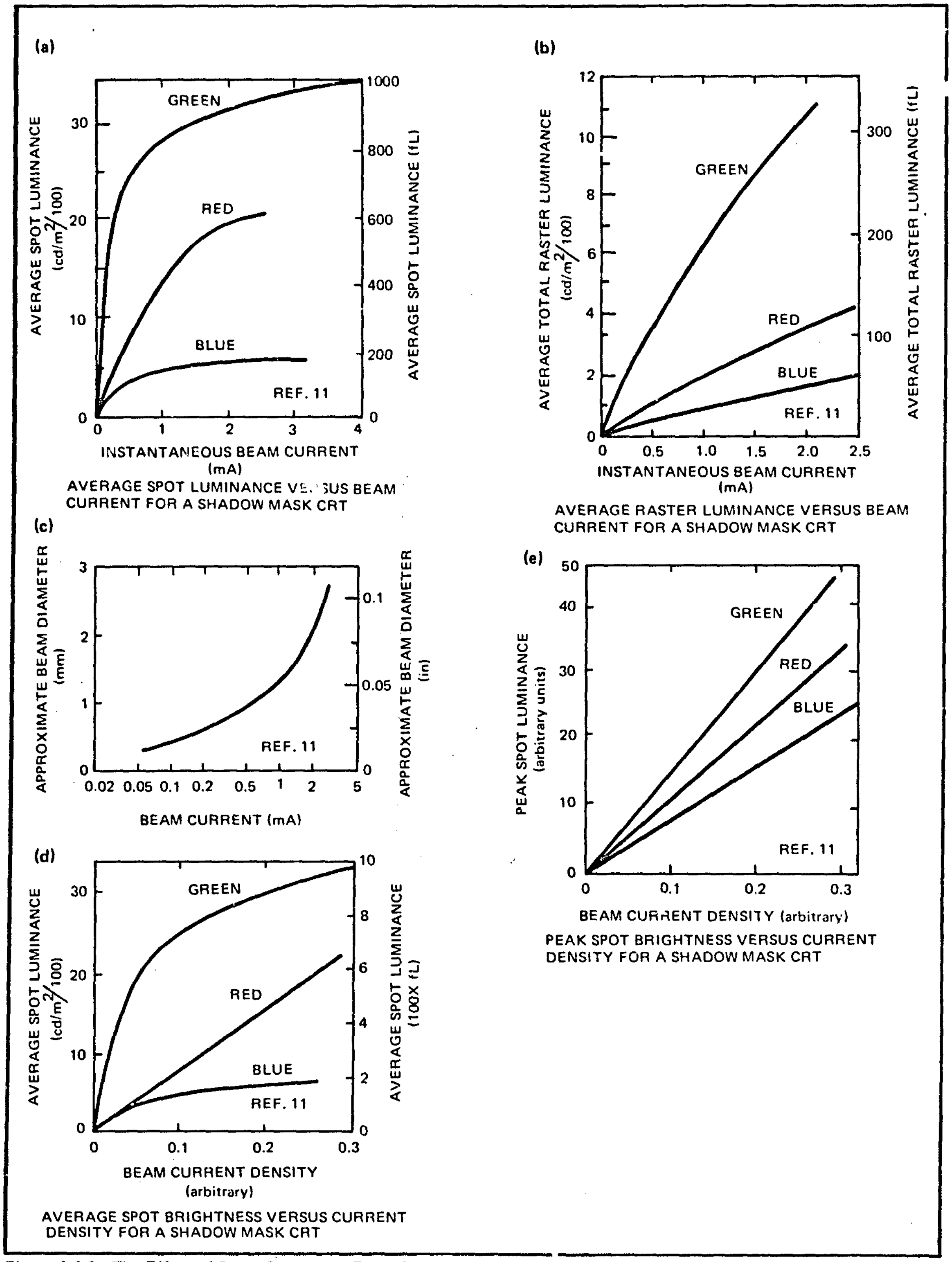
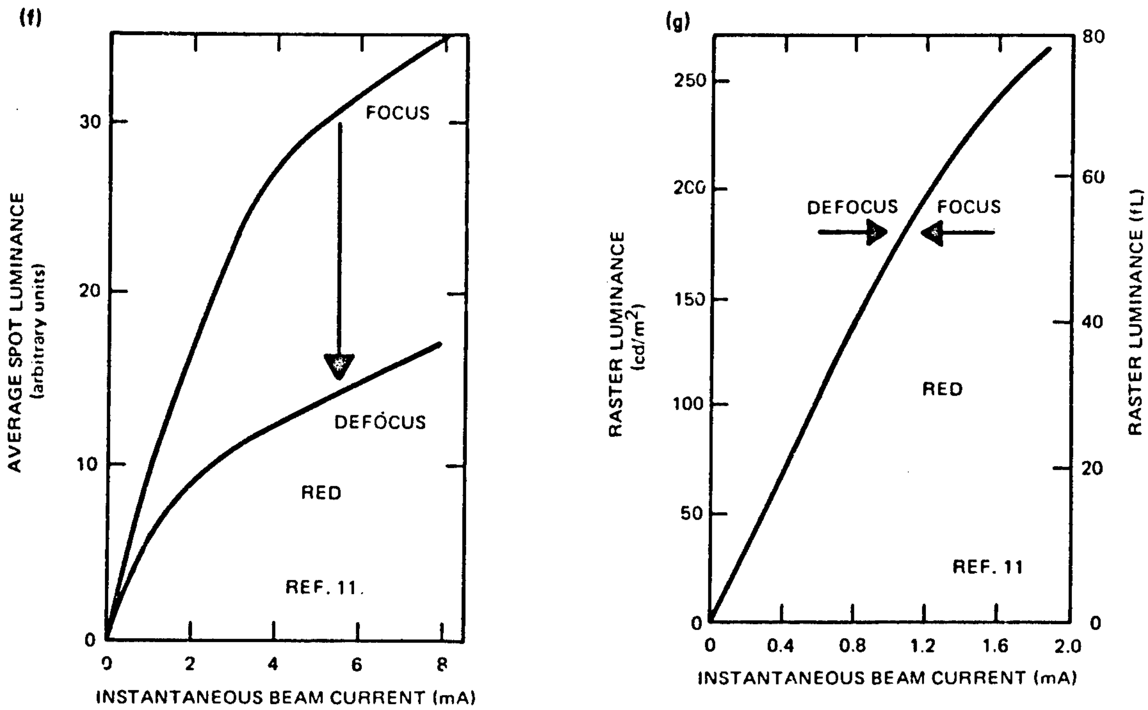


Figure 4.4-9. The Effect of Beam Current on Three Measures of CRT Luminance: Peak Luminance, Average Luminance, and Raster Luminances. (Continued)

4.4.1 CRT LUMINANCE (CONTINUED)



SPOT BRIGHTNESS, FOCUS/DEFOCUS EFFECTS, RED PHOSPHOR FOR A SHADOW MASK CRT

RASTER BRIGHTNESS, FOCUS/DEFOCUS EFFECTS, RED PHOSPHOR FOR A SHADOW MASK CRT

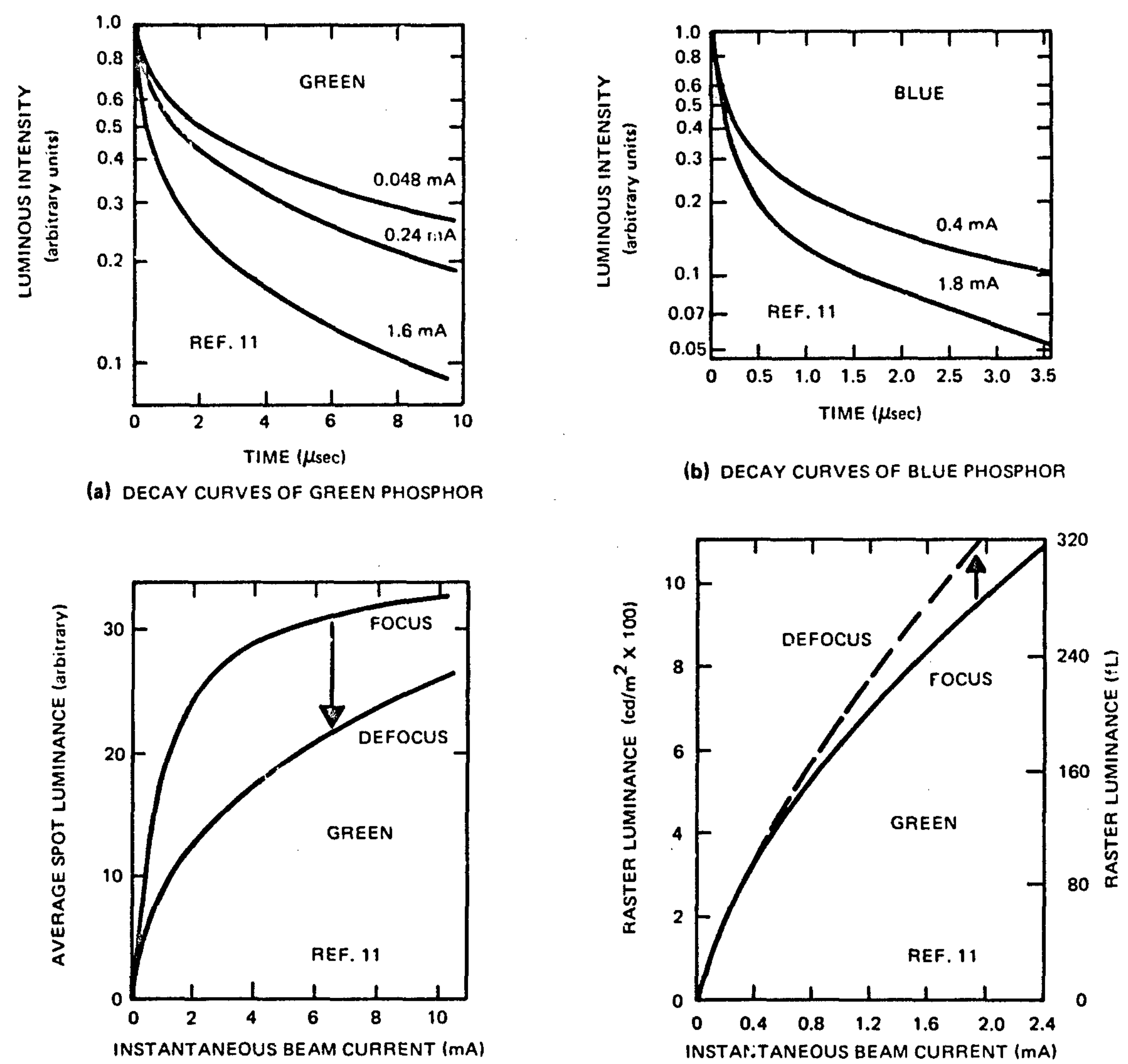
Figure 4.4-9. The Effect of Beam Current on Three Measures of CRT Luminance: Peak Luminance, Average Luminance, and Raster Luminance. Parts (a) and (b) of this figure show the difference in spot and raster luminance as a function of beam current for a shadow mask CRT. The nonlinearity of the spot luminance is considerably greater than that for the raster (Ref. 11). Part (c) shows one of the causes for this difference. As beam current is increased, the spot grows in diameter. The increase in size accelerates as the beam current increases. As a result, the increased current is being spread over a larger area so the average luminance increases more slowly than the beam current.

The change in spot size also affects resolution and contrast transfer in both the horizontal and vertical directions (see Figure 4.1-2) as well as ripple modulation (Figure 4.4-16).

Part (d) shows the average spot luminance curves plotted as a function of current density, which compensates for the increased area. The luminance of the red phosphor has now become linear. The peak spot luminance shown in 4.4-9 (e) is linearly related to current density for all three phosphors.

Parts (f) and (g) represent the effects of spot size on both the average spot and raster luminances for the red phosphor. The spot has been made larger by intentionally defocusing it. While the spot luminance is less because the energy of the beam is being spread over a larger area, the raster luminance remains constant. This is an illustration of the integrating effect of the raster. The effects of spot size on raster luminance for the blue and green phosphors involve an interaction with a change in decay time as a function of beam current and are covered in Figure 4.4-10.

4.4.1 CRT LUMINANCE (CONTINUED)



(a) DECAY CURVES OF GREEN PHOSPHOR

(b) DECAY CURVES OF BLUE PHOSPHOR

(c) AVERAGE SPOT LUMINANCE FOCUS/DEFOCUS EFFECTS, GREEN PHOSPHOR FOR A SHADOW MASK CRT

(d) RASTER LUMINANCE FOCUS/DEFOCUS EFFECTS, GREEN PHOSPHOR FOR A SHADOW MASK CRT

Figure 4.4-10. Spot and Raster Luminance for Blue and Green Phosphors as a Function of Beam Current and Spot Size. Unlike the red phosphor reported in Figures 4.4-9 (e) and (f), the raster luminance of the blue and green phosphors change with changes in spot size. This is attributed to the fact that decay time for both phosphors is a function of beam current, as shown in parts (a) and (b) of this figure.

As with other phosphors, spot luminance declines as spot size increases if the beam current is kept constant. However, because of their current-dependent decay characteristics, the raster luminance increases, rather than staying the same. This is because as the beams for these two phosphors spread and activate the surrounding dots of either color at low current levels, those dots respond with relatively long decay times. The net effect is to increase the integrated luminance of the raster (Ref. 11).

4.4.1 CRT LUMINANCE (CONTINUED)

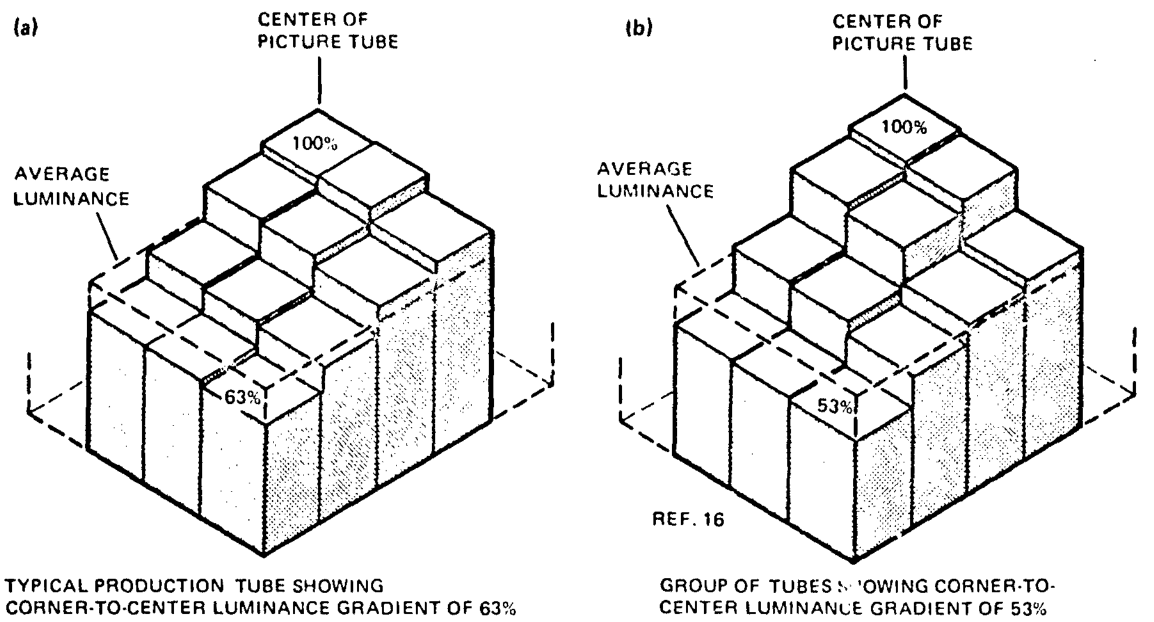


Figure 4.4-11. Nonuniformities in CRT Luminance. Both systematic and nonsystematic nonuniformities are found in the luminance of CRT displays. Unless they are severe, they are generally unnoticed even by practiced observers. No data are available to provide information on the effects of these differences on photo interpretation tasks.

Nonuniformities can be caused by phosphor burn. If a beam of too high an intensity strikes the phosphor, or if the scanning circuit fails and the beam either stops or moves very slowly, the energy can vaporize the phosphor, leaving spots or streaks (Ref. 12). Photosensitive surfaces of vidicons are very susceptible to similar burns by intense light (Ref. 13).

Nonsystematic variations in screen luminance caused by CRT defects are called *blemishes*. The definition of blemish given below and the four general categories listed are from Ref. 14 and were developed for *cathode ray charge storage tubes*. With the exception of the storage assembly, the definition is useful for normal CRT's. A blemish is defined as ". . . . a localized imperfection of the storage assembly, phosphor screen, or faceplate that produces an abrupt variation in output luminance."

Four general categories of blemishes are identified in the reference document:

- Static, whose presence is not a function of writing or erasing rates
- Dynamic, whose presence is a function of writing or erasing rates
- Light, which, under specified test conditions, are brighter than the background luminance
- Dark, which, under specified test conditions, are darker than the background luminance

(Continued)

4.4.1 CRT LUMINANCE (CONTINUED)

Reference 15 categorizes blemishes as follows:

The variation in luminance as the screen is scanned by an unmodulated electron beam. The amplitude of the apparent screen noise will depend on screen structure, effective beam size, and many other factors.

- Mottled Screen

  Screen areas of ¼" to 1" diameter with broad, diffuse boundaries which form a mosaic of generally low light output.

- Spots

  Areas with discrete boundaries which, under cathode ray excitation, may be dark or any color; for example, black for a particle of opaque material, and blue or green for point-poisoned phosphor or a so-called "water-mark."

- Halo Spot

  A hazy dark spot with surrounding halo which appears only on the excited portion of nonaluminized screens, changing in size with time, sometimes even disappearing and reappearing.

- Yellow Center *

  A large centrally located screen area which appears more yellow than surrounding screen areas.

- Dark Center

  A screen area which is darker than the surrounding area, and which becomes more pronounced as anode voltage is decreased.

- Blue Edge *

  An edge area of the screen which appears bluer than the central screen area.

- Yellow Edge *

  An edge area of the screen which appears more yellow than the central screen area.

- X Burn

  An "X" shaped dark pattern visible only under cathode ray excitation which becomes more pronounced with continued operation.

- Ion Burn

  A centrally located dark area that becomes more pronounced with continued operation.

* Applies particularly to P4-type screens.

- Pattern Burn

  An area of higher or lower light output with sharp boundaries corresponding to the size and location of the previously used excitation pattern.

- Raster Burn

  A special case of a pattern burn in which no video information is present.

Defects peculiar to color CRT's are listed as:

- Cross Contamination

  Contamination of one primary phosphor by one or more of the other phosphors.

- Poisoned Primary

  Unintentional change in color or efficiency of a phosphor during tube processing.

- Desaturated Primary

  Colorimetric dilution of a primary.

- Misregistry

  Improper alignment of screen elements relative to the proper impingement of the electron beam.

- Nonuniform White

  Variation in luminance and/or chromaticity of a white field.

- Color Haze

  A band of color at the far edge of a white field associated with the observer's viewing angle.

Systematic nonuniformity is found in the difference between the center and edges of the tube, caused largely by the oblique angle with which the beam strikes the tube. The two illustrations in this figure show the results of measurement on production color CRT's (Ref. 16,C). Only the results for one quadrant of the tube are shown. In part (a) of this figure, the luminance of the corner cell is 63 percent of the center luminance. In (b) it is 53 percent. Observers were reported to be unaware of the differences between the tubes when viewed side-by-side until they were told what to look for. The article reporting these results was directed at luminance measurement techniques rather than CRT luminance nonuniformities. As a result, details of the conditions for obtaining the subjective comparison data are lacking. However, it is valuable to note that the 37-percent fall-off in luminance for the tube in Figure 4.4-11(a) (100 to 63 percent) is reported to a typical production tube and thus represents a normal rather than unusual condition.

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES

For the purpose of this book, the topics of resolution and modulation (or contrast) transfer for CRT's are considered together. As shown in Sections 3.1.3, 3.1.4, and 3.1.5, visual performance depends upon both the spatial and contrast characteristics of the object being viewed. In addition the two interact in the image-forming process of electro-optical systems. To treat them separately here would add unnecessary complexity to the discussion.

The periodic nature of the sampling process used in electro-optical imagery generates artifacts in both the spatial content and contrast of the imagery. These problems were introduced in Figures 4.1-3 and 4.1-4. In addition, the quantizing of the intensity signal for digital systems introduces additional artifacts and errors in the area of contrast (Figure 4.1-5).

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

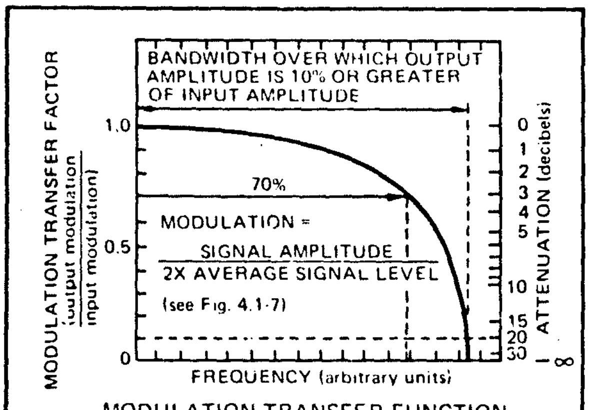


Figure 4.4-12. Relationships Among Bandwidth, Signal Modulation, and Resolution for an Analog Line Scan System. Analog line scan system displays are those in which the strength of a signal is determined by its amplitude. As was pointed out in Figure 4.1-7, part of which is reproduced here, this amplitude is not transmitted equally well for all signal frequencies, the amplitude of the higher frequencies being attenuated by the electronic circuits of the system. The bandwidth of a system, defined in terms of modulation transfer, is the frequency at which the output signal modulation is too low to serve the purposes of the system. In the illustration shown here, one level was chosen as the point at which the output modulation was one-tenth of the input modulation, (20 dB of attenuation). Frequently in TV systems this level is chosen at a 70 percent modulation transfer factor level (3 dB of attenuation). Whatever value of modulation transfer factor is chosen as representing the bandwidth of the display electronics, calculations of the theoretical horizontal resolution of the CRT can be based upon it.

In calculating horizontal resolution from bandwidth information for analog line scan systems, it is necessary to consider the following:

- Frame rate
- TV line number of the system
- Aspect ratio of the raster
- Proportion of each line scan period required for horizontal retrace
- The fact that 1 cycle of the signal equals 2 TV lines

The use of these factors in bandwidth calculations have been presented before in Figure 4.1-8.

The relationship between horizontal resolution and the aspect ratio of the raster is described in Figure 4.1-6. In TV systems, horizontal resolution is measured over a distance equal to the vertical dimension of the raster. Therefore, in a rectangular display 3 units high and 4 units wide, horizontal resolution will be expressed in the number of equivalent TV lines resolved in 3 of the 4 horizontal units, or 3/4 the horizontal dimension. For a square raster, the vertical and horizontal dimensions are the same, so horizontal resolution is expressed as the number of equivalent TV lines across the entire horizontal dimension.

For NTSC 525-TV-line systems, the horizontal retrace time takes approximately 17 percent of the time available for each active TV line, leaving 83 percent for writing the line, sometimes referred to as the *active portion* of the line.

The theoretical value for horizontal resolution is obtained by the following formula:

$$TVL_h = \frac{BW_h}{R_f \times TVL_s} A \times T_w \times 2$$

where:

TVL_h	=	horizontal resolution in equivalent TV lines
BW_h	=	highest frequency in the bandwidth
R_f	=	frame rate
TVL_s	=	the system's TV line number
A	=	1/aspect ratio
T_w	=	active time proportion of each line
2	=	*number of TV lines per cycle*

The expression $(A \times T_w \times 2)$ can be reduced to one factor for a raster with a 4:3 aspect ratio, and to another for a square raster (1:1) aspect ratio, as follows:

For a raster with a 4:3 aspect ratio:

$$A = 0.75$$
$$T_w = 0.83, \text{ therefore}$$
$$(A \times T_w \times 2) = 0.75 \times 0.83 \times 2 = 1.245$$

For rasters with 1:1 aspect ratio:

$$A = 1$$
$$T_w = 0.83, \text{ therefore}$$
$$A \times T_w = 1 \times 0.83 \times 2 = 1.66$$

Horizontal resolution calculations for a display with a 4:3 aspect ratio becomes.

$$TVL_h = \frac{1.245\, BW_h}{R_f \times TVL_s}$$

(Continued)

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

Figure 4.4-12 (continued)

For the following system:

- Bandwidth = 4.5 MHz
- Frame Rate = 30
- TVL_S = 525

$$TVL_h = \frac{(1.245)(4.5 \times 10^6)}{30 \times 525}$$

$$= 356$$

Caution should be used in employing the 0.83 figure for the active portion of the scan line. Non-NTSC systems may have other values, and, if critical calculations are to be made, the value to be used for the active portion should be checked in each case.

If a square raster rather than one with a 4:3 aspect ratio were used:

$$TVL_h = \frac{(1.66)(4.5 \times 10^6)}{30 \times 525}$$

$$= 474$$

These formulas can also be used to calculate the horizontal resolution in TV lines for any specific frequency in the bandwidth. For instance, for a 1-MHz bandwidth displayed on a raster with a 4:3 aspect ratio using a 525-TV-line system with a 30-Hz frame rate:

$$TVL_h = \frac{1.245 \times (1 \times 10^6)}{30 \times 525}$$

$$= 79$$

If this signal were displayed over a distance of 20 cm (7.9 in), each equivalent TV line would be 20/79 or 0.25 cm (0.1 in) long. The spatial frequency of the signal would be 4 cycles/cm (10 cycles/in).

The numerical value for horizontal resolution determined by these calculations must be considered as theoretical because the modulation transfer factor chosen as the limiting value for band-width determinations refers to the modulation of the electrical signal and not to the modulation of the electrical signal and not to the modulation of the luminances created by the image generator (usually a CRT or optical line scan image generator). These latter values are more important to the interpretation function and must be considered by the designer. The reason for this is that, in effect, the useful resolution limit of the system is set by the visual detection of the signal. The modulation in the electrical signal may be such that a linear transfer to luminance modulation would put the resultant image above the threshold needed for vision (see Sections 3.1 and 3.2), but such transfer rarely occurs. Major sources of modulation loss for CRT images occur through internal scattering in the phosphor and CRT faceplate (Figure 4.4-25) and through the reflection of ambient illumination falling on the faceplate and phosphor screen (Figure 4.4-26). To determine the effective visual resolution of the system, the display designer must determine values for these factors from the characteristics of the particular tube he intends to employ and the ambient illumination predicted to fall on the face of the tube in the particular work environment planned for the system.

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

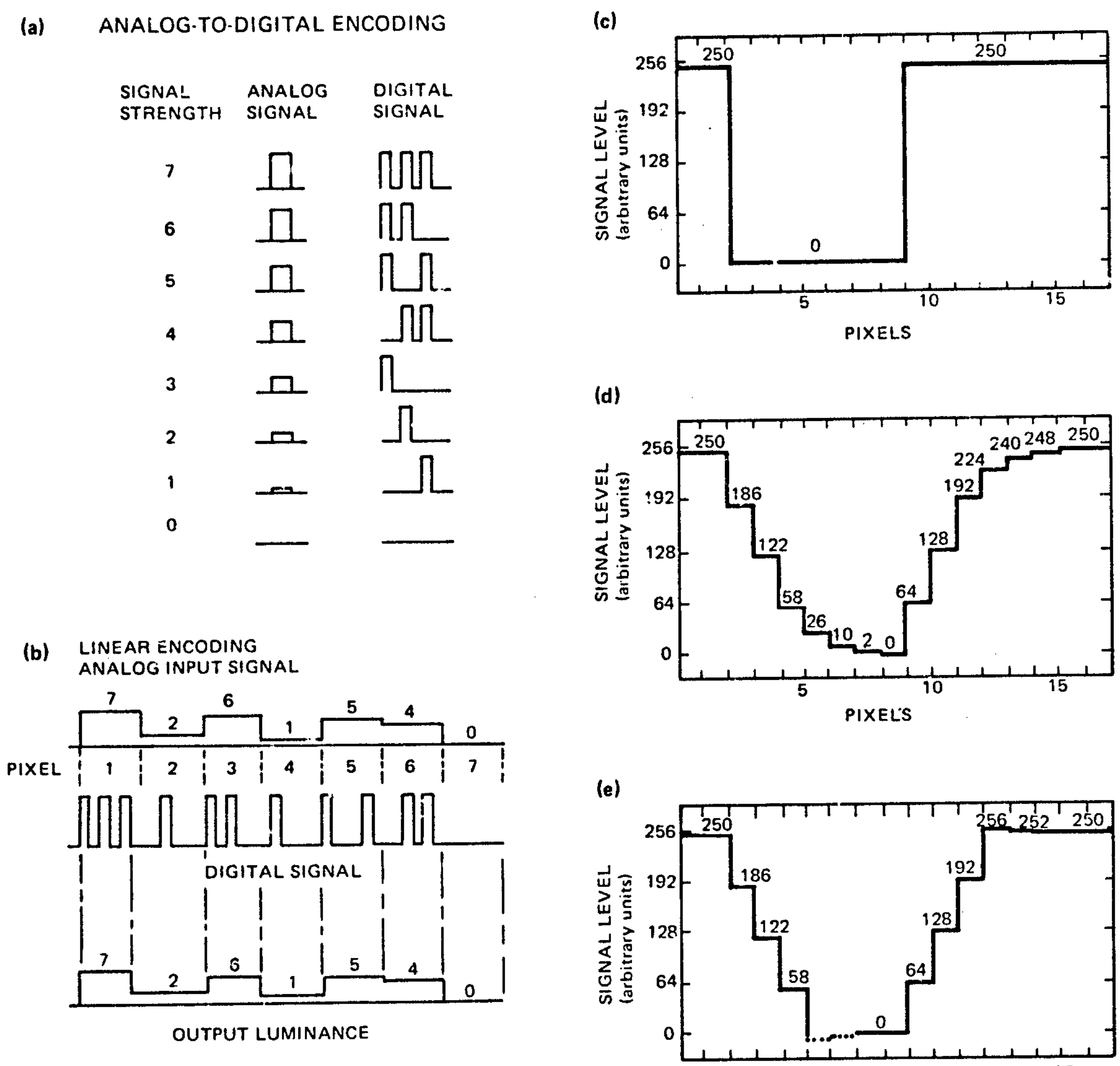


Figure 4.4–13. Relationships Among Bandwidth, Resolution, and Modulation Transfer in Digital Systems. (Continued)

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

Figure 4.4-13. Relationships Among Bandwidth, Resolution, and Modulation Transfer in Digital Systems. In *digital* systems, the signal strength is quantized and converted into a binary signal, usually in the form of a string of discrete pulses. (See Figure 4.1-5 for a description of the quantizing process.) The present figure discusses the use of *pulse code modulated* transmission systems for digital imagery. Two types are illustrated, *linear encoded PCM* and *differential encoded PCM*. These are commonly referred to as PCM and DPCM systems respectively. The treatment is intended to give the display designer an insight into the implications of such systems with regard to the imagery they generate. It is not intended as a treatment of the systems themselves.

The circuitry of the camera, or other device such as a computer, which generates the signal, codes the signal strength into a chain of pulses having the appropriate pattern. The circuit in the receiver or display device decodes the signal and converts it into an appropriate voltage for use by the CRT, optical line-scan image generator, or other display device. Part (a) of this figure illustrates a linear encoding scheme. In such a scheme the range of the analog signal strength to be used is divided into equal steps and each is assigned a coded strength value. Part (b) illustrates how a train of analog and digital signals relate to each other. It is important to note that the three-position digital pulse code must be repeated for each half of the cycle for analog signal, or, in terms of horizontal TV resolution, once for each TV resolution line.

With respect to the circuitry of the system and for bandwidth calculations, each pulse represents a cycle. For the 3-bit quantizing illustrated here, six cycles are required to carry the digitized signal level code for each cycle of the analog signal. The bandwidth required, then, is a factor of 2x (quantizing level in bits) greater than the bandwidth needed for an analog system having equivalent resolution.

PCM systems offer advantages over analog systems, particularly in their ability to operate at much lower SNR's and, for a given circuit, at lower MTF's, making a greater portion of the circuit's frequency range available. These features, especially the first, make digital systems desirable for many applications in spite of the bandwidth penalty they impose. In addition, many techniques are available for reducing the bandwidth requirements. A detailed discussion of these techniques is beyond the scope of this book; however, one technique involves transmitting the change in signal level, not the level itself, and further, limiting the number of steps by which the signal can be changed between adjacent resolution elements or pixels (1/2 cycle of the analog signal). This technique is called differential pulse code modulation (DPCM).

Parts (d) and (e) of this figure illustrate two simple implementations of this technique. There are many others. For this illustration a 4-bit quantizing level has been chosen, and two of the many possible ways of using those levels to transmit changes of up to 256 levels of signal strength are illustrated. The four-bit signal will require 2x4 or 8 times the bandwidth of the analog signal, but only one-half the bandwidth of the 8-bit signal.

In DPCM systems, 1 bit is used to designate the direction of the change (up or down), so for a 4-bit system the other three are used to designate the amount of change. By letting 1's designate a pulse, and 0's no pulse, the four bits are used to encode the changes as follows:

Signal-level binary code	Number of steps
000	0
001	1
010	2
100	4
011	8
110	16
101	32
111	64

Part (c) of this figure shows a hypothetical analog signal whose strength changes from a level of 250 to zero in one step, and then from zero back to 250 in another.

Part (d) shows the steps taken to go from 250 to zero without generating any negative values. For the first three steps the signal is dropped the maximum amount the coding system will allow, 64 levels. At the end of the third drop, the value (58) is above that of the largest step, so the next largest (32) is chosen for the fourth step. After the fourth step the signal value is 26, so 16 is chosen as the fifth step. The signal strength remaining after the fifth step has a value of 10, so 8 is selected as the largest step which can be subtracted without creating a negative signal. The remaining signal now has a value of 2, and this is set to zero in the last step.

Step	Amount subtracted	Signal level
–	–	250
1	64	186
2	64	122
3	64	58
4	32	26
5	16	10
6	8	2
7	2	0

The signal is returned to 250 in a similar fashion. In part (e) the signal is allowed to assume negative values, so on the fourth step 64 is subtracted, which causes the signal to overshoot the zero level and results in a signal strength of -6. On the next step 4 is added to this value, and on the succeeding step 2 is added, returning the signal level to 0. Since in a CRT display, signal strengths below that which cuts off the electron beam are displayed as having zero strength, the display will be correct after just four steps, rather than the seven needed in the previous example. However, as suggested by the diagram, the overshoot will be displayed when the signal is being returned to the 250 level.

These examples are used to illustrate the nature of the errors that occur in the visual representation of DPCM coded signals. Many other schemes exist for coding the changes. A full discussion of this topic is outside the scope of this book. The interested reader should consult Ref. 17 for additional sources of information.

No studies could be found which systematically related interpreter performance to a range of DPCM schemes.

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

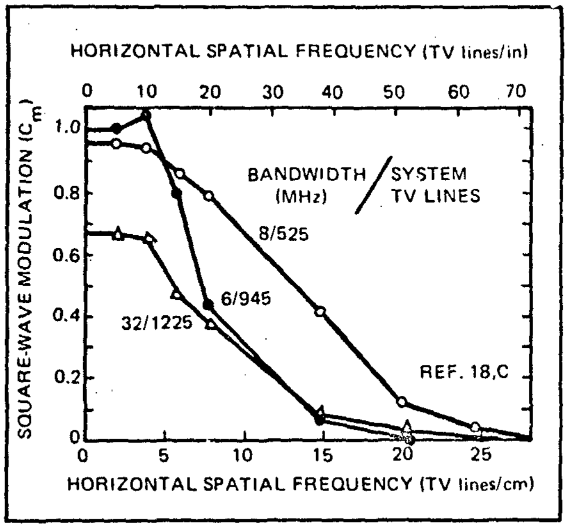


Figure 4.4-14. Effect of Display System Bandwidth on Image Modulation Response. This figure is included to illustrate the fact that increasing the bandwidth of a CRT display system does not necessarily improve its resolution (Ref. 18,C). The modulation transfer factors for horizontal square-wave targets were measured for three bandwidth/TV line conditions: 8 Hz and 525 TV lines, 16 MHz and 945 lines, and 32 MHz and 1,225 lines. Approximating horizontal resolution with the formula:

$$\text{Horizontal resolution} = \frac{1.245\ (\text{bandwidth})}{(\text{frame rate})(\text{TV lines})}$$

(See Figure 4.4-12)

The ratios of the horizontal resolution for the 8, 16, and 32 MHz systems were approximated using this formula and found to be:

Bandwidth (MHz)	TV lines	Relative Horizontal Resolution: Approximated	Relative Horizontal Resolution: Measured (at MTF ~ 0)
8	525	1.00	1.00
16	945	1.11	0.86
32	1,225	1.72	0.71

The calculations are only approximations, but they are accurate enough to shov that for the system studied there was a failure to achieve the horizontal resolution increase which would be predicted using bandwidth calculations. In addition the higher bandwidth configurations should have improved the modulation transfer factors for the lower frequencies. The author reported that no unambiguous reason was found for these results.

The designer of CRT display systems must recognize that to obtain the benefits of increased bandwidth, great care must be taken to ensure that all elements of the system will operate effectively at the planned frequencies.

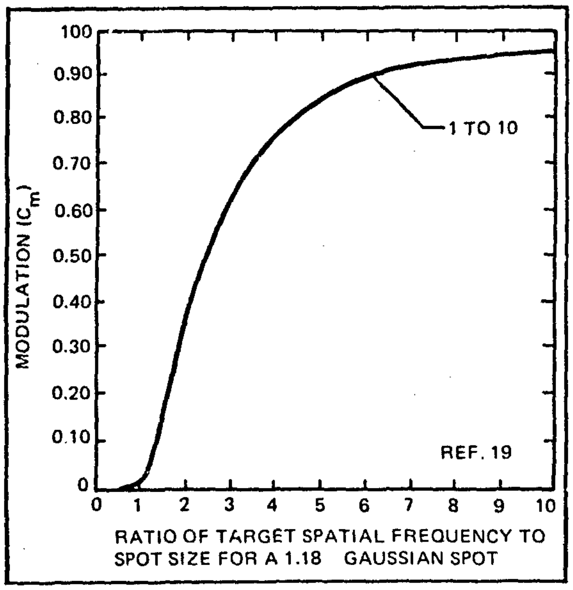
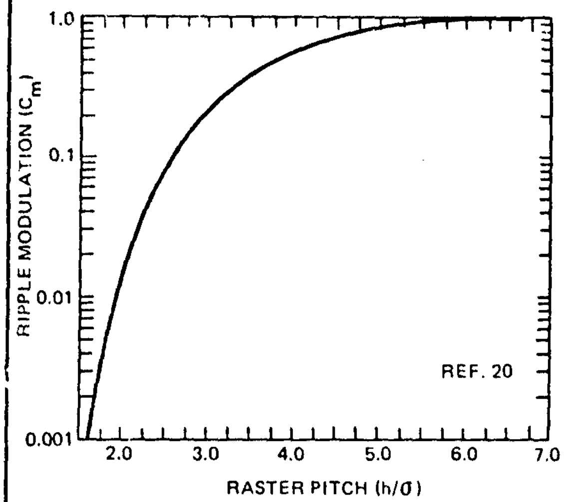


Figure 4.4-15. Effect of Spot Size on Horizontal Modulation Transfer in Line Scan Systems. The accompanying graph shows the effect of the size of a scanning spot having a Gaussian point spread function on the horizontal modulation transfer characteristics of a CRT (Ref. 19). The data are plotted as the ratio of the spatial frequency of the signal to the spot size. The spot size is taken to be 1.18σ which gives an overlap between scan lines at the 50-percent intensity level of the line spread function.

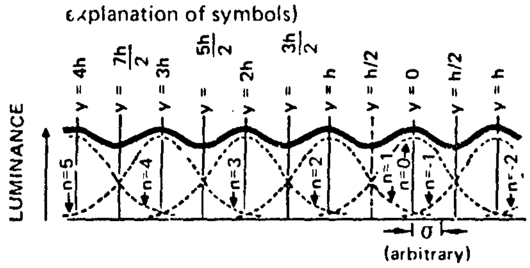
The curves represent the modulation transfer function for the spot and do not take into consideration the modulation losses in other parts of the system. If a high-frequency signal has a modulation transfer factor of 0.1 and has a spatial extent on the screen 1.3 times the diameter of the spot, the modulation on the screen will be the product of the modulation transfer factor of the signal and the modulation transfer factor of the spot. In this case, the value is 0.1 x 0.1, or 0.01. A modulation in the original scene of 1.0 would be reproduced at 0.01 for that spatial frequency. In actual practice, the modulation of the imagery will be reduced still further through the effects of internally scattered light in the faceplate (Figure 4.4-25) and by reflected ambient light (Figure 4.4-26).

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

(a) RIPPLE MODULATION FOR A GAUSSIAN POINT SPREAD FUNCTION



(b) RIPPLE MODULATION OF OVERLAPPED GAUSSIAN SCAN LINES (see text for explanation of symbols)



(c)

RASTER PITCH (h/σ)	MODULATION (C_m)
1.50	0.0003
1.55	0.0005
1.60	0.0009
1.65	0.001
1.70	0.002
1.75	0.003
1.80	0.004
1.85	0.006
1.90	0.008
1.95	0.011
2.00	0.014
2.25	0.040
2.50	0.085
2.75	0.147
3.00	0.223
3.25	0.223
3.25	0.308
3.50	0.397
3.75	0.488
4.00	0.574
4.25	0.654
4.50	0.725
4.75	0.787
5.00	0.838
5.25	0.880
5.50	0.913
5.75	0.938
6.00	0.957
6.25	0.970

Figure 4.4-16. Ripple Modulation and Contrast Function of Raster Pitch. Ripple modulation—the variations in luminance across a raster caused by overlapping scan lines—is described in Figure 4.4-1. For overlapping lines with Gaussian line spread functions, the ripple is nearly sinusoidal up to a raster pitch of approximately 4 (Ref. 20). Part (a) of this figure can be used to determine the ripple modulation for a flat field display condition. It also can be used to estimate the maximum modulation for a series of evenly spaced lines separated by chosen distances whether or not they are adjacent scan lines of a raster. The actual values of the ripple modulation will also depend upon scattered light within the faceplate of the tube (Figure 4.4-25), the amount of ambient illumination falling on the face of the tube (Figure 4.4-26), and any filters used to reduce the effect of the ambient light (Figure 4.4-27).

Luminance values, without consideration for scattered or ambient light, can be calculated for any spot on a raster or periodic series of scan lines of equal intensity by using the formula (Ref. 20):

$$B = \sum_{n=-\infty}^{n=\infty} e^{-(nh-y)^2/2\sigma^2}$$

where

- B = luminance at a point at distance y from the center of a reference scan line in the raster
- n = number of scan lines from the reference line
- h = center-to-center spacing of the scan lines
- σ = standard deviation of the line spread function

(Continued)

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

Figure 4.4-16. (continued)

The summation is shown in the formula for values of n between ± infinity. While theoretically correct because of the nature of the Gaussian spread function (see Figure 4.1-9), in practice summing over n = ±10 will introduce no significant errors. For pitches of 2.67 or less, summing over only ±3 scan lines is usually sufficient.

By calculating values for L (y) at y = 0 and y = h/2, the maximum and minimum luminances of the raster can be obtained. Adding these values to the formula for modulation (C_m), we have:

$$C_m = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

where

L_{max} = maximum luminance and
L_{min} = minimum luminance

(See Figure 3.1-10.)

The results of these calculations are shown in the table in part (c).

As Figures 4.4-25 and 4.4-26 suggest, in practice these values may be high depending upon the amount of internally scattered and ambient light present.

For an illustration of the luminous intensity profiles of widely spaced lines, see Figure 4.3-20.

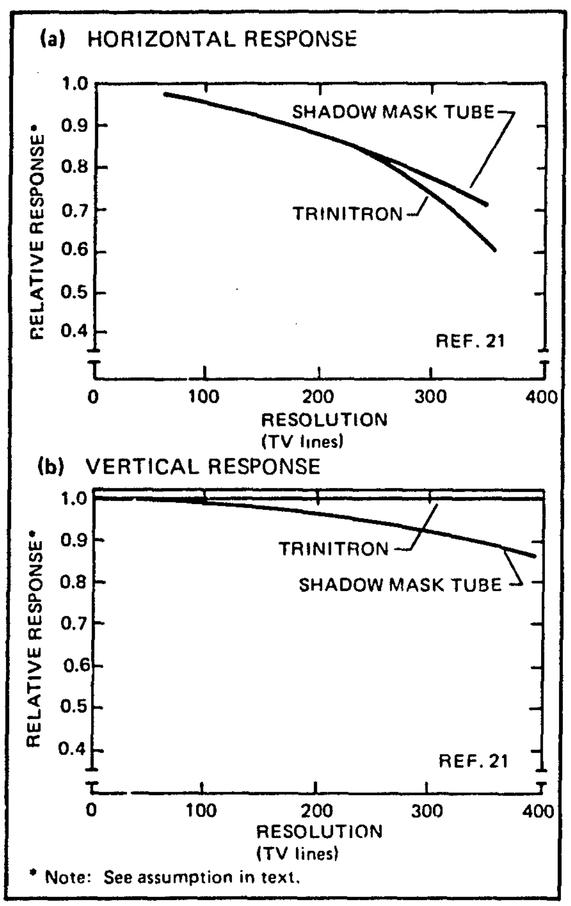
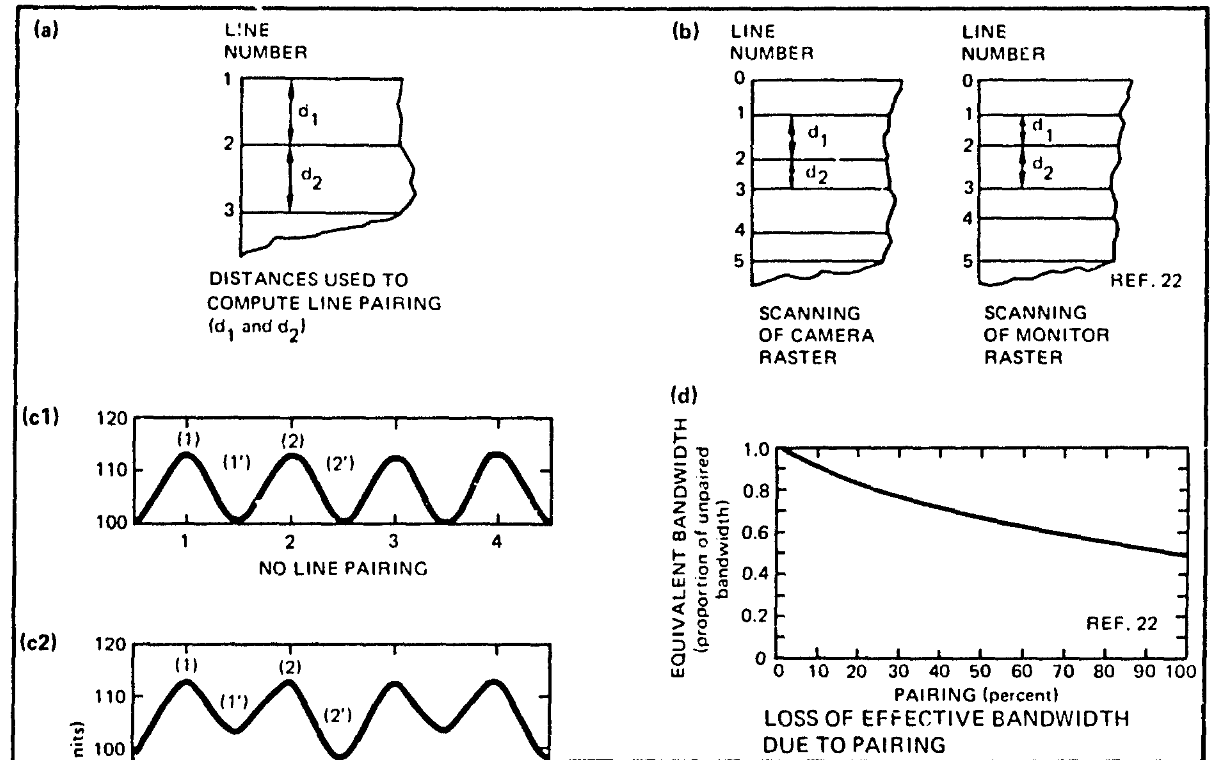


Figure 4.4-17. Relative Horizontal and Vertical Response of Shadow Mask and Trinitron Color Tubes. These two curves (Ref. 21) show the relative horizontal and vertical responses of the shadow mask and trinitron color CRT's.

Although not stated by the authors, it is assumed that these curves represent the relative responses of tubes with aperture grills and discontinuous phosphors (matrix or stripes) compared to those in tubes lacking aperture grills and having continuous phosphor coatings. Because of the difference in the geometry of the two aperture masks and phosphor patterns described in Figure 4.4-8, the tubes display different response characteristics. The shadow mask tube having horizontally staggered phosphor dots as opposed to the discrete grill of the trinitron, shows somewhat better horizontal response. On the other hand, the trinitron, having a continuous aperture in the vertical direction, shows (as would be expected) no loss in comparison to tubes with continuous phosphor coatings that do not have aperture grills.

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)



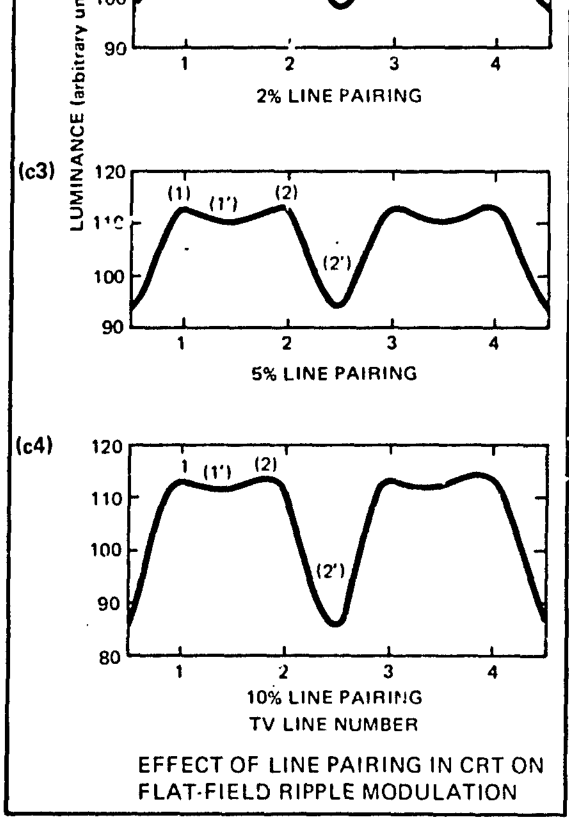


Figure 4.4-18. Effects of Line Pairing on Vertical Resolution and Modulation Transfer. Line pairing occurs to some extent in practically all interlaced line scan systems. It occurs when the lines of the two interlaced fields do not fall exactly between one another. It is expressed in percent and calculated by the formula: (Ref. 22):

$$\text{Percent pairing} = \frac{|d_1 - d_2|}{d_1 + d_2} \times 100$$

where d_1 = distance from line 1 to line 2, and
d_2 = distance from line 2 to line 3 (see part (a) of this figure)

Four types of line pairing can occur:

- In the camera only
- In the monitor or CRT only
- In both camera and monitor in equal amounts
- In both camera and monitor by differing amounts

An example of this last case is shown in part (b) of this figure.

Part (c) of this figure shows the effect of line pairing on the flat-field ripple modulation of the monitor. The example is for a raster with a pitch of 2.36 (line overlap at the 50-percent intensity level). For the four conditions the modulations between points (1) and (1') and between points (2) and (2') are as follows:

(Continued)

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

Figure	Line Pairing (percent)	Modulation (C_m) Points (1)–(1')	Points (2)–(2')
c_1	0	0.059	0.059
c_2	2	0.044	0.069
c_3	5	0.026	0.093
c_4	10	0.004	0.136

These figures do not take into account any modulation loss due to illumination of the screen by ambient light or internal reflections in the faceplate. They represent the maximum that would be expected. Values for other raster pitches and percentage of line pairing can be calculated from summed intensity values using the formula from Figure 4.4-16:

$$L(y) = \sum_{n=-\infty}^{n=\infty} e^{-(nh-y)^2/2\sigma^2}$$

This formula is also presented in Figure 4.1-9. For pitches of 2.67 or less, summing over only ± 3 scan lines will not introduce a significant error into the calculations.

Line pairing reduces modulation transfer in two ways. First, the uneven spacing of the lines creates uneven sampling of the scene by the camera. This limits the maximum spatial frequency that can be resolved in the scene. Second, when the pairing in the image generator (camera or other device) and the monitor are different, the detail response is lowered for all line numbers, but more for the higher ones than the lower. The presentation is equivalent to two misregistered images. This condition also occurs when either image generator or monitor exhibits pairing. The loss of resolution can be equated to a loss of bandwidth. Part (d) of this figure shows the effective bandwidth loss as a function of the amount of pairing (Ref. 22).

Pairing in the monitor is easier to detect visually than pairing in the image generator. This is because when pairing occurs in the monitor, banding becomes apparent in the imagery. However, where pairing occurs only in the image generator, the monitor still presents an image that appears normal to casual inspection.

Figure 4.4-19. Number of Visually Detectable Contrast Steps. In designing displays for digital imagery, it is useful to have an estimate of the number of contrast steps the visual system is capable of detecting. If the display is designed to deliver too few, image content will be unnecessarily lost; if the display delivers too many, it may be unnecessarily expensive and complex. Unfortunately, at this time it is only possible to estimate visual performance with regard to the viewing conditions and task requirements. The graph accompanying this figure gives the number of contrast (C_d) steps which can be displayed for several contrast increments. They were calculated from the formula

$$N = \frac{\log\left(\frac{L_{max}}{L_{min}}\right)}{\log(1 + C_d)}$$

where

N = the number of steps,
L_{max} = maximum display luminance,
L_{min} = minimum display luminance, and
C_d = the contrast increment determined by the formula:

$$C_d = \frac{L_{max} - L_{min}}{L_{min}}$$

(See Figure 3.1-10 for a description of the relationships between the various measures of contrast.) The number of quantizing levels represented by the contrasts steps is shown on the lower scale.

Caution must be exercised in interpreting the data shown because no account has been taken of the contrast losses which occur from internally reflected light (see Figure 4.4-25) or from the reflection of ambient illumination (Figure 4.4-26).

The fact that the display may be capable of delivering the number of contrast steps or quantized levels does not imply that they can be detected visually. The contrast required for visual detection depends upon the luminance of the display, the size (in visual angle) of the target to be detected, its edge gradients, whether or not it is cyclical in nature, and the background in which it is imbedded (see Section 3.1). In addition, the nature of the visual task will influence the contrast needed for its performance (see Section 3.10). The detection of the presence or absence of an object requires considerably less contrast than its identification as a specific type of target.

These factors make the establishment of requirements for contrast in displays or quantizing levels very difficult and preclude the selection of a single value for all applications. Furthermore, while the display and visual system may limit the range of quantized levels visible at any one time, this does not mean that the signal from the sensor should be so limited. With electronic displays, and optical line scan printers, the signal can be manipulated and various portions presented at a time, thus preserving information which might otherwise be lost.

The notations at the top of the figure give visual performance data from studies previously reported in other sections. They are provided to give the reader an idea of the wide range of visual contrast detection thresholds and their dependence upon viewing conditions and type of task.

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

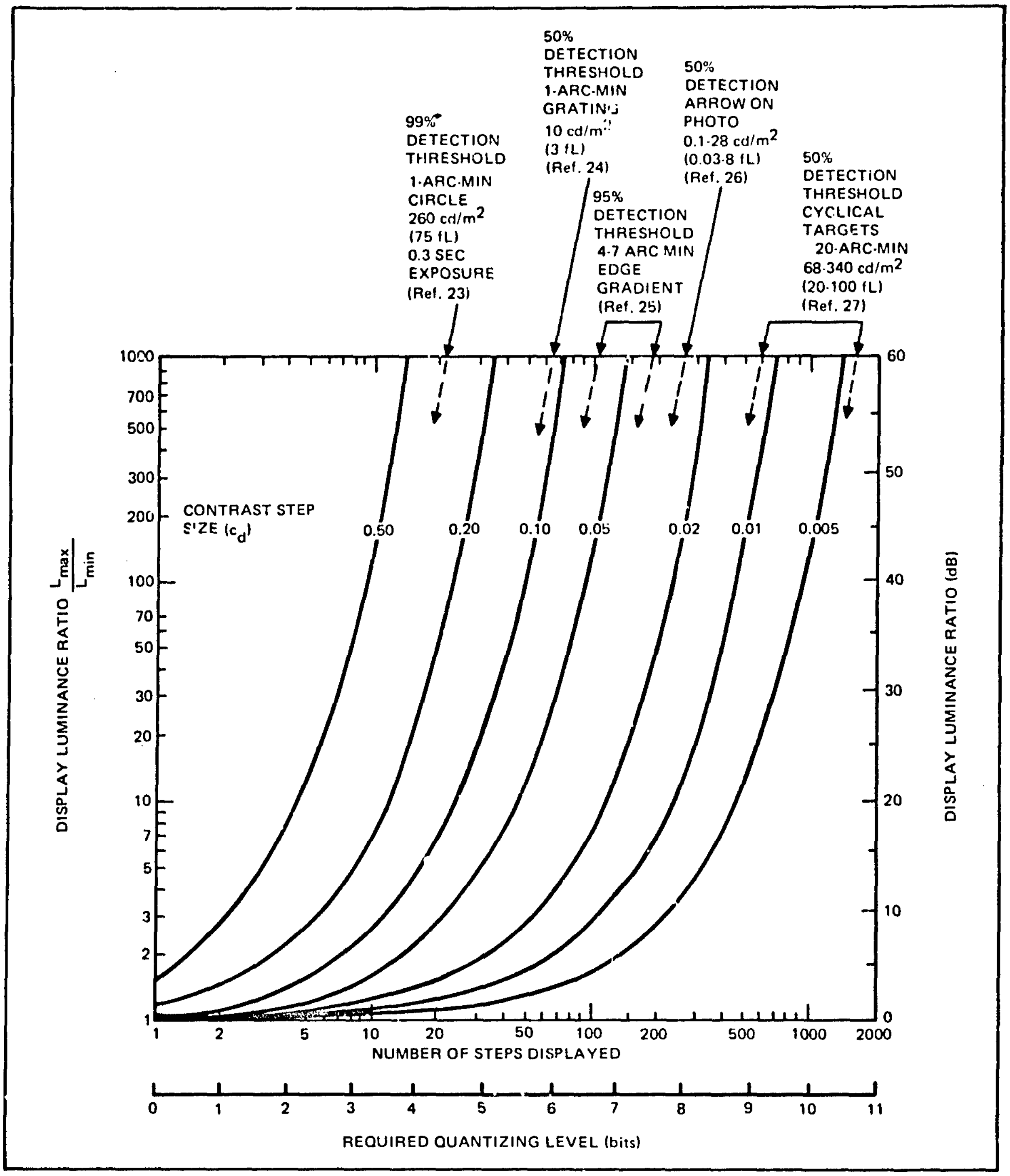
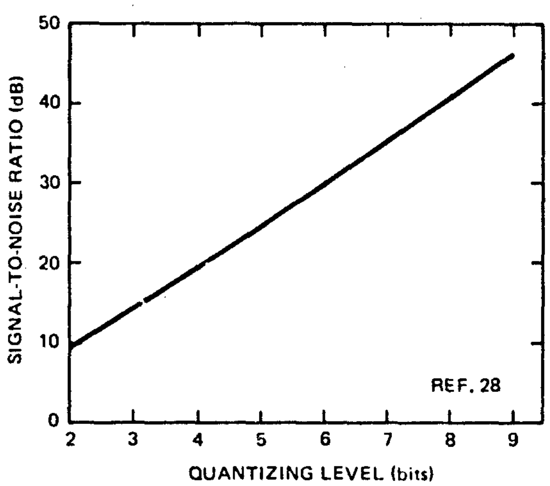


Figure 4.4-19. (text on preceding page) Number of Visually Detectable Contrast Steps

-76)

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)



SIGNAL-TO-NOISE RATIO IDEAL, UNIFORM QUANTIZER, GAUSSIAN INPUT

Figure 4.4-20. Quantizing Errors Expressed as Signal-to-Noise Ratios. *Quantizing errors* are the errors in signal strength introduced when a continuously varying analog signal is converted into a fixed number of discrete steps in the quantizing process (see Figure 4.1-5). The distribution of these errors is such that they may be expressed in terms of a signal-to-noise ratio, defined in the same way as has been used in previous discussions:

$$SNR_{(db)} = 20 \log \frac{\text{rms signal}}{\text{rms noise}}$$

This figure shows the dependence of the quantizing SNR on the number of quantizing levels for a quantizer using Gaussian signal strength steps. The figure is included here as an example of the type of relationship which exists between quantizing levels and signal-to-noise ratios (Ref. 28). Other quantizing schemes will have similar relationships but different absolute values of SNR as a function of quantizing level. To determine the resulting SNR in decibels when a quantized signal is displayed on a CRT system with a known SNR, both ratios are converted to power and added. The result is then reconverted to decibels. For instance, if a display system has an SNR of 35 dB and a 6-bit quantized signal with an SNR of 30 dB displayed on it (see the graph), the new SNR is:

$$SNR_{tot} = 10 \log \frac{10^{\frac{SNR_1 + SNR_2}{10}}}{10^{\frac{SNR_1}{10}} + 10^{\frac{SNR_2}{10}}}$$

$$= 10 \log \frac{10^{3.5 + 3.0}}{10^{3.5} + 10^{3.0}}$$

$$= 10 \log 760$$

$$= 28.8 \text{ dB}$$

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

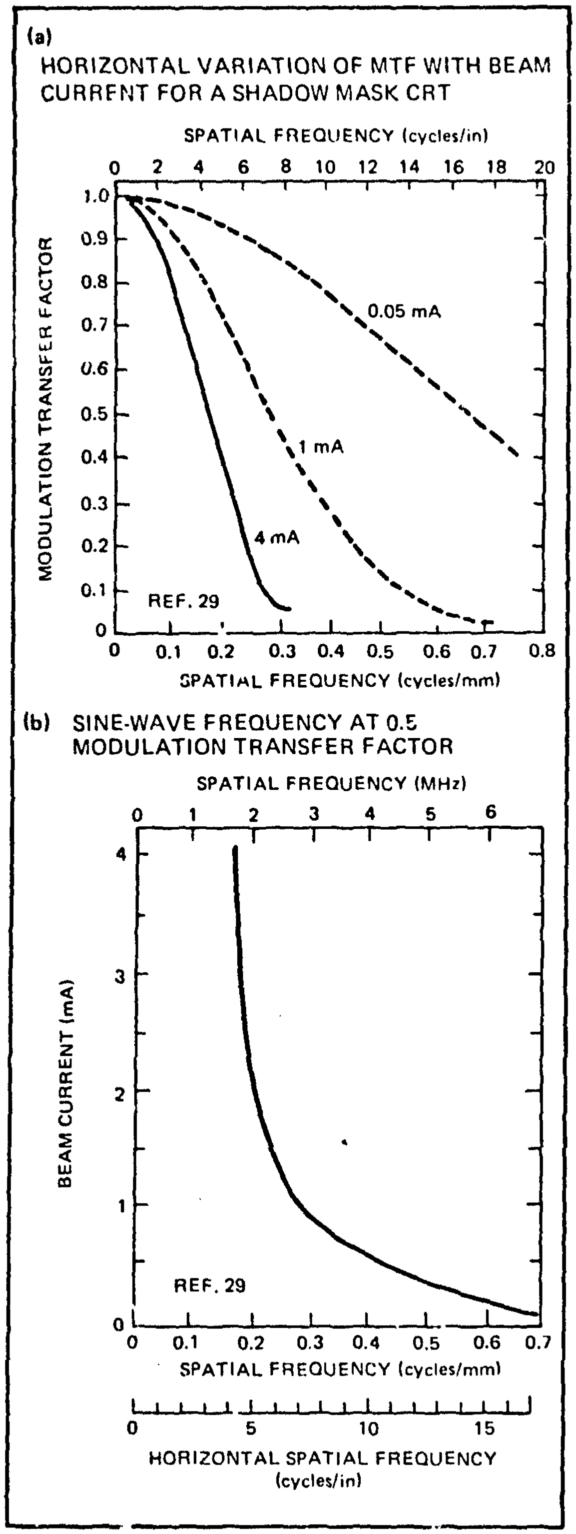


Figure 4.4-21. Effect of Beam Current on Horizontal Modulation Transfer Function for a Shadow Mask Color CRT. It was shown in Figures 4.4-2(b) and 4.4-9(c) that spot size increases as beam current increases. The effect of this size change on the horizontal MTF for a shadow mask CRT is shown in these graphs. In part (a) of the figure, the MTF's of three levels of beam current are shown. In part (b), the locus of the points representing sine-wave modulation transfer factor of 0.5 is plotted as a function of beam current and target spatial frequency. (Ref. 29).

Since the variations in luminance comprising an image on the face of a CRT are produced by variations in the beam current, it is apparent that the modulation transfer characteristics of a CRT vary as a function of scene luminance.

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

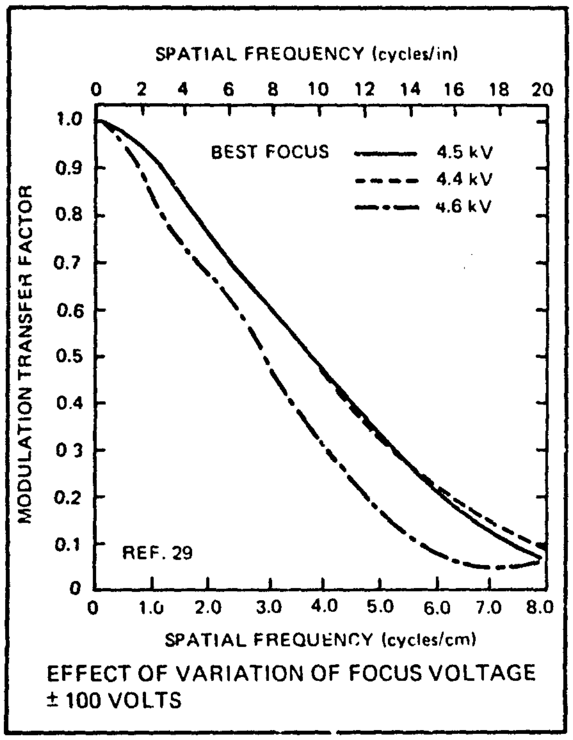


Figure 4.4-22. Effect of Focus Voltage on the Modulation Transfer Function of a Shadow Mask CRT. The voltage applied to the *focusing coils* in CRT's affects the modulation transfer function of the signal displayed on the screen as shown in this graph. The "best focus" condition was subjectively determined by viewing the CRT on which a test pattern was displayed. The horizontal MTF was measured for this voltage and for ±100 volts from that figure. There was very little difference for the decreased voltage, but considerable difference for the increased voltage. The author reports that the higher voltage resulted in a "significantly degraded image" and that "the MTF results are in agreement with the subjective viewing results" (Ref. 29). The method of obtaining the subjective viewing results was not reported.

These data have important implications for the calibration of CRT's to be used in critical viewing situations. The voltage producing the best image should be determined and the display circuitry adjusted to provide it. Furthermore, it should be checked at intervals consistent with the stability of the circuit.

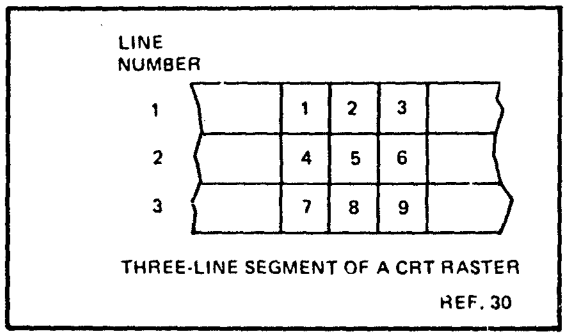


Figure 4.4-23. Vertical and Horizontal Aperture Equalization. The loss in signal modulation that occurs for high-frequency signals can be compensated for by *horizontal aperture equalization*. The loss in imagery modulation caused by the line *spread* overlapping of scanning lines can be compensated for by *vertical aperture equalization*.

In horizontal aperture equalization, the high-frequency components of the signal are amplified to increase their modulation. Unfortunately, this amplification must take place after noise has been introduced into the circuit; the frequency components of the noise that correspond to those of the signal being amplified are also amplified. The result is an overall decrease in the signal-to-noise ratio of the system.

Horizontal aperture equalization circuits are routinely installed in high-quality commercial TV systems.

Vertical aperture correction can be explained with the aid of the diagram in this figure. The numbers 1 through 9 represent areas along three adjacent scan lines, as shown. Using area 5 for illustration, during the time that areas 2 and 8 were being written, the spread function of the beam caused signals from these areas to be written in area 5 also, but at a much lower intensity. By electronically delaying the signals from areas 2, 5, and 8 so that they are all present simultaneously, the appropriate proportions of 2 and 8 can be subtracted from 5, and then 5 can be written with the spread function compensated for (Ref. 31). The result is a much sharper appearing picture. The electronics associated with the delay circuits is complicated, and vertical aperture equalization is not incorporated in TV monitors as standard practice.

The compensation contains some errors because the line spread is not uniform across adjacent lines, being greatest at the point of overlap and decreasing following a Gaussian distribution as it crosses the adjacent line. Since the subtraction process applies to the entire width of the line being corrected, errors are introduced. The effect these errors would have on the extraction of information from the imagery is unknown.

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

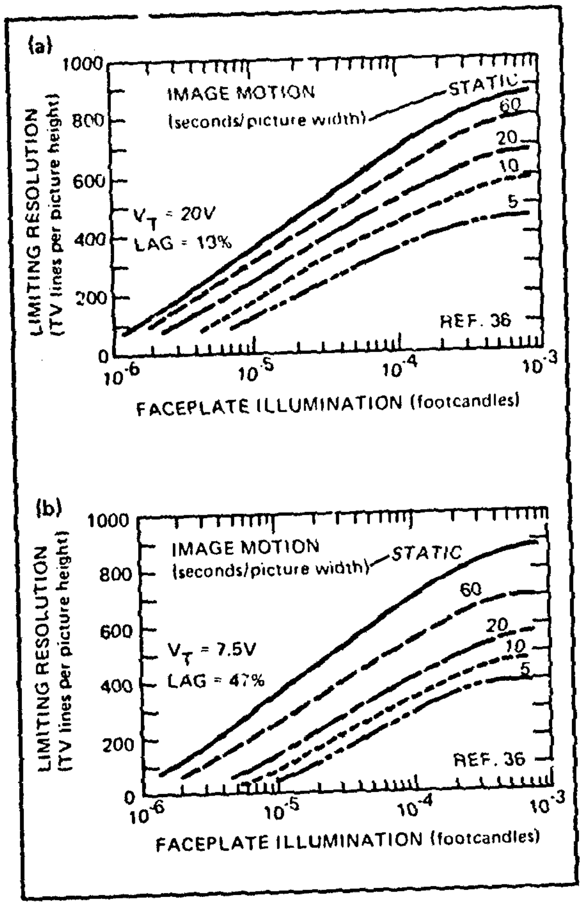


Figure 4.4-24. Limiting Resolution in TV Camera Tubes as a Function of Image Motion. Two principal factors degrade the resolution of TV cameras for moving images. One, called *signal mixing*, is analogous to the blur caused when the shutter speed of a conventional camera is too slow to "stop" the motion of a moving object. In the case of the TV camera, the image formed on the photosensor is scanned once every frame for conventional systems (1/30 second in the NTSC system). If the image of the scene moves during this time, the light from several spots in the scene will pass over a single spot on the photosensor and will become "mixed," or added, together; the result will be a blurred image.

A second major source of resolution loss is called "lag." The term "*lag*" is used to designate the residual image left on the photosensor or other element after the passage of the electron beam. It is measured after the removal of illumination from the photosensor as the *third field decay lag*; i.e., the residual signal strength remaining on the third scan after the removal of the illumination divided by the signal strength obtained during illumination. It may also be reported as the proportion of the signal left as a function of time. (See Ref. 31 for information on the lag characteristics of specific types of tubes.)

The results shown here (Ref. 32) are for electron bombarded silicon devices (EBS's), a camera tube of medium resolution (Ref. 9) primarily used for low light level work. While each type of tube will exhibit its own absolute values for resolution loss for moving images, these curves indicate the qualitative effects for all. The scene (a high-contrast square-wave target) was moved at four speeds—60, 20, 10, and 5 seconds per picture width. In camera-tube terminology, "target" refers to the surface scanned by the electron beam. In EBS's the performance of the tube varies with the voltage on the target. For the results reported, two target voltages were employed, 7.5 and 20 volts, and two lag values were used, 19 percent and 47 percent.

The method of displaying the information and performing the observations was not reported.

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

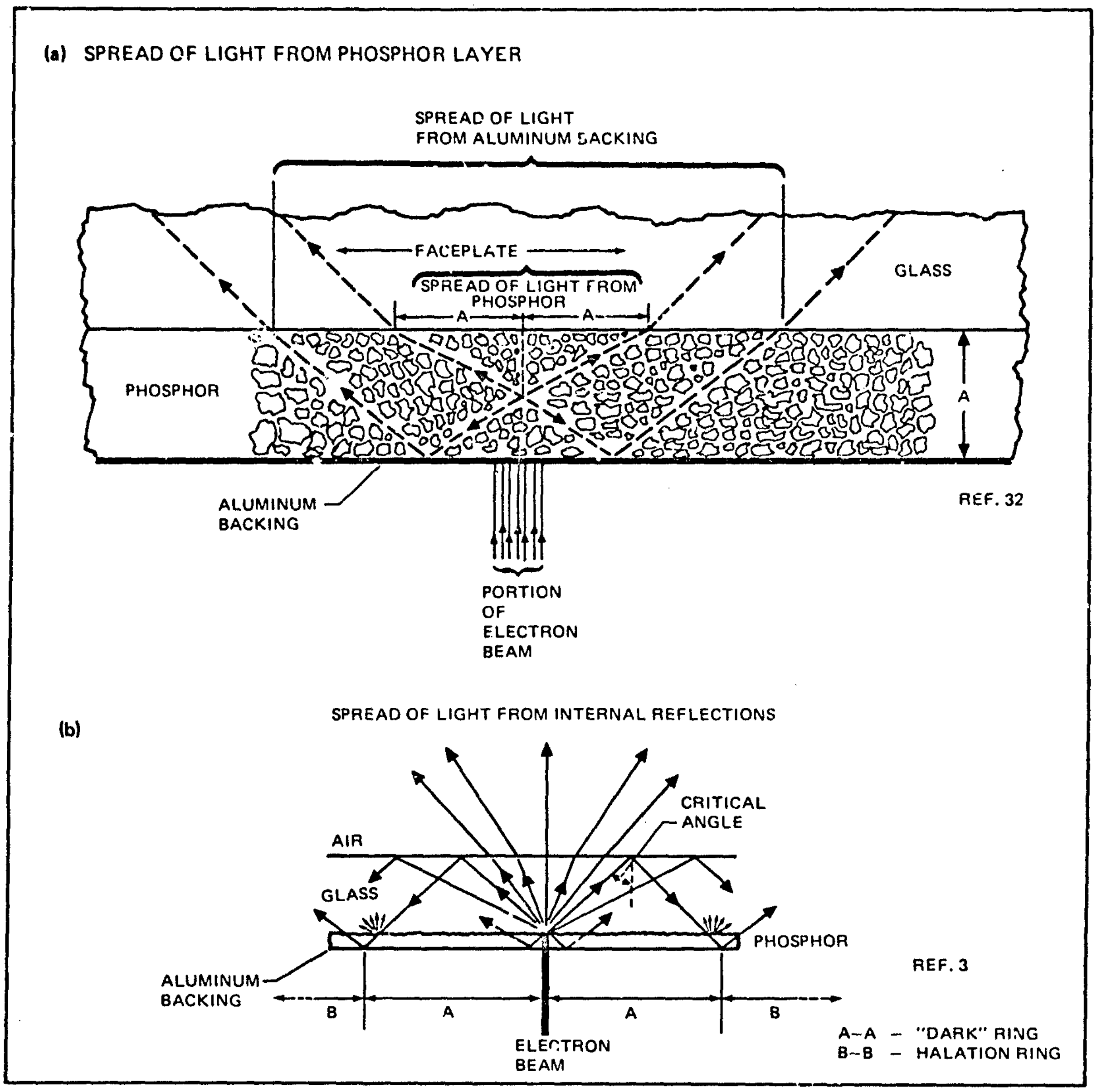
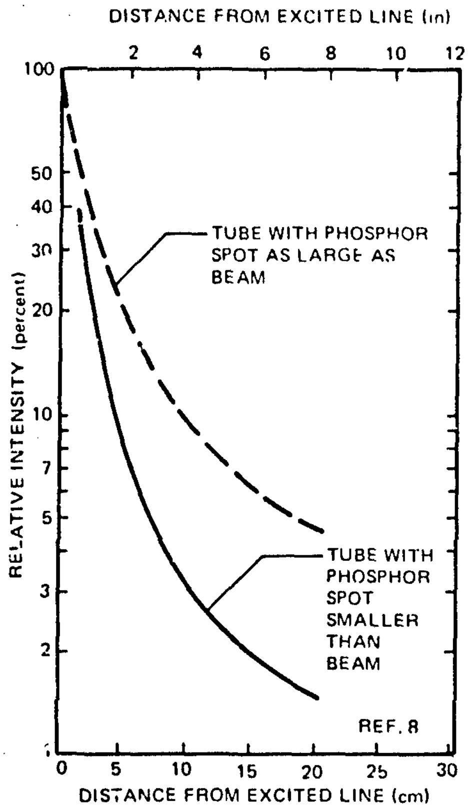


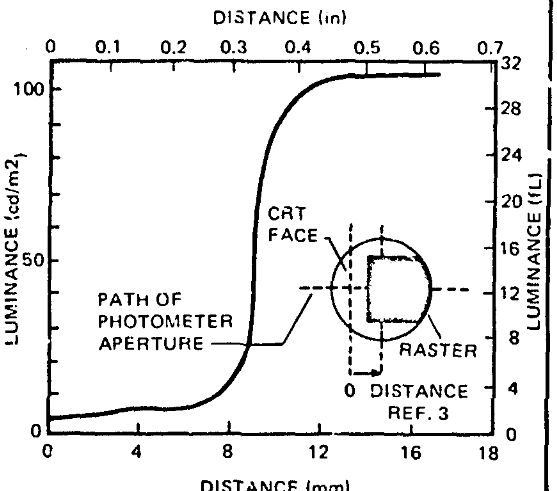
Figure 4.4-25. Scattering and Internal Reflection of Light in Cathode Ray Tubes. The contrast of images generated on CRT's can be seriously degraded by reflection within the faceplate. A small contribution is made by light scattered within the phosphor and reflected from its aluminum backing. Part (a) of this figure shows the geometry of the scattering that takes place within the phosphor and from the aluminum backing (Ref. 33). As noted by dimension A in the figure, the scattering within the phosphor is approximately equal to the phosphor thickness (Ref. 34). Since this thickness is typically only a few micrometers compared to spot sizes of several hundred micrometers, the image degradation from this source is negligible. While the light scattered from the aluminum backing covers a wider area, it is still small compared to the spot size. **(Continued)**

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

(d) SPREAD OF LIGHT IN SHADOW MASK COLOR CRT'S



(d) SPREAD OF LIGHT IN A BLACK AND WHITE CRT



GLASS THICKNESS: 11.4 mm (approx)
PHOTOMETER APERTURE
DIAMETER: 0.31 mm (approx)
SPOT DIAMETER: 0.51 mm (approx)

The geometry of the internally reflected light is shown in part (b) of this figure. The phosphor closely resembles a *Lambertian radiator* (Ref. 35); that is, the intensity of the light it emits is a junction of the cosine of the angle a given ray makes with a line perpendicular to the surface of the phosphor. This means that substantial amounts of light are emitted in directions which intercept the surface of the faceplate at angles greater than the *critical angle*. The critical angle is the angle at which light is totally reflected when going from a medium of one index of refraction to another medium with a different index of refraction; e.g., from glass to air The angle at which the total refraction occurs going from glass to air is.

$\theta_c = \sin^{-1}\left(\frac{1}{N}\right)$ where

θ_c = the critical angle and

N = refractive index of the glass

(Ref. 36)

The light that is refracted returns and illuminates the phosphor at some distance from the place it was emitted.

Parts (c) and (d) of this figure give measurements of the luminance caused by internal light being reflected from the phosphor. Part (c) gives measurements on two configurations of shadow mask CRT's (Ref. 8). The one exhibiting the lower reflected luminance has a configuration like that shown in Figure 4.4-8.

Part (d) of this figure shows measurements taken on a black and white CRT. In both cases, considerable luminance is created at some distance from the excited phosphor. This luminance decreases the contrast of the imagery it coincides with. For a low-luminance, low-contrast area close to a bright portion of the image, the effect can be great enough to reduce the contrast below the threshold of vision. The author of Ref. 3 states that for a dark area 14 mm (0.55 in) away from excited areas on either side "... the brightness enhancement by internally reflected light is about 4 fL for 27 fL of direct intensity, which is approximately 15 percent."

Interpretation of the data in part (d) is somewhat arbitrary because the location of the edge of the raster with regard to the distances shown on the ordinate is not clear. However, the curve does serve to illustrate the nature of the spread in luminance caused by internally scattered light.

This phenomenon is sometimes referred to as *halation*, and in some instances may result in the appearance of a bright ring around a brightly illuminated spot situated in a darker surround.

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

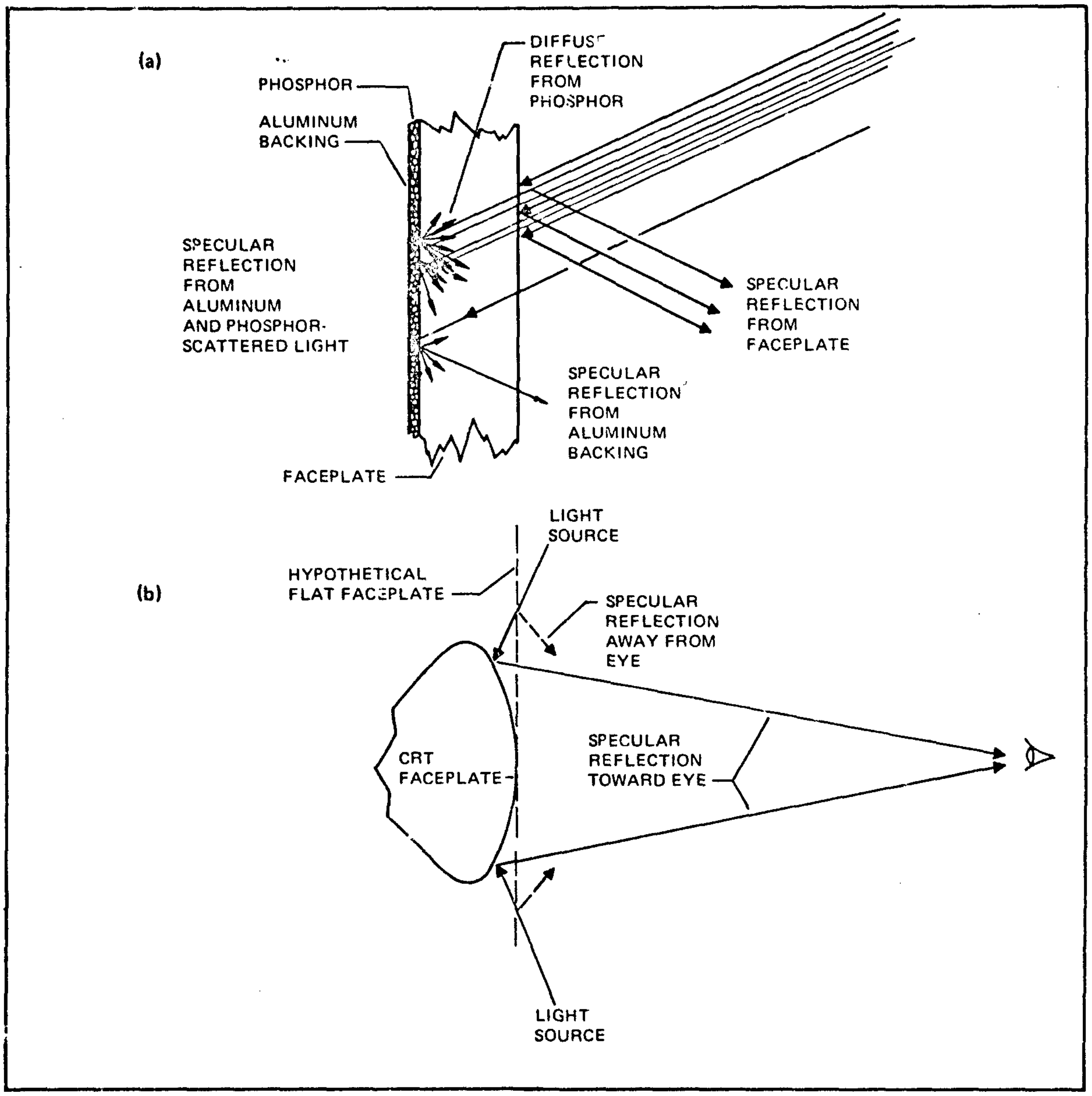


Figure 4.4-26. Effect of Reflected Ambient Light on CRT Contrast Ratio and Modulation

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

Figure 4.4-26. Effect of Reflected Ambient Light on CRT Contrast Ratio and Modulation. Ambient light acts two ways to reduce the contrast of CRT imagery: First through *specular reflection* from the faceplate and the aluminum backing of the phosphor and second through diffuse reflectance from the surface of the phosphor. The specular reflection from the aluminum backing is subject to scattering as it passes out through the phosphor. These sources are illustrated in part (a) of this figure. Part (b) illustrates the effect of the slight curvature of the face-plate on the locations from which light sources can be reflected into the eye. As is shown, light sources at high angles from the line of sight that would be reflected away from the eye by a flat faceplate are reflected into the eye by the curved one.

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

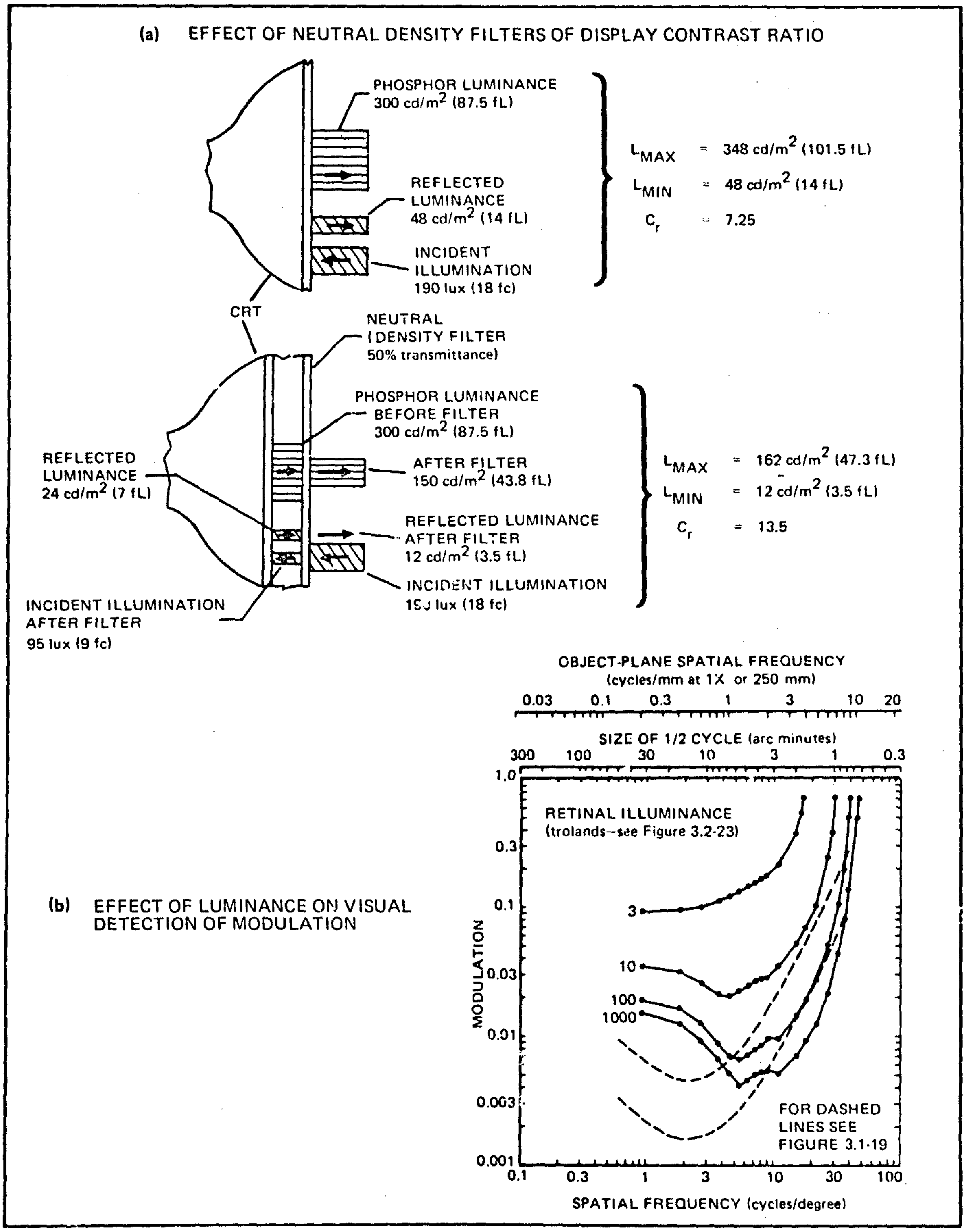


Figure 4.4-27. Methods of Reducing Modulation Losses in CRT's Due to Ambient Illumination (Continued)

4.4.2 RESOLUTION AND MODULATION TRANSFER IN CATHODE RAY TUBES (CONTINUED)

Figure 4.4-27. Methods of Reducing Modulation Losses in CRT's Due to Ambient Illumination. The most effective way to eliminate the modulation losses caused by reflected ambient illumination is to prevent it from reaching the face of the CRT. Proper lighting control in the interpretation area is essential (see Section 7.3.3). Where ambient illumination on the face of the display cannot be eliminated, antireflective coatings to reduce specular reflection from the glass surfaces of the faceplate and filters to reduce the effects of diffuse reflection from the phosphor surface should be used. Part (a) of this figure shows the way in which *neutral density* filters act. Neutral density filters pass all visible wavelengths equally well.

The top illustration in part (a) of this figure shows the effect of ambient light on the contrast ratio of a CRT without a filter. The maximum luminance produced by the phosphor is taken to be 300 cd/m^2 (88 fL). Ambient illumination is taken to be 190 lux (18 fc), and the *reflectivity* of the phosphor assumed to be 80 percent. The luminance on the phosphor produced by the ambient illumination is calculated by the formula:

$$L_r = \frac{E_a R}{\pi} \quad \text{where}$$

L_r = The luminance produced by the reflected light in cd/m^2 (fL)
E_a = The ambient illumination in lux (fc)
R = The reflectivity of the screen

This formula assumes the phosphor screen is a perfect Lambertian reflector. In the illustration the reflected luminance is

$$L_r = \frac{190\,(.8)}{\pi}$$

$$= 48 \text{ cd/m}^2 \text{ (14 fL)}$$

This value is the minimum luminance from an unactivated area of the phosphor, assuming no internal scattering of the light in the face of the tube. Assuming that the ambient illumination is uniform across the face of the tube, this same value is added to the phosphor-generated luminance making the maximum luminance 348 cd/m^2. The contrast ratio (C_r) of the CRT for this condition is

$$C_r = \frac{L_{max}}{L_{min}} \quad \text{where}$$

L_{max} = The maximum luminance of the display

L_{min} = The minimum luminance of the display

therefore:

$$C_r = \frac{348}{48}$$

$$= 7.25$$

The lower illustration in part (b) shows the situation for a CRT with a faceplate filter having 50 percent *transmittance*, that is a filter which passes 50 percent of the light falling on it. Ambient illumination is reduced from 190 lux to 95 lux by passing through the filter. Following the first formula in this figure, the luminance created by the reflection of this illumination from the phosphor is 24 cd/m^2 (7 fL). This value is reduced 50 percent by its passage out through the filter, giving it a final value of 12 cd/m^2, (3.5 fL). As with the case illustrated in part (a) this value represents the minimum luminance of the display, if the spread of luminance within the faceplate is ignored. The 300 cd/m^2 (87.5 fL) maximum luminance of the phosphor is also reduced by 50 percent by its passage, out through the filter, resulting in an effective phosphor luminance of 150 cd/m^2 (43.8 fL) adding the reflected luminance (12 cd/m^2) to this figure gives a value of 162 cd/m^2 for the maximum luminance of the display. The contrast ratio, then is

$$C_r = \frac{162}{12} = 13.5$$

an increase of 86 percent over that for the CRT without the faceplate filter.

The drawback of this method is the reduction of the light from the phosphor. Part (b) of the figure shows the effect on the detection of a sine-wave grating that occurred when the luminance of a CRT was reduced by the use of filters (Ref. 38). (Other data on the topic of visual resolution and luminance appears in Section 3.2.6.)

Another type of filter that can be used is one which is matched to the wavelength of the light emitted by the phosphor. For phosphors with distinct colors such as the P31, which emits mostly green light, a filter can be selected which will pass most of the light emitted by the phosphor and block all other wavelengths in the ambient illumination. This greatly reduced the amount of ambient light reaching the phosphor.

Polarizing filters can also be used. The ambient light is polarized as it passes through the filter, but that portion which is specularly reflected from internal faceplate structures will have its direction of polarization changed and will then not pass back out through the filter.

Meshes and grids have been imbedded in faceplates to trap the ambient light, but while they are effective for their intended purpose they degrade the resolution of the display (Ref. 38). The same author found fiber optic faceplates less effective than meshes for controlling the effects of ambient illumination.

SECTION 4.4 REFERENCES

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SECTION 5.0
SPECIAL IMAGERY DISPLAY TOPICS

5.1 STEREO

5.2 COLOR

5.3 COMPARATORS

5.4 SEARCH

SECTION 5.0 SPECIAL IMAGERY DISPLAY TOPICS

General characteristics of optical and electro-optical imagery displays are covered in Sections 3.0 and 4.0 respectively. There are several specific imagery display topics that impact both these display techniques and are of sufficient importance to justify separate consideration. This section covers four such topics: stereo imagery, color imagery, comparators, and search.

5.1 STEREO

5.1.1 Definitions and Terms

5.1.2 Parametric Relationships

5.1.3 Depth Perception Ability

5.1.4 Special Stereo Viewing Situations

5.1 STEREO

RECOMMENDATIONS:

Provide a convenient means of positioning the two members of a stereo pair relative to each other in the display.

Unless the members of the stereo pair are certain to be on chips that can be positioned separately, or if attached to each other are certain to have the proper relative orientation for viewing in stereo, provide image rotation and translation capability within the display. In the case of a microstereoscope with rhomboid arms, this would mean that the objective lenses at the ends of the arms should be translatable relative to each other.

Refer to Section 3.7 for the requirements imposed on all binocular displays, and to Section 3.7.4 for the image alignment requirements for stereo displays.

In order to allow stereo pairs in which one member has a different scale than the other to be viewed in stereo, provide the capability of magnifying one more than the other.

Many cues contribute, or at least can contribute, information about the distance to a particular object (Ref. 1). *Monocular*, or single-eye, cues include perspective, movement parallax, relative size, overlap, shadows and highlights, atmospheric obscuration, and the accommodation of the eye when it focuses on the object. *Binocular* (two-eye) cues include *lateral disparity* and the convergence angle between the eyes when they are both fixated on the object. Some of these cues, such as eye accommodation and convergence, are very weak and may contribute more illusion than information. Others, such as lateral disparity (Sections 3.7.4.4, 3.7.5.4, and 5.1.1), are very strong cues and generally provide valid information, at least about relative distance.

The two images of a *stereoscopic*, or *stereo*, display, potentially provide the user with two advantages over the single image seen in a *monoscopic* display. First, because they have been collected from different directions, they contain information about the distances to different objects recorded as lateral disparity. This section is devoted primarily to the use of lateral disparity as a means of perceiving relative distance to objects recorded in stereo imagery. A second potential benefit from stereo is that by visually combining two images, the effect of grain noise and other random irregularities in the individual images can be partially canceled.

Whether the potential benefits from stereo imagery justify the additional cost of collecting, distributing, and displaying two pieces of imagery instead of only one is not the subject of this document. However, observation of interpreters indicates that if stereo coverage is available, it is almost always used whenever an important or confusing target is being studied in detail. Stereo is very seldom used when large amounts of imagery are being searched for new targets, usually because setup is too time consuming. Stereo is essential, of course, for tasks such as contour plotting, and it is important whenever the heights of objects must be measured.

Many articles on stereo vision illustrate and analyze the stereo image, or model, as if it actually exists in space in a location defined by the convergence and accommodation of the eyes (Ref. 2). As Figure 5.1-5 illustrates, the stereo image exists only within the mind of the observer. It has no true existence in space, as is illustrated by the fact that it persists even though the two members of the stereo pair have been separated to the point where the eyes are parallel, or even diverge slightly if the individual is capable of diverging his eyes (Ref. 3). Changes in eye convergence may, however, change the apparent height or size of objects in the stereo image (Ref. 4). As a result, there has been considerable analytical and experimental consideration of what viewing conditions yield the most valid visual impression of the height, the size, and the ratio of height to size for an object seen in a stereo image (Ref. 5).

Which aspects of stereo vision are the most important in a particular situation depends on the display user's task. If the task is stereo mensuration or contour mapping, the most critical factors are the minimum perceptible height difference (Section 5.1.2) and the possible existence of any constant error for particular classes of objects (Section 5.2.6). For a different task, viewing a stereo image in order to determine the shape or function of an object, the critical parameters are the minimum perceptible height difference and the existence of any illusions that might interfere with obtaining a valid impression of the object.

For a third task, estimation of terrain slope or estimation of the height-to-width ratio of some object in the stereo image, the goal is to obtain a valid height estimate. In this case, the estimate may be affected by the eye convergence angle in use. The best available test data show that, at least for some types of targets, when the eye convergence angle is approximately 11 degrees (0.2 radian) the best estimate of the true slope can be obtained (Ref. 5).

In order to view two images in stereo they must be rotated as described in Figure 5.1-5. This rotation can occur optically or by physically turning each of the two pieces of imagery. The latter approach drastically increases the distance the image can be translated while being viewed in stereo. If instead, the rotation is achieved optically, translation will cause the images to appear to move in different directions, destroying the stereo alignment. Optical rotation can also make stereo alignment more difficult to achieve (Section 3.10.7). Any display intended for extensive stereo viewing should allow the two pieces of imagery to be rotated, even if they are in roll form.

Although most image interpreters appear to make effective use of stereo imagery, there is limited evidence that some do not fully understand stereo. For example, experienced interpreters using a *microstereoscope* with a field slightly greater than 40 degrees expressed satisfaction with the stereo, even though further discussion revealed that because of poor registration of the images they were only able to fuse the central 20 degrees or so of the field (Ref. 6). The advantage of improving registration so that more of the display field could be fused went unnoticed initially. After discussion to draw the user's attention to the change, it was judged to be helpful. On other occasions, image interpreters, and individuals presumably proficient in image interpretation, were observed using *inverted stereo* (Figure 5.1-6) with no awareness of any problem beyond an occasional comment that "it doesn't look quite right" (Ref. 6).

One of the difficulties with stereo is the time required for setup. No good published data are available, but observation of skilled interpreters using a Bausch and Lomb Zoom 240 microstereoscope with rhomboids and separate rolls for the two members of a stereo pair (as in Figure 3.10-15) suggests that about 1 minute is typical (Ref. 7). Because alignment of the two images is so critical, the means provided for moving the images can have a large impact on setup time.

Stereo is not limited to photographic imagery. As an example, if it is collected in the proper manner even relatively exotic imagery such as side-looking radar can be viewed in stereo (Ref. 8).

Stereoacuity, or ability to perceive differences in depth in a stereo image, is usually expressed in terms of the smallest perceptible lateral disparity. Common test techniques involve measuring the variability of the settings as a test subject attempts to adjust two objects to the same distance, or recording the lateral disparity at which he achieves a certain level of success in stating which of several objects is nearer (Ref. 9). Typical values appear in Section 5.1-3 and Figure 3.5-11.

Under the proper conditions, a single photograph can yield a strong sensation of depth (Ref. 10), and it has even been suggested that this phenomenon can be used to enhance the perception of visual information in the image (Ref. 11). This effect apparently works best with a photograph in which the peripheral details in the scene were closer than the central details. It is also more successful when the photograph is viewed with an optical device such as a *biocular* magnifier that would be expected to cause the image to appear curved in the same direction as the prominent details in the original scene. Although there is no evidence that this effect can increase the correct perception of details in the imagery, it may increase interest in the displayed image.

Most of the design recommendations for stereo displays appear in other sections of this document. In particular, Section 3.7 covers the need to match the two optical trains of a stereo display geometrically and in terms of other parameters such as image distance and luminance. As is noted there, the display alignment tolerance is greater for stereoscopic viewing than for binocular monoscopic viewing because with stereo some misalignment can be corrected by moving one of the images relative to the other. Requirements for orienting and interchanging the two members of a stereo pair are discussed in Section 3.10.

SECTION 5.1 STEREO

5.1.1 DEFINITIONS AND TERMS

This section summarizes some of the more important terms and concepts involving stereo.

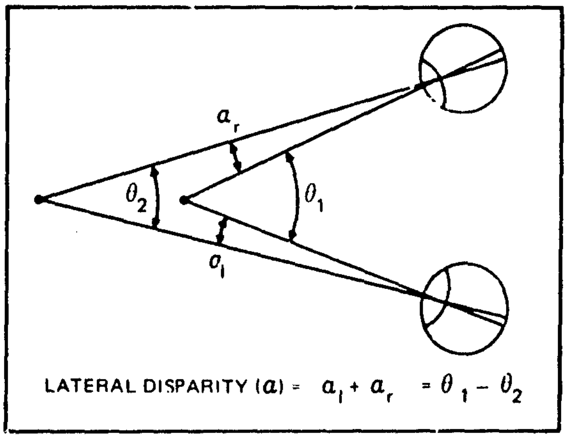


Figure 5.1-1. Lateral Disparity in Unaided Vision. Because of their lateral separation, the two eyes receive slightly different images of objects which differ in distance. These differences are known as *lateral disparity* or sometimes as *parallax*.

Lateral disparity expressed in angular units is identified by the symbol "a" in this document. The symbol "η" is also used in many publications. Lateral disparity can also be expressed as linear extent on the imagery or on some comparable plane.

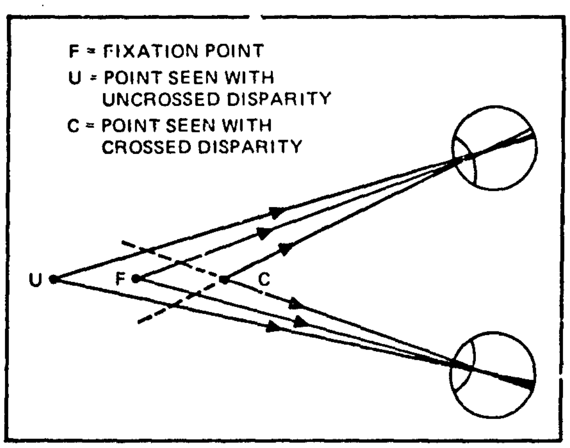


Figure 5.1-2. Crossed and Uncrossed Disparity. It is common in the literature on stereo to refer to objects closer than the fixation point as having *crossed disparity* and those farther away as having *uncrossed disparity*. (Crossed and uncrossed disparity can also be defined in terms of the relative positions of the two objects C and U, without regard to the fixation point.)

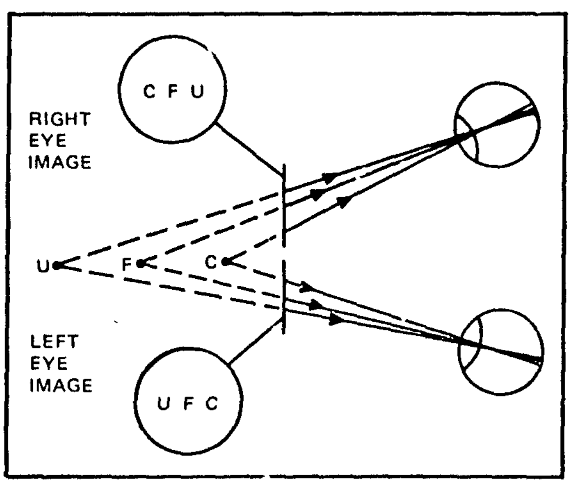


Figure 5.1-3. Simulation of Depth. Figure 5.1-2 shows three objects located at different distances. These can be simulated by providing each eye with an image in which details are displaced slightly, relative to each other, in the lateral direction. In this example, the object (C) will appear closer than (F), and (U) will appear farther away. Note that in this viewing situation the retinal images are identical to those which would exist if the points (C), (F) and (U) were actually in front of the observer just as they are in Figure 5.1-2. Thus, since the input to the visual system is the same as that when actual objects are present, the visual system output is the same: the objects appear to be at different distances.

Wide changes in the lateral separation between the right and left eye images, if accompanied by corresponding changes in eye convergence angle, do not change the basic characteristics of the stereo image (see, for example, Figures 5.1-5 and -16). However, they do make it inconvenient to illustrate the stereo image, and they may result in changes in the perceived relative heights of objects in the image.

5.1.1 DEFINITIONS AND TERMS (CONTINUED)

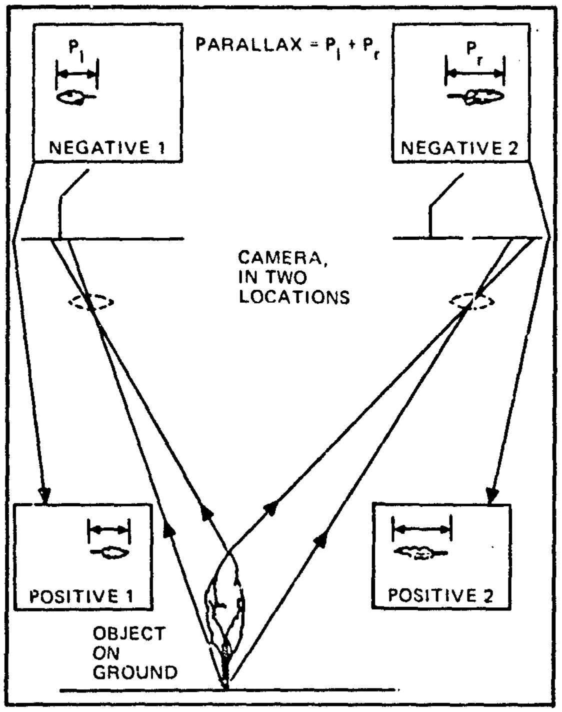


Figure 5.1-4. Parallax in Stereo Imagery. In photographs taken from two different locations, objects will be displaced according to their relative distance from the camera, just as they are displaced on the retinas of the eyes in Figure 5.1-1. These differences are usually known as *parallax* and correspond to lateral disparity as described in Figure 5.1-1.

Symmetry is not a requirement in stereo imagery. For example, in this illustration both camera locations could be to the same side of the tree.

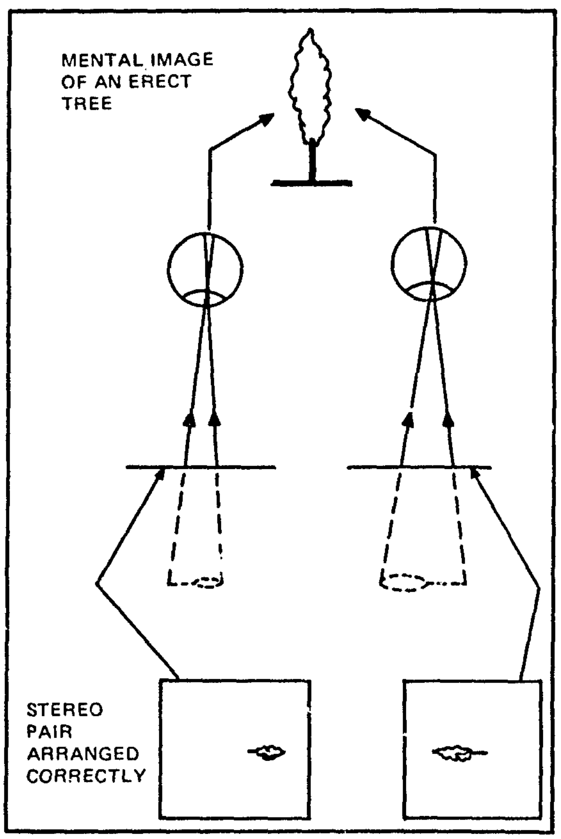


Figure 5.1-5. Correct Stereo Viewing. There are two basic requirements for positioning the two images when viewing stereo:

- The images of higher points along a vertical object such as the tree shown here, must be closer than the images of lower points; if the object was between the two camera locations, the two images will fall toward each other.
- Lines connecting the two images of any particular elevation along a vertical object must all be parallel to each other and to a line through the two eyes of the observer; these lines are also approximately parallel to a line through the two camera locations.

If these two conditions are met, the lateral disparity in the pair of photos will produce lateral disparity on the retinas which will be interpreted as depth, at least over a range of disparities as described in Figure 5.1-13.

With the exception of situations like those shown in Figure 5.1-16, optical elements such as prisms, lenses, mirrors, or filters are provided in stereo displays to allow each eye to view only the appropriate photograph and to ensure at least a tolerable match between eye accommodation and convergence.

The stereo image, as it is drawn here, is simply a convenient way of showing what the viewer perceives. It does not exist in space and it does not directly impose any requirements on the convergence angle between the eyes nor on the accommodation of the eyes. In fact, a very satisfactory stereo image can be obtained in a display with the eyes parallel, or even diverged. Changes in eye convergence and accommodation may, however, change the appearance of the stereo image (Ref. 5).

5.1.1 DEFINITIONS AND TERMS (CONTINUED)

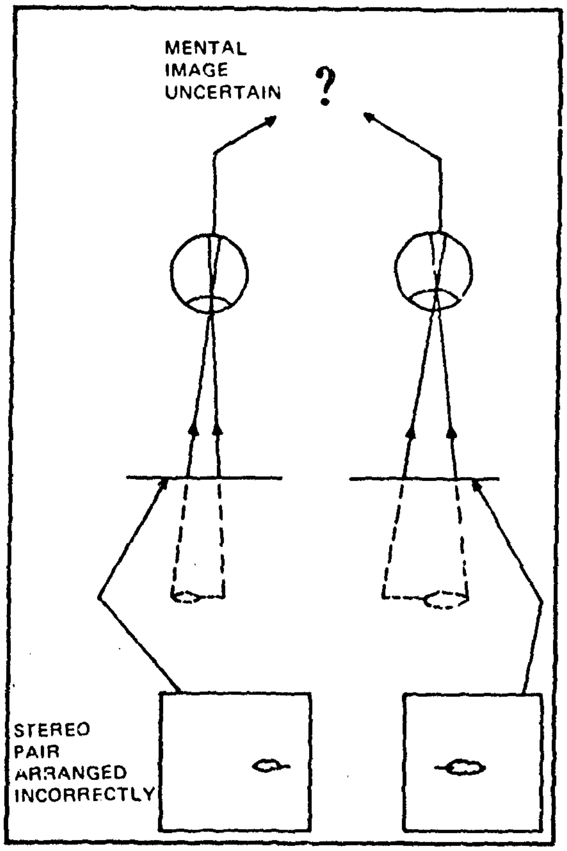
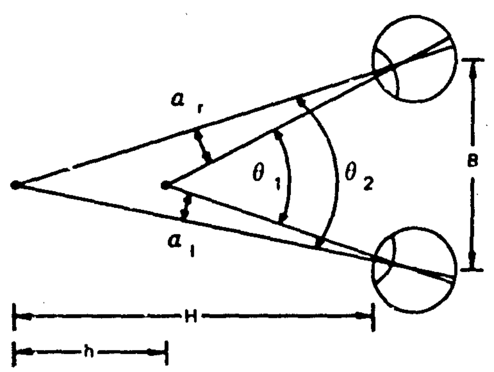


Figure 5.1-6. Inverted Stereo. If the two photos in the previous figure are rotated 180 degrees, or if they are interchanged but not rotated, the two images of a raised object will fall away from each other rather than toward each other. The result will be an inverted stereo image. In this image, simple raised objects such as buildings may appear as holes in the ground. However, because other perceptual cues such as knowledge of the true shape of trees and buildings are so strong, inverted stereo may simply be mistaken for poor quality but correct stereo, or the image may simply seem "strange" (Ref. 12).

SECTION 5.1 STEREO

5.1.2 PARAMETRIC RELATIONSHIPS

Equations required to calculate lateral disparity in typical viewing situations are summarized in this section. They are useful whenever it is necessary to compare test data on ability to detect differences in depth to the height differences existing in imagery in a stereo display.



EQUATIONS: $\alpha = \alpha_r + \alpha_l = \theta_1 - \theta_2 = \frac{hB}{H^2}$

DIMENSIONS:

- α = LATERAL DISPARITY ANGLE (IN RADIANS· MULTIPLY BY 3,438 TO GET ARC MINUTES)
- B = INTERPUPILLARY DISTANCE
- H = EYE-TO-OBJECT DISTANCE
- h = OBJECT HEIGHT ($h \ll H$)
- θ_1, θ_2 = EYE CONVERGENCE ANGLES FOR THE TWO OBJECTS

SUBSCRIPTS:

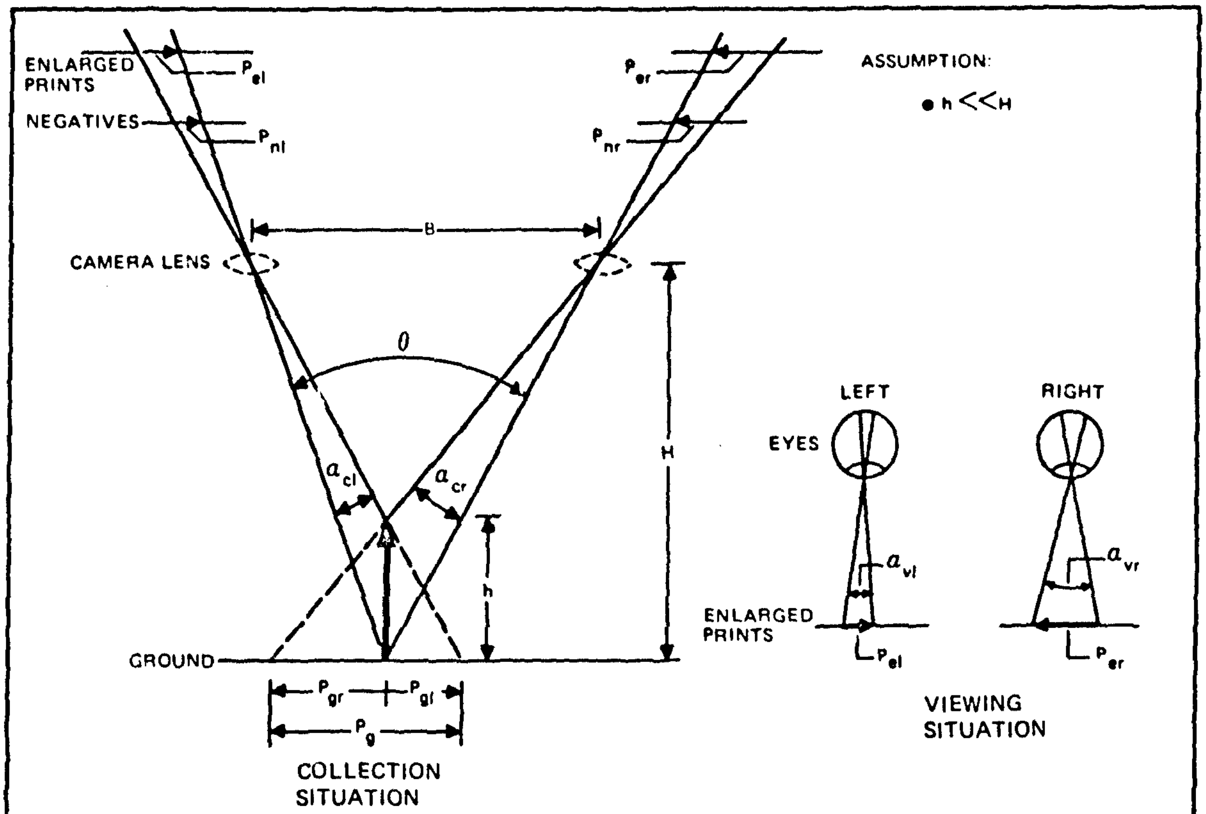
l = LEFT EYE
r = RIGHT EYE

NOTE: ALL DISTANCES (B, H, and h) IN THE SAME UNITS

ASSUMPTION: $h \ll H$; $B \ll H$

Figure 5.1-7. Parametric Relationships for Direct Viewing of Depth. This figure illustrates the basic set of equations for lateral disparity in direct viewing situations. They are adapted from Ref. 9. In Figure 5.1-8 these equations are extended to the viewing of stereo photographs.

5.1.2 PARAMETRIC RELATIONSHIPS (CONTINUED)



DIMENSIONS:

- P = lateral disparity distance (parallax)
- α = lateral disparity angle (in radians; multiply by 3,438 to get arc minutes)
- B = camera base distance (lens separation)
- H = camera lens height
- h = object height
- θ = object convergence angle ($\theta \cong \arctan B/H$; $B/H \cong 2 \tan \theta/2$)
- S = photo scale = camera focal length (for objects at infinity) divided by H
- E = photo enlargement ratio (for a contact print, E = 1)
- M = display magnifying power (see Figure 3.3-1)
- D = effective distance to photo print in display (see Figure 3.3-1) = 0.25/M meters (10/M in inches)

SUBSCRIPTS:

- g = ground
- n = negative in camera
- e = enlarged print
- c = camera
- v = visual
- l = left
- r = right

Note: All distance are in meters

DISTANCE EQUATIONS:

On ground: $P_g = P_{gl} + P_{gr} = \frac{Bh}{H} \cong 2h \tan \theta/2$

On negative: $P_n = SP_g = \frac{SBh}{H} \cong 2 Sh \tan \theta/2$

On print: $P_e = E P_n = E S P_g = \frac{ESBh}{H} \cong 2 ESh \tan \theta/2$

ANGLE EQUATIONS:

For camera: $\alpha_c = \alpha_{cl} + \alpha_{cr} = \frac{P_g}{H} = \frac{Bh}{H^2} \cong \frac{2h}{H} \tan \theta/2$

For display: $\alpha_v = \alpha_{vl} + \alpha_{vr} = \frac{P_e}{D} = \frac{MP_e}{0.25} = \frac{ME\,SBh}{0.25\,H} \cong \frac{2\,MESh}{0.25} \tan \theta/2$

Figure 5.1-8. Parametric Relationships in Stereo Photographs. The Lateral disparity seen by a display user while viewing a pair of stereo photographs can be calculated from several different sets of collection system and display parameters. The equations relating these parameters are illustrated here (Ref. 13).

5.1.2 PARAMETRIC RELATIONSHIPS (CONTINUED)

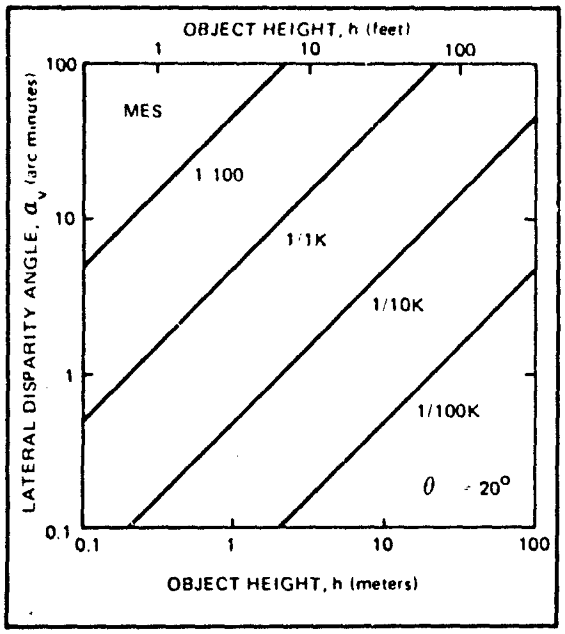


Figure 5.1-9. Displayed Disparity as a Function of Object Height. In order to relate depth perception ability in an imagery display to depth perception ability as measured in a laboratory experiment, it is necessary to calculate the lateral disparity experienced by the display user. This figure illustrates the lateral disparity in a typical imagery viewing situation.

Referring to Figure 5.1-8, the relationship between angular lateral disparity in the displayed stereo image to object height on the ground is:

$$a_v = \frac{2\,\text{MESh}}{0.25} \tan\frac{\theta}{2},$$

where M, E, and S are display magnifying power, imagery enlargement, and imagery scale, and θ is the collection system convergence angle.

This figure shows values of a_v for various values of h and MES, with θ held constant at 20 degrees. The value of a_v is increased by one-third if θ is increased to 26.5 degrees, and it is decreased by one-third if θ is decreased to 13.4 degrees.

Note that each curve in the figure represents a single value for MES, and hence a range of values for M, E, and S. For example, if MES = 1/1K and a contact print is being viewed, so that E = 1, then:

- If M = 10X, S = 1/10K
- If M = 40X, S = 1/40K
- If M = 100X, S = 1/100K

5.1.3 DEPTH-PERCEPTION ABILITY

Data on the ability of individuals to perceive depth in several different kinds of viewing situations are summarized in this section. Similar information appears in Figures 3.5-10 and -11.

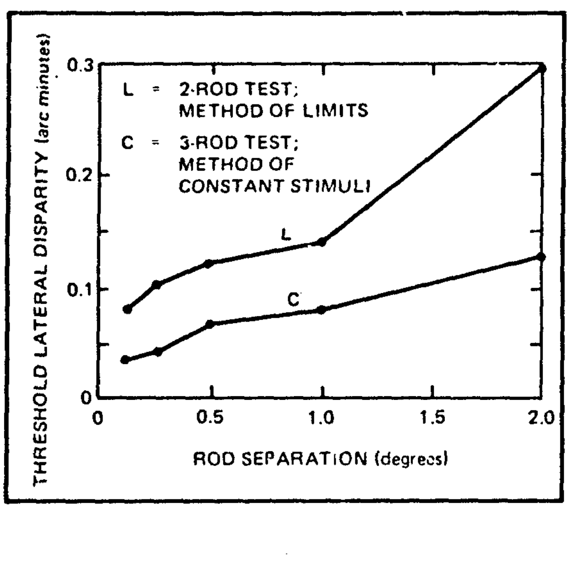


Figure 5.1-10. Depth Perception Ability for Simple Scenes. The equations in Figure 5.1-8 show that lateral disparity in a displayed image is increased by magnification. However, as these data illustrate, part of the benefit of the increase in lateral disparity may be lost (Ref. 14,X). This is because the separation between image details whose relative height is being judged is also increased, thereby decreasing ability to detect lateral disparity. These data are similar to those in Figure 3.5-12 in showing a large reduction in ability to detect differences in depth as the targets were separated laterally.

The two curves here, L and C, represent slightly different viewing conditions and test procedures (Ref. 15). In the absence of any information on how the test data were analyzed, they cannot be compared exactly on an absolute basis with each other nor with other viewing situations (Ref. 16).

These values are similar to the results of other studies. In one, for example, a group of 96 subjects adjusted two vertical black rods to be equidistant (Ref. 17,B). Their stereo thresholds, expressed as the standard deviation of the lateral disparity remaining in the settings made by each subject, ranged from 0.03 to 1.7 arc minutes. Approximately 80 percent of the subjects had thresholds of less than 0.3 arc minute.

5.1.3 DEPTH PERCEPTION ABILITY

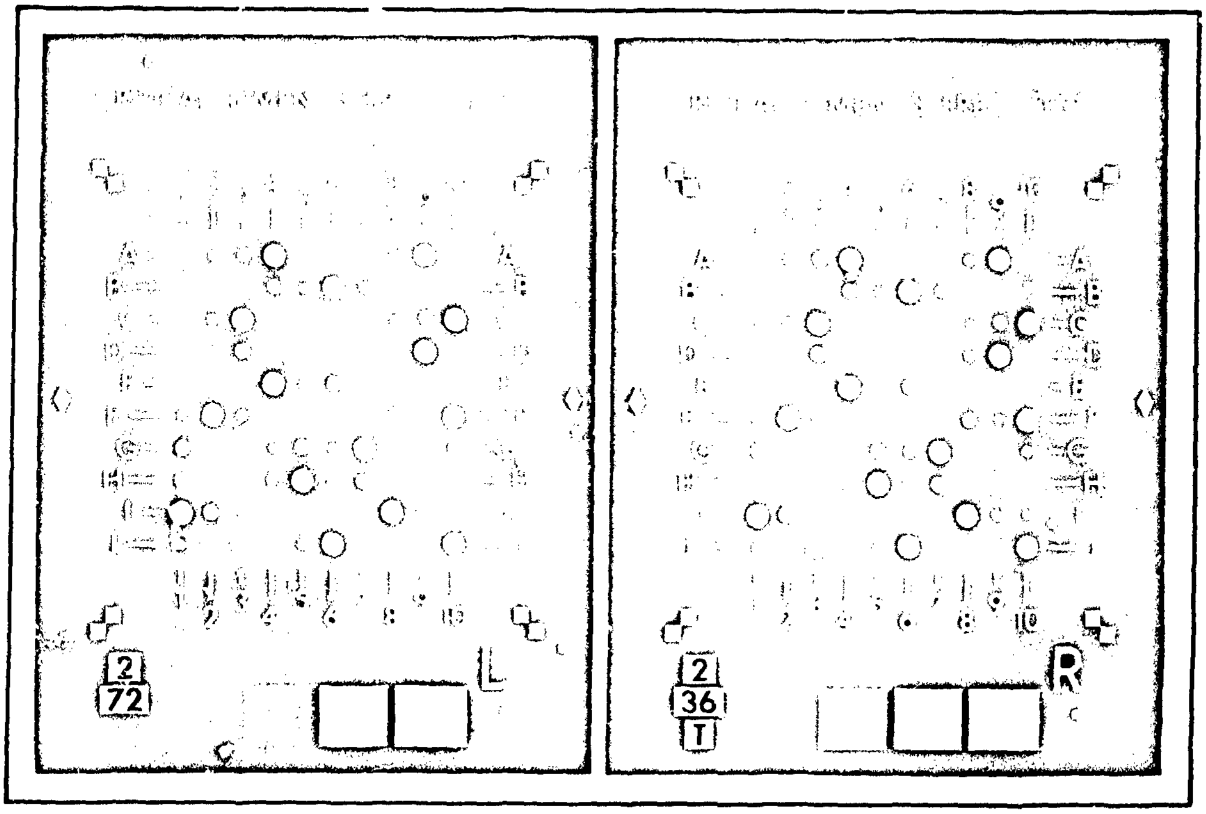


Figure 5.1-11. Depth Perception Test With Realistic Confusion Cues. Unlike most laboratory test situations, reconnaissance imagery does not usually consist of simple geometric targets and a homogeneous background. As a result, the lateral disparity threshold for an interpreter viewing such imagery is likely to be larger than the values obtained in test situations like Figure 5.1-10.

The test illustrated here was designed to provide a more realistic method of measuring ability to detect lateral disparity in an imagery display (Ref. 17). The stereo pair shown, which is representative of the eight pairs making up the test, contains eight raised discs, one in each of the central eight rows. These are also limited to the inner eight columns, two through nine. The subject's task is to name the raised disc in each row.

The task of detecting the raised discs is made more realistic by inclusion of two confusion cues, disc size and brightness, which in many real viewing situations provide limited information about the relative nearness of objects (Ref. 18).

In addition to the achromatic version of this test illustrated here, a color version has been used to evaluate the impact of *chromostereopsis* on ability to detect depth in color imagery (Ref. 19).

Another approach to constructing a more realistic test of ability to perceive depth in reconnaissance stereo image is to use a computer-generated stereogram of random dots. This technique is usually associated with Julesz (Ref. 20).

5.1.3 DEPTH PERCEPTION ABILITY (CONTINUED)

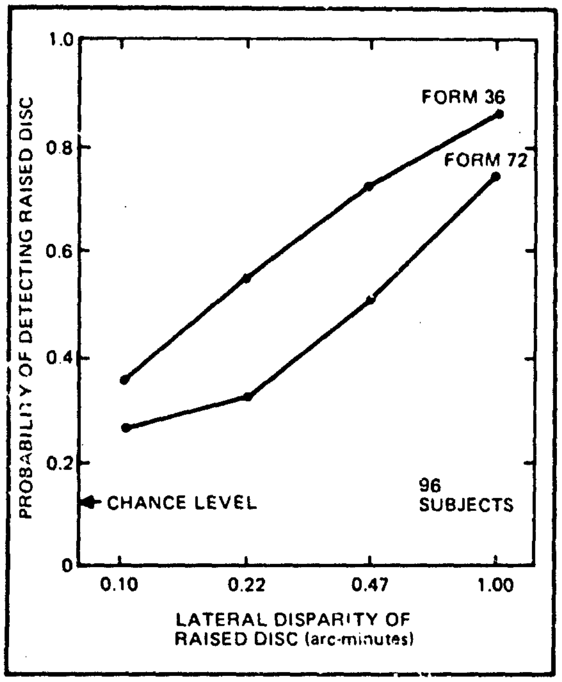


Figure 5.1-12. Height Discrimination Performance in a Complex Scene. Performance data for 96 subjects on the test described in Figure 5.1-11 are shown here (Ref. 17,B). The subjects were considerably less than 100 percent successful in finding the raised disc in each row, even when the disc had a lateral disparity several times the value studies such as that illustrated in Figure 5.1-9 suggest should be detectable. This is presumably due to the additional confusion cues present.

Form 36 of the test was viewed at 2X magnifying power and had a between-disc spacing of 36 arc minutes. Form 72 was photoreduced to a smaller size but was magnified 15X to obtain a disc spacing of 72 arc minutes. Probably both the greater photoreduction of the Form 72, which resulted in a lower quality image, and the greater between-disc distance, contributed to the drop in performance experienced by the subjects.

In another study with this test, the same disc heights and sizes were retained but film transmission was manipulated to produce four different versions of the test (Ref. 21). Ordered according to depth discrimination performance, from best to worst, these were as follows:

- A single achromatic contrast equal to the lowest of the four contrasts in Figure 5.1-11
- Four achromatic contrasts, exactly as in Figure 5.1-11
- A single contrast approximately equal to the lowest of the four contrasts in Figure 5.1-11, plus a blue monochromatic illuminant
- Four contrasts as shown in Figure 5.1-11, plus five different colors distributed among the discs

These results all support the conclusion that increasing the number of dimensions over which an image varies makes it more difficult to discriminate differences in depth.

5.1.3 DEPTH PERCEPTION ABILITY (CONTINUED)

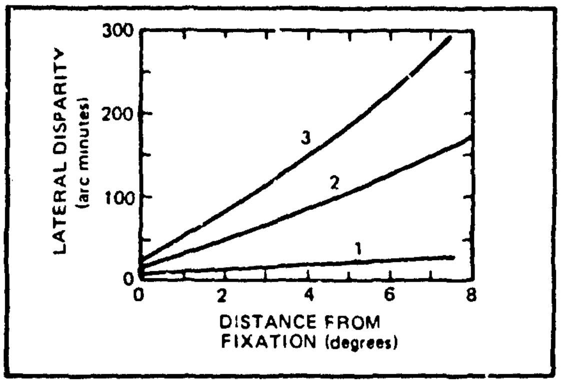


Figure 5.1-13. Limits of Depth Perception. Lateral disparities much too large to fuse into a single image (Figure 3.7-16) may still yield a sensation of depth that may be useful in some display applications, though probably not in the interpretation of imagery. The curves in this figure (Ref. 22) show the maximum lateral disparity at which:

- Curve 1– Fusion was maintained; beyond this value the image was seen as double; double images are undesirable in an imagery display.
- Curve 2–The relative distance of objects seen as a double image could be judged.
- Curve 3–A judgment of nearer or farther could be made.

Note that these limits increase toward the periphery. Also, they are for very simple geometric targets viewed against a uniform background. More complex scenes should yield larger fusion limits. See, for example, Figure 3.7-19.

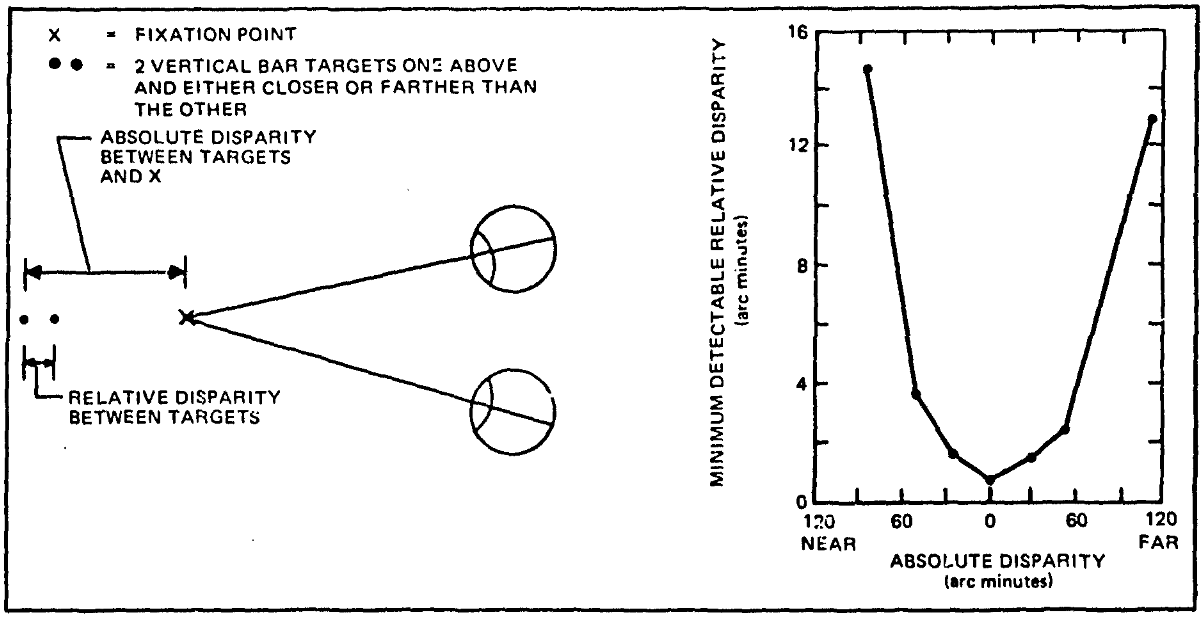


Figure 5.1-14. Limits of Depth Perception. Figure 5.1-13 shows that the ability to interpret lateral disparity as depth is lost when the lateral disparity becomes too large (Ref. 23,C). The study summarized here shows that this loss does not occur abruptly. In this study, the test subject attempted to state which of two vertical bars was closer (relative disparity) when both bars were closer or farther away than the fixation point (absolute disparity). When the absolute disparity, or distance from both bars to the fixation point, was 30 arc minutes, he required a slight increase in relative disparity in order to detect the closer bar. When the absolute disparity reached 90 arc minutes, he required a very large relative disparity.

Although not reported explicitly in this study, it is likely that the two targets, which were two vertical bars positioned one above the other, were seen double even at the smallest lateral disparity of 30 arc minutes. Hence the specific values obtained do not apply directly to most image interpretation situations, where a double image is usually avoided except for very tall objects such as smokestacks and towers.

5.1.3 DEPTH PERCEPTION ABILITY (CONTINUED)

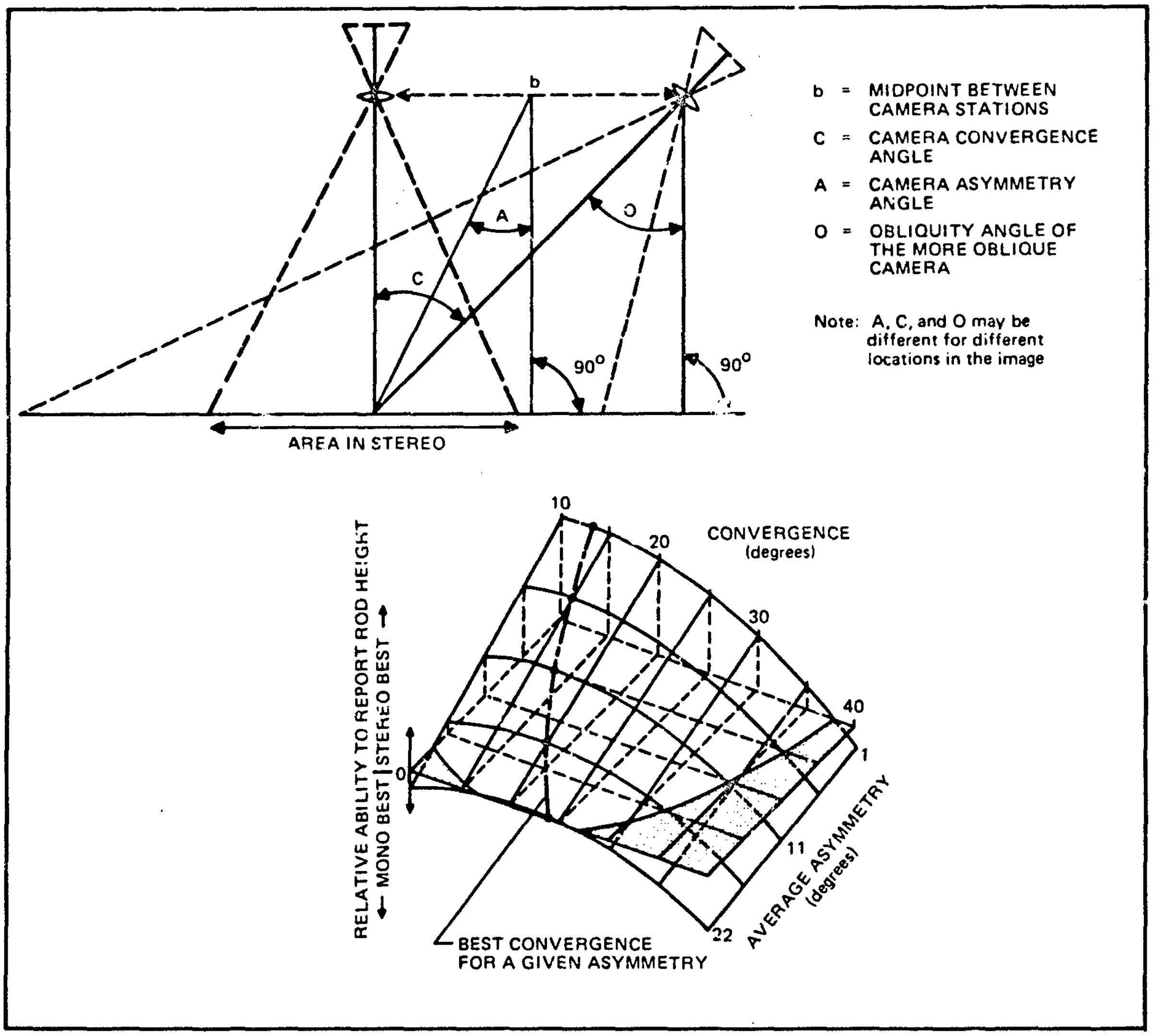


Figure 5.1-15. Contribution of Stereo to Height Discrimination. One of the advantages of stereoscopic versus near vertical monoscopic imagery of a ground scene is that it provides more information about the heights of objects. Because oblique imagery shows the sides of objects, it provides this kind of information in a single, monoscopic view, though at the sacrifice of ground resolution due to the scale reduction and obscuration of the areas immediately behind raised objects.

The study illustrated here compared the ability of subjects to determine the relative height of white rods viewed against a mottled gray background using either stereo or mono (nonstereo) imagery (Ref. 24,B). The rods were photographed at a range of camera convergence and asymmetry angles, defined as is shown. Using these photographs, subjects attempted to order the rods according to their relative heights. The photographs were viewed either singly or as stereo pairs (Ref. 24).

The data were analyzed to show the contribution of stereo to performance. For each stereo pair, the performance score obtained for the most oblique member of the pair, viewed binocularly, was subtracted from the score obtained for the pair viewed stereoscopically. The results, plotted here, show that as obliquity increased, the contribution of stereo to height discrimination ability decreased.

The data summarized in this figure are potentially misleading in that they indicate only ability to distinguish height. As a result, they do not provide any estimate of the usefulness of information about nearness of objects available from oblique stereo photographs.

5.1.4 SPECIAL STEREO VIEWING SITUATIONS

Several special stereo viewing situations can occur. One is summarized in Figure 5.1-15 above and two others are illustrated in Figures 5.1-16 and -17.

A fourth special situation is the viewing of high oblique imagery. Obliquity stretches a square object on the ground into an approximate parallelogram with its long axis in opposite directions for the two members of the stereo pair. The resulting *misregistration* reduces the proportion of the display field that can be simultaneously fused to obtain a good stereo image. The exact point where this reduction becomes serious cannot be determined, but it is likely in the 30- to 40-degree region. *Anamorphic magnification*, which enlarges the image along only one dimension instead of two, can greatly reduce this misregistration, but will also distort the appearance of vertical objects in the scene. Training may be required to use anamorphic magnification effectively.

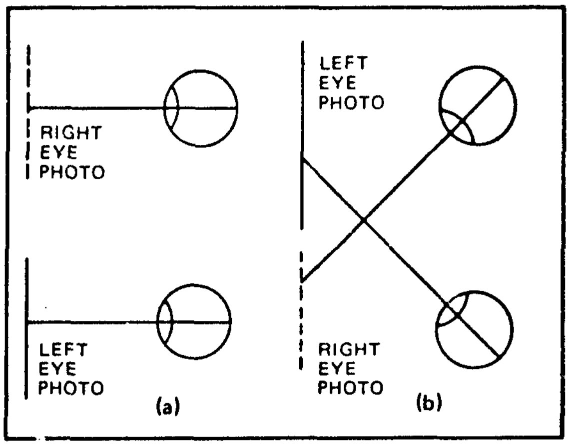


Figure 5.1-16. Eye Convergence in Unaided Stereo Viewing. Normally stereo photographs are viewed with mirrors or prisms to redirect the lines of sight. However, some individuals can learn to change the relationship between viewing distance and eye convergence angle in order to view stereo without optical aids. One method (a) is to diverge the eyes more than normal for the distance to the photos, while the other (b) involves the use of greater than normal convergence.

Though both of these techniques are in extreme violation of the principle of making eye accommodation and convergence match (Figure 3.7-13), many individuals are able, with practice, to use them for extended periods. Many others can only use them for a few seconds at a time, or cannot use them at all.

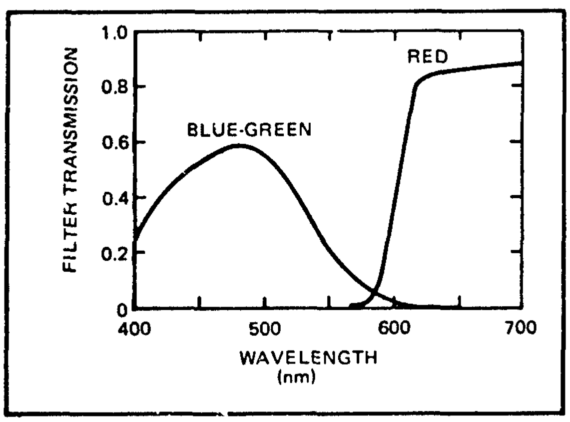


Figure 5.1-17. Anaglyphic Stereo Displays. *Anaglyphic* stereo viewers illuminate the two members of a pair of stereo photographs with different color illumination and use corresponding color filters before the eyes to ensure that each eye sees only one of the two images. Typical illuminant color filters, such as those illustrated here, yield red and blue-green light (Ref. 25).

Because of the chromatic aberration of the eye, if the display user's eyes are normal, the one viewing the blue-green image will effectively have more refractive power than the one viewing the red image. Referring to Figure 3.4-4, and taking the dominant wavelengths for these two illuminants as 480 and 620 nm, the difference in refractive power is about 0.75 diopter. Some individuals may require a corrective spectacle lens to compensate for this large a difference.

SECTION 5.1 REFERENCES

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   Also see Ref. 9.

2. Kurtz, H. F. Orthostereoscopy. *J. Opt. Soc. Am.*, Vol. 27, 1937, pp. 323-339.

   LeGrande, Y. *Form and Space Perception* (Rev. Ed.), Translated by Millodot, M. and Heath, G. G. Indiana University Press, Bloomington, Indiana, 1967.

   Also, see almost any of the numerous articles on the stereo image published in *Photogrammetric Engineering.*

3. This does not imply that it may not be useful for some purposes to draw the stereo image as if it is projected into space, much as a virtual image is drawn. However, the assumptions implicit in such a drawing must be considered very carefully if it is to be used as the basis for some conclusion about the stereo image.

4. See Ref. 5 for a summary of this type of research as it applies directly to the viewing of stereo imagery.

   McCready, D. W., Jr. Size-distance perception and accommodation–convergence micropsia--a critique, *Vision Res.*, Vol. 5, 1965, pp. 189-206.

   Gogol, W. C. The effect of convergence on perceived size and distance. *J. Psychol.*, Vol. 53, 1962, pp. 475-489.

5. LaPrade, G. L. Stereoscopy–Will data or dogma prevail? *Photogram. Engr.*, Vol. 39, 1973, pp. 1271-1275.

   LaPrade, G. L. Stereoscopy–A more general theory. *Photogram. Engr.*, Vol. 38, 1972, pp. 1177-1187.

   LaPrade, G. L. *A more general theory of stereoscopy*. GIB-9268, Rev. A. The Goodyear Aerospace Co., Litchfield Park, Ariz., 1973.

   Also see the LaPrade article in Ref. 1.

6. These statements are based on personal observations by the senior author while working with image interpreters to evaluate new imagery displays.

7. Unpublished observational-type data collected by military image interpreters.

8. LaPrade, G. L. *Subjective Considerations for Stereo Radar*, GIB-9169, Goodyear Aerospace Co., Litchfield Park, Ariz., 1970.

9. Graham, C. H. Visual space perception. Chapter 18 in Graham, C. H. (Ed.) *Vision and Visual Perception.* Wiley, New York, 1965.

10. Schlosberg, H., Stereoscopic depth from single pictures. *Am. J. Psychol.*, Vol. 54, 1941, pp. 601-605.

    Ames, A., Jr. The illusion of depth from single pictures. *J. Opt. Soc. Am.*, Vol. 10, 1925, pp. 137-148.

    Judge, A. W. *Stereoscopic photography, its application to science, industry and education* (3rd ed.). Chapman and Hall, London, 1950. See Chapter XIV, Monocular relief impressions.

11. Schwartz, A. H. Stereoscopic perception with single pictures. *Optical Spectra*, Vol. 5, September 1971, pp. 25-27.

12. Tuckman, M. *A Report on the Art and Technology Program of the Los Angeles County Museum of Art*, 1967-1971.

    On page 342, John Forkner, of the Aeronutronics Division of Philco-Ford in Newport Beach, California, describes attempts to produce reversed, or "pseudoscopic," stereo images of real objects. With simple objects such as corner cubes and spheres, this was apparently very successful. However, familiar objects like a hand or a face would not invert, except occasionally in an ambiguous way.

13. These equations are an expanded form of equations developed for this document by P. M. Fagan of The Boeing Company, Seattle, Washington.

14. Graham, C. H. Visual perception. Chapter 23 of Stevens, S. S. (Ed.) *Handbook of Experimental Psychology*. Wiley, New York, 1951. These data appear in Figure 20. They were originally reported by A. Matsubayashi in 1937.

15. Curve L in Figure 5.1-10 is based on measurements using the method of limits and a two-rod test. Curve C is based on the method of constant stimuli and a three-rod test. These test methods are discussed, in general terms, in Woodworth, R. S. and Schlosberg, H. *Experimental Psychology* (rev), Holt, New York, 1958, Chapter 8.

16. It is common for the minimum detectable differences in experiments of this type to be defined as the standard deviation of the distances at which the subject switched between "closer" and "farther" responses, or half the interval over which the subject responded "equal" if this response was allowed. See, for example, Ref. 15.

17. Farrell, R. J., Anderson, C. D. and Boucek, G. P. *Construction and Standardization of the CL Stereo Acuity Test* (Form 2). Documents D180-19059-1 and D180-19059-2, The Boeing Company, Seattle, Washington, 1975.

18. In Ref. 9 it is noted that increases in the size or brightness of an object make it appear nearer. That this occurs in static images was confirmed in Ref. 17, where the errors made by the subjects were more likely to involve large discs or light discs.

19. Kraft, C. L., Booth, J. M. and Boucek, G. P., Jr. *Achromatic and Chromatic Stereoscopic Performance*, 12th Cong. Internatl. Soc. Photogrammetry, Ottawa, Canada, July 1972.

Kraft, C. L. and Anderson, C. D. *Development of Criteria for Printing Color Reconnaissance Stereo Strip Photography for Interpretation Under Dynamic Viewing Conditions.* AMRL-TR-73-104, Aerospace Medical Research Labs, 1973.

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23. Blakemore, C. The range and scope of binocular depth, discrimination in man. *J. Physiol.*, Vol. 211, 1970, pp. 599-622. Although this article is not easy to read, it contains very useful, and unique, information on the limits of stereopsis.

24. Fagan, P. M. and Briggs, S. J. *Viewing of Asymmetric Stereo Imagery.* D180-19060-1, The Boeing Company, Seattle, Washington, 1975.

In this study, the members of each stereo pair were magnified differentially to obtain the best scale match. The magnification was linear, not anamorphic.

25. Wright, W. D. Stereoscopic vision applied to photogrammetry. *Photogrammetric Record*, Vol. 1, 1954, pp. 29-45.

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5.2 COLOR

This section summarizes the aspects of *color* that are important in the design of imagery displays. More complete coverage is available in several excellent books and summary papers (Ref. 1). Concepts presented here without a specific citation are generally covered in these references.

Color in an imagery display may result from color imagery, recorded either on film or electronically, or from use of color to display a parameter like the strength of a radar return that is not normally experienced as color. The implications of color for the display designer depend largely on the potential benefits anticipated through the use of color:

- If color imagery has been collected in order to make targets more noticeable and therefore easier to detect during search, then the primary design requirement is to provide an illuminant with a spectral distribution that will maximize the color contrast of target objects against their backgrounds. Design recommendations on this topic appear in Section 3.2.9 and are summarized here in Section 5.2.3.

- A second potential application for color is as an aid in target identification. It might be used for this purpose with a new target that is difficult to identify, or it might be included in the report of a target that has been identified in order to help identify similar targets found at a later time. In either case, it is assumed that it will be necessary to quantify the color of the target or at least to compare it with reference colors in a key. The viewing conditions that should be considered if colors are to be quantified by visual matching are discussed in Section 5.2.4. The test results summarized there show that it will be difficult to control all the variables that affect the results.

- If color is used to display parameters other than color, such as signal strength, then the designer is concerned with assigning a color to each signal strength value so that differences in signal strength can be discriminated and the user can easily learn to perceive which of two signal strengths is greater. A brief discussion of the factors involved appears in Section 5.2.5.

In order to provide a basis for describing the characteristics of a color image, Section 5.2.1 contains a summary of several techniques used to define color space, and Section 5.2.2 describes color vision testing.

The final section, 5.2.6, summarizes data on apparent displacement of colors from their true location. In many instances these displacements are experienced as variations in distance to different colors, causing this phenomenon to be known as *chromostereopsis*.

SECTION 5.2 COLOR

5.2.1 COLOR SPACE

The term "color" is used in so many different ways that it has proven very difficult to define in a manner that is both precise and brief (Ref. 2). One approach is to speak of visual experience as consisting of three basic attributes: extent, duration, and color (Ref. 3).

Color is traditionally considered to have three dimensions. For a subjectively assessed color, these are known as *hue, saturation,* and *brightness* or lightness (Figure 5.2-4). The different sets of names applied to the corresponding dimensions when color is measured physically, or when it is reported in terms of a subjective match to a specific set of reference colors, are listed in Figure 5.2-1. Additional dimensions, such as transparency and glossiness, provide a more complete description of color for certain kinds of materials, particularly reflective surfaces, but these are usually not required for imagery displays (Ref. 4).

Two pairs of nearly dichotomous usages of the term "color" are of importance to the display designer. Fortunately, the meaning that is intended can usually be inferred from the context. First, although color is a visual experience and is therefore properly specified perceptually, it is more common to apply the term "color" to a specific radiant energy spectral distribution; for example, a certain paint sample viewed under a certain kind of lamp. This specific radiant energy spectral distribution is then said to be a specific, physically defined "color" (Section 5.2.1.3), even though the "color" experienced by an observer viewing this same radiant energy will vary widely with the viewing conditions (Section 5.2.4).

The second dichotomy involves the assignment of either two or three dimensions to the term color. Color scientists define color to include the two chromatic dimensions, hue and saturation, plus a third achromatic dimension, brightness (Figure 5.2-4). However, it is very common to use the term color to mean only the two chromatic dimensions, as for example in the statement, "Should we add color to this black and white image?"

Perhaps the largest single effort in the area of color science has involved the development of methods for describing, defining, and measuring color. Systems developed for this purpose fall roughly into two groups: subjective and objective. Subjective measurement systems depend on visually matching the unknown color against a set of reference colors. One of the more popular systems is the Munsell color system described in Figure 5.2-5.

One of the difficulties with subjective techniques for measuring color is the fact that variation in how different individuals perceive color has an effect on the results. This problem is eliminated by objective techniques that depend on mathematical analysis of physical measurements to determine how a standard observer would perceive the color. The principal objective system for measuring color, the CIE chromaticity system, is described in Section 5.2.1.3.

SECTION 5.2 COLOR

5.2.1.1 TERMS AND BASIC CONCEPTS

This section summarizes a few of the terms and concepts essential to a description of color.

COLOR DIMENSION	OBJECTIVE TERM	SUBJECTIVE TERM	MUNSELL TERM (subjective, quantitative)
1 (equivalent to Y in Section 5.2.1.3)	LUMINANCE	BRIGHTNESS (luminosity in England)	–
	LUMINANCE FACTOR • REFLECTION FACTOR, OR REFLECTANCE (surface colors)	LIGHTNESS	VALUE
	• TRANSMISSION FACTOR, OR TRANSMITTANCE (transmitting colors)	BRIGHTNESS	
2	DOMINANT WAVELENGTH	HUE	HUE
3	PURITY	SATURATION	CHROMA

Figure 5.2-1. Summary of Color Terminology. The terms applied to the three color dimensions, arbitrarily numbered 1, 2, and 3 in this figure, depend on how the color has been determined and to some extent on the kind of colored material involved. The most commonly used terms are summarized here (Ref. 5). They are defined in subsequent figures.

In most cases in this document, the subjective color terms are used unless the intent is to refer to color dimensions measured objectively, or by use of the Munsell color system.

If the first of the three dimensions in the table is given as an absolute quantity, such as *nits* or *footlamberts*, it is known as *luminance*. If it is expressed as a relative quantity, such as transmittance, it is known as "luminance factor." The luminance factor generally has a range of 0 to 100 percent or 0 to 1.

The three dimensions of color are sometimes reduced to two:

- *Achromaticness*, which refers to brightness or lightness, or to shades of *gray*
- *Chromaticness*, which includes both hue and saturation

As is discussed in the introduction to Section 5.2.1, the term "color" is often used to refer only to chromaticness, rather than to all three color dimensions.

5.2.1.1 TERMS AND BASIC CONCEPTS (CONTINUED)

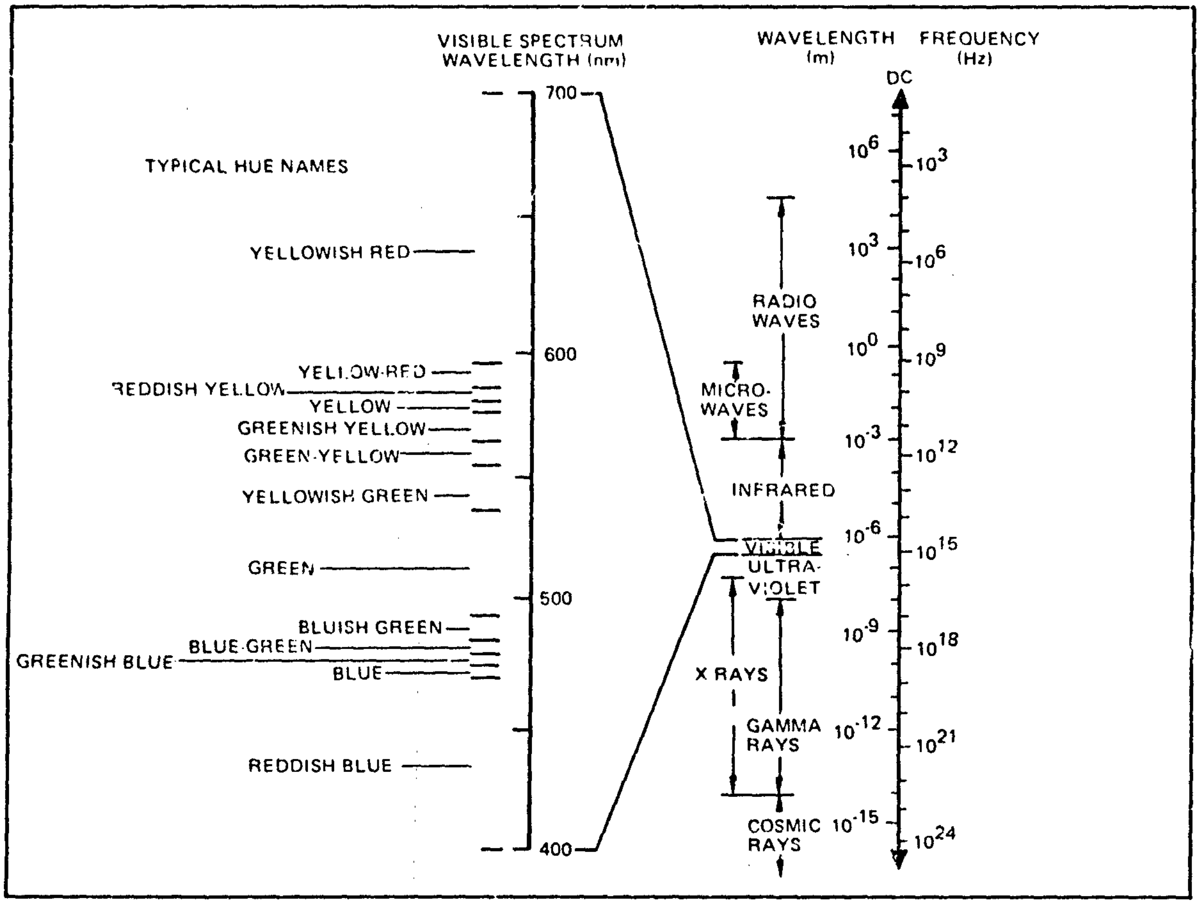


Figure 5.2-2. The Visible Spectrum. The position of the visible spectrum within the electromagnetic spectrum is illustrated here, along with the color names assigned to the various parts of the visible spectrum by one authority (Ref. 7). These colors, though not necessarily these names, correspond to the spectral locus in Figure 5.2-9.

One of the striking features of this assignment of color names to spectral regions is the fact that very narrow wavelength bands produce the pure colors blue and yellow. Also pure red, with no tinge of yellow or blue, is not on this list and can only be obtained by mixing wavelengths; 400 nm and 700 nm in appropriate proportions make up one such combination.

Note that the visible spectrum is plotted on a linear scale, while the larger portion of the electromagnetic spectrum is on a log scale.

5.2.1.1 TERMS AND BASIC CONCEPTS (CONTINUED)

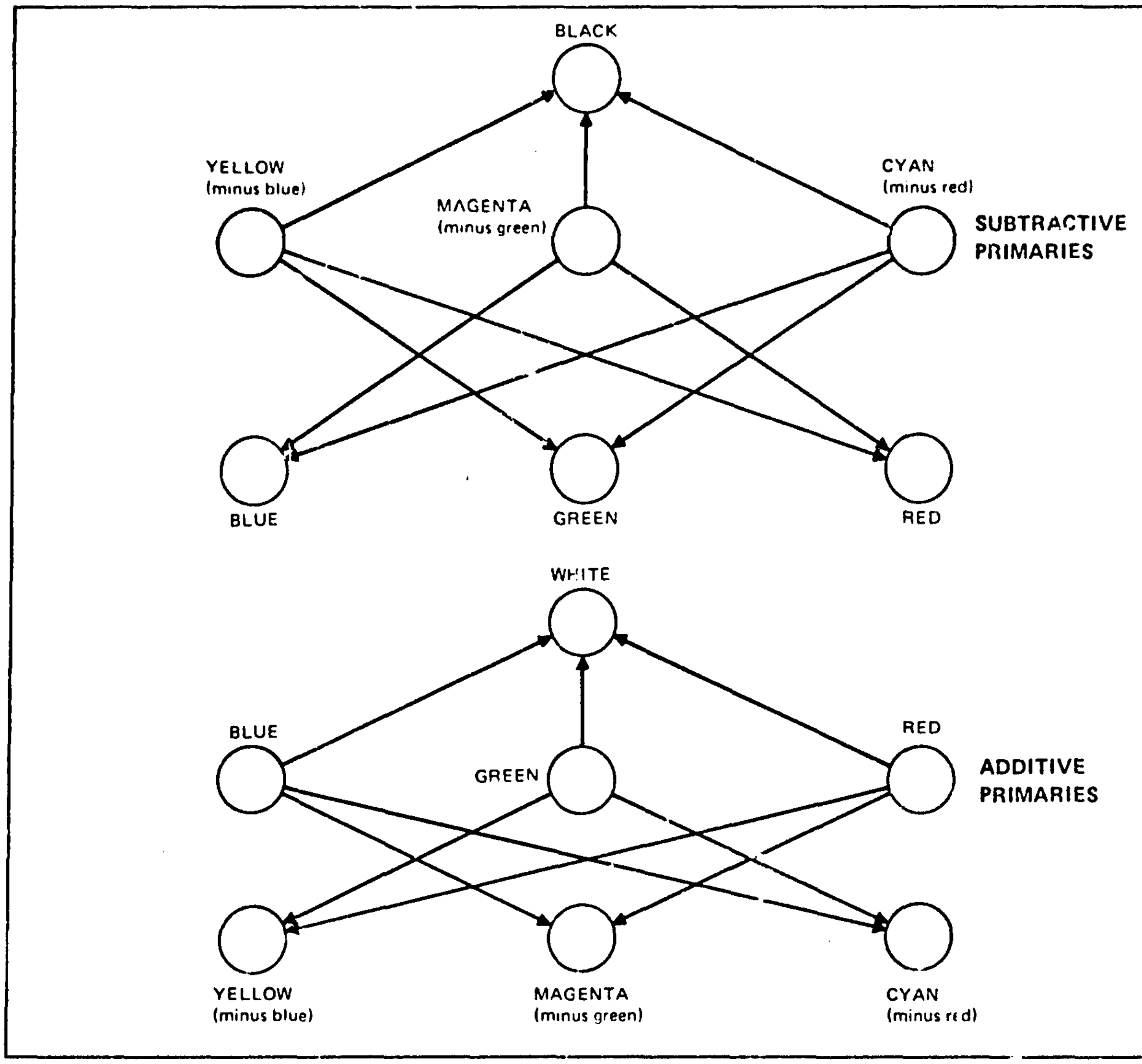


Figure 5.2-3. Primaries (Ref. 7). Colors specially chosen to be mixed together in various proportions in order to produce a wide range of other colors are known as *primaries*. Primaries are usually, though not always, used in sets of three. No set of three real primaries can produce all possible colors, but only a few restrictions on their selection are necessary in order to use them to obtain a visual match against any real color (Ref. 8).

For some applications, more than three primaries may be useful. As an example, visual matches against color fields larger than 5 to 20 degrees are more consistent over a wide range of luminance values if four primaries are used instead of three (Ref. 9).

Primaries fall into two general categories, subtractive and additive. In most colored materials, including color imagery, color is produced by dyes or pigments that selectively absorb the radiant energy in a portion of the visible spectrum. The primaries for this subtractive process are yellow, magenta, and cyan. They are also known by the colors they eliminate, minus blue, minus green, and minus red. Although they are not ideal, red and blue materials can function as subtractive primaries and are often listed along with yellow instead of magenta and cyan (Ref. 10).

When the additive primaries, red, green and blue, are combined, the radiant energy spectral distribution is the sum of the spectral distributions of the three primaries. The usual demonstration of additive primaries is illumination of a white surface by three projectors, one providing each of the three primaries. Color television utilizes additive primaries (Section 4.1).

5.2.1.2 SUBJECTIVE COLOR

This section describes the dimensions of subjective or perceptual color and introduces in Figure 5.2-5 the most popular general-purpose system for quantifying colors by visual matching, the Munsell color system.

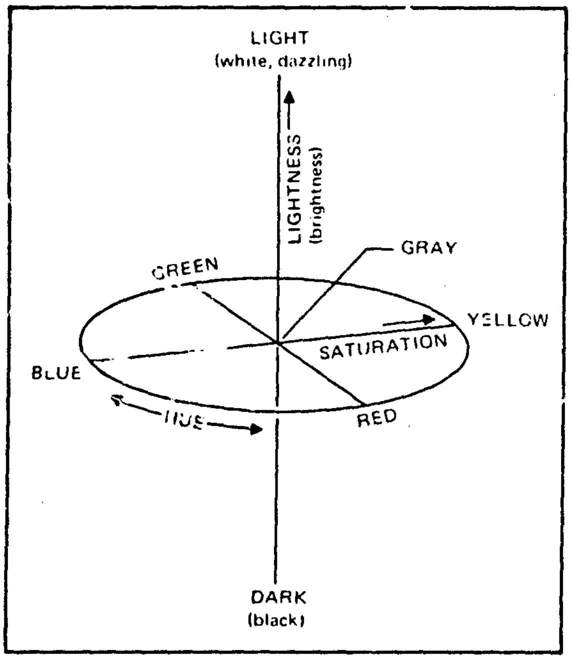


Figure 5.2-4. Subjective Dimensions of Color (Ref. 11). Color has three dimensions—hue, saturation, and brightness or lightness—related as shown here by a color wheel on a shaft.

Brightness, or *lightness*, refers to the attribute of a color that locates it along an achromatic (gray) continuum from light to dark, or white to black. The term "lightness" is generally applied to reflecting surfaces, and "brightness" to self-luminous ones. The Munsell term for lightness or brightness is "value."

Hue refers to the attribute of a color known by terms such as red, yellow, green, and blue. It corresponds approximately to dominant wavelength as defined in Figure 5.2-10. The Munsell term for hue is "hue."

Saturation refers to the departure of a color from an achromatic color, or gray, of the same lightness. For example, the two colors known as pink and red would have nearly the same hue, but red would have high saturation while pink would have low saturation. Zero saturation colors are black, gray, and white. Saturation corresponds approximately to purity, as defined in Figure 5.2-10. The Munsell term for saturation is "chroma."

5.2.1.2 SUBJECTIVE COLOR (CONTINUED)

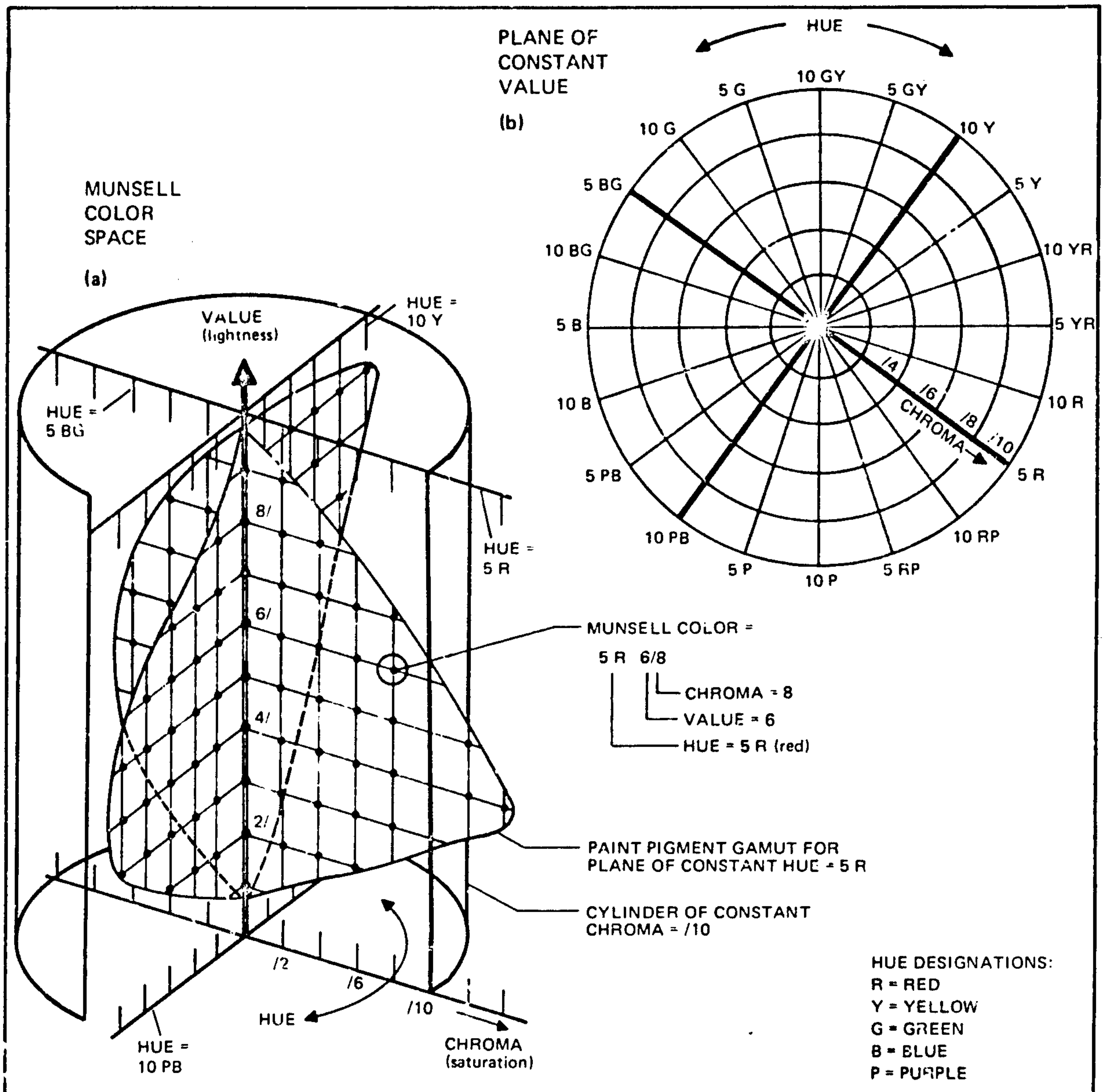


Figure 5.2-5. The Munsell Color System. Perhaps the best known technique for specifying a color according to its appearance is the Munsell color system illustrated here (Ref. 12). In this system, a color is assigned a number by matching it against a standard series of paint chips.

Part (a) of this figure shows four planes of constant Munsell hue and a cylinder of constant Munsell chroma, in Munsell color space. Part (b) is a cross section through this space, showing the Munsell hues in a plane of constant munsell value. (Chroma and value are comparable to saturation and lightness in Figure 5.2-4.)

The Munsell system has proven to be very useful for quantifying surface colors. If necessary, it can be used for this purpose with an imagery display. However, it has several problems (see Section 5.2.4).

- Matching two colors when one is a surface or reflective color such as a Munsell paint chip and the other is a self-luminous color on an imagery display can be more difficult than if both are self-luminous.

- Both the color of the Munsell paint chips and of the imagery will vary with the spectral distribution of the illuminant, making it necessary to view both under standard sources.

5.2.1.3 CIE CHROMATICITY SYSTEM

The Munsell color system described in the previous section allows a color to be described in terms of the member of a set of reference colors that provides the best visual match. Another approach is to specify the amounts of three primaries that must be mixed together to provide a visual match. All visual matching techniques for measuring color suffer from the practical difficulty of making such matches routinely. In addition, disagreements arise because observers vary in spectral sensitivity.

Many of these difficulties are eliminated in a color system developed by the International Commission on Illumination (Commission Internationale d'Eclairage, or *CIE*). Known as the CIE *chromaticity system*, it allows use of a physical measurement of the spectral energy distribution in a color to calculate the amounts of three primaries required by a standard observer to obtain a visual match with the color. For convenience in comparing different colors, these amounts are usually expressed in relative units known as chromaticity. The following six figures, 5.2-6 through 5.2-11, describe the development and use of the CIE chromaticity system.

Two standard observers have been defined for the CIE chromaticity system. One, based on a 2-degree color field, was published in 1931 (Ref. 13). It should be used whenever the color field is 4 degrees or smaller (Ref. 14), which will include most imagery display applications. A minimum field size of 0.5 degree has been suggested, but in the absence of directly relevant test data, is only approximate (Ref. 15) (see Section 5.2.4.1). The second, or supplementary CIE standard observer, is based on a 10-degree color field and was published in 1964 (Ref. 13).

The CIE chromaticity system is based on three primaries. There is some recent evidence that, at least for areas larger than 5 to 10 degrees, computations based on four primaries rather than three yield values that are more consistent with subjective color over a range of luminances (Ref. 9).

It is important to remember that in many articles the chromaticity coordinates reported for a particular color are not the result of physical measurement of that color. Instead, they are the chromaticity coordinates of a second color matched visually to the first. In this case, all the variables discussed in Section 5.2.4, plus measurement uncertainty as described in Section 5.2.1.5, may have affected the reported value.

5.2.1.3 CIE CHROMATICITY SYSTEM (CONTINUED)

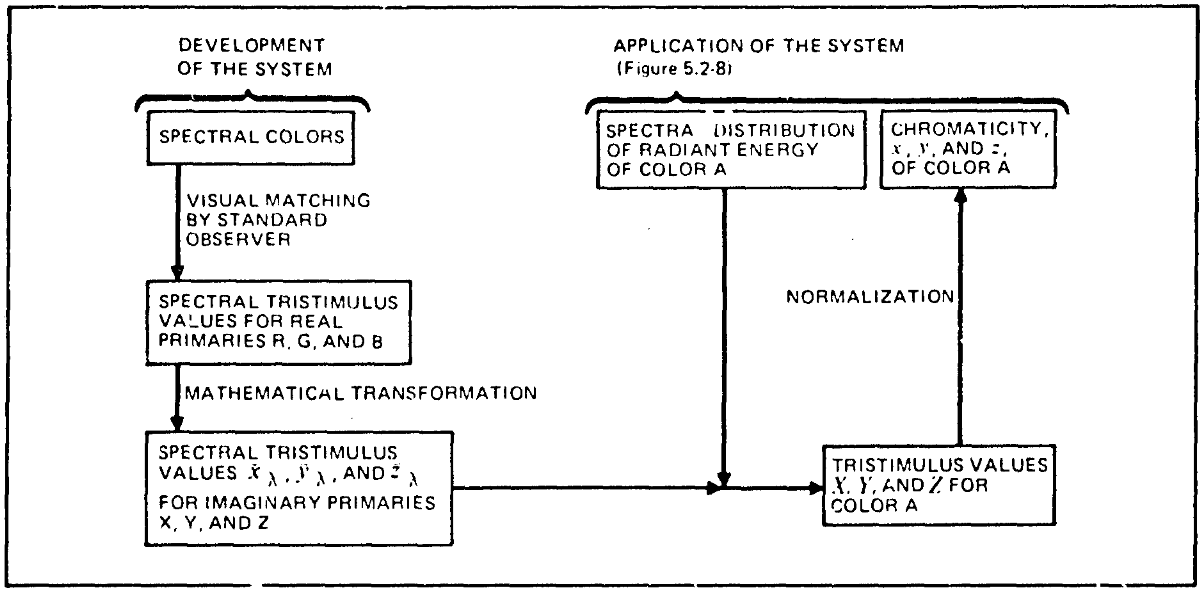


Figure 5.2-6. Development and application of the CIE Chromaticity System (Ref. 16). One way to describe a color quantitatively is to match it visually with a color produced by combining appropriate amounts of three primaries (Figure 5.2-3) and then to list the amount of each primary present. These quantities are known as *tristimulus values* and they are specific to that color and observer and to the set of primaries used. The tristimulus values obtained when the color being matched is spectral, or monochromatic, are known as *spectral tristimulus values*. The CIE chromaticity system is based on spectral tristimulus values measured for the entire range of spectral colors, using several observers with normal color vision.

Most of the spectral tristimulus values used to develop the CIE system were obtained using three monochromatic primaries, red (R), green (G), and blue (B). Any color can be matched using these three primaries, but in some cases, one of the primaries must be added to the color being matched rather than to the other two primaries. To make calculations with the CIE chromaticity system more convenient, these negative values have been eliminated by a mathematical transformation to spectral tristimulus values for three imaginary, or physically impossible primaries, X, Y, and Z (Ref. 17, Figure 5.2-7).

Spectral tristimulus values have the special property that they can be combined with the spectral distribution of radiant energy for a particular color to determine the tristimulus values for that color. This is normally done separately for each of the three primaries by multiplying the amount of radiant energy in the color at each 5, 10, or 20 nm point along the spectrum by the spectral tristimulus value of that primary at that particular wavelength and summing the products. The resulting tristimulus values, X, Y, and Z, are identical to the amounts of the three imaginary primaries, X, Y, and Z that would provide a visual match to the color for the CIE standard observer.

For convenience in comparing different colors, the tristimulus values, X, Y, and Z are usually normalized to obtain relative values, x, y, and z. These are known as chromaticity and are usually presented graphically as in Figure 5.2-9.

Computational details for the CIE chromaticity system are summarized in Figure 5.2-8.

5.2.1.3 CIE CHROMATICITY SYSTEM (CONTINUED)

WAVE-LENGTH(λ) (nm)	$\bar{x}_\lambda$	$\bar{y}_\lambda$	$\bar{z}_\lambda$
380	0.0014	0.0000	0.0065
390	0.0042	0.0001	0.0201
400	0.0143	0.0004	0.0679
410	0.0435	0.0012	0.2074
420	0.1344	0.0040	0.6456
430	0.2839	0.0116	1.3856
440	0.3483	0.0230	1.7471
450	0.3362	0.0380	1.7721
460	0.2908	0.0600	1.6692
470	0.1954	0.0910	1.2876
480	0.0956	0.1390	0.8130
490	0.0320	0.2080	0.4652
500	0.0049	0.3230	0.2720
510	0.0093	0.5030	0.1582
520	0.0633	0.7100	0.0782
530	0.1655	0.8620	0.0422
540	0.2904	0.9540	0.0203
550	0.4334	0.9950	0.0087
560	0.5945	0.9950	0.0039
570	0.7621	0.9520	0.0021
580	0.9163	0.8700	0.0017
590	1.0263	0.7570	0.0011
600	1.0622	0.6310	0.0008
610	1.0026	0.5030	0.0003
620	0.8544	0.3810	0.0002
630	0.6424	0.2650	0.0000
640	0.4479	0.1750	0.0000
650	0.2835	0.1070	0.0000
660	0.1649	0.0610	0.0000
670	0.0874	0.0320	0.0000
680	0.0468	0.0170	0.0000
690	0.0227	0.0082	0.0000
700	0.0114	0.0041	0.0000
710	0.0058	0.0021	0.0000
720	0.0029	0.0010	0.0000

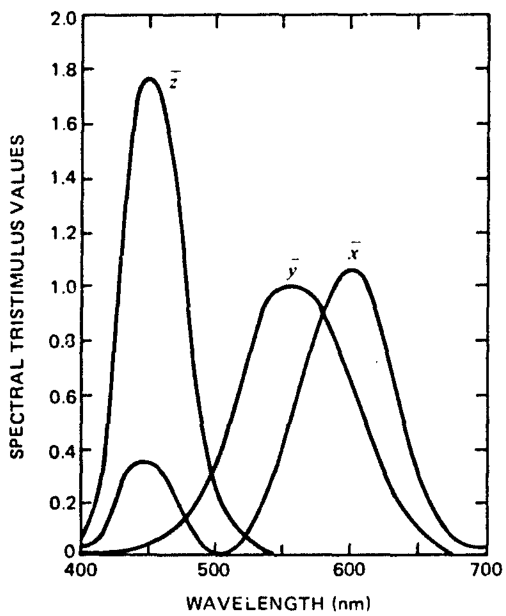


Figure 5.2-7. Spectral Tristimulus Values for the 1931 Standard Observer. Since the CIE primaries, X, Y, and Z, do not exist physically, the easiest way to illustrate them is in terms of the amount of each required to provide a visual match to the spectral colors. These quantities are referred to as *spectral tristimulus values*, or sometimes as *color matching functions.* The spectral tristimulus values for the CIE 1931, 2-degree standard observer are illustrated here. Tables are also included in most texts on color (Ref. 13).

The CIE Y primary was defined so that for the 1931 standard observer it has a spectral tristimulus value that matches the photopic luminosity function of the eye. That is, the curve labeled $\bar{y}$ in this figure is identifical to the solid curve in Figure 3.2-2. As a result, the wavelength-by-wavelength multiplication of spectral radiant transmission by the spectral tristimulus value for the Y primary, $\bar{y}_\lambda$, yields a tristimulus value, *Y*, equal to luminous transmission. If radiant energy is used instead of radiant transmission, *Y* will be equal to luminance. (This conversion is used in Section 6.8.1.3.)

5.2.1.3 CIE CHROMATICITY SYSTEM (CONTINUED)

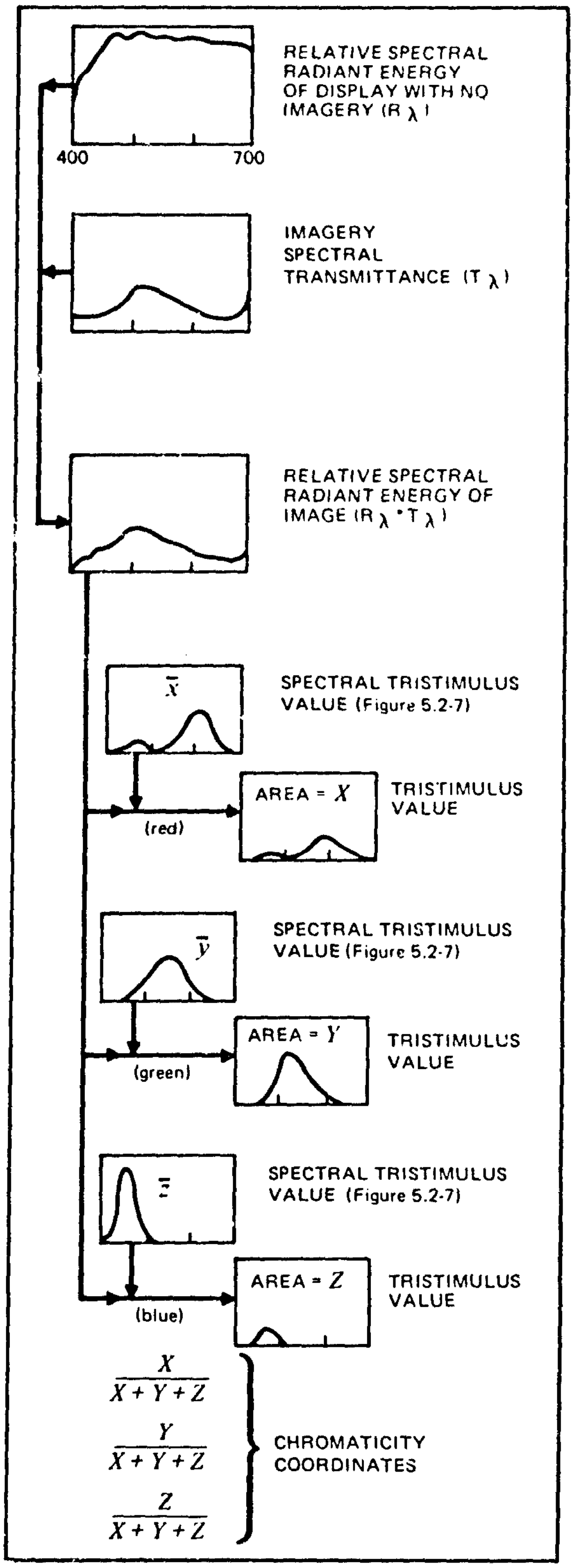


Figure 5.2-8. Calculation of Chromaticity Coordinates. The computational procedures for determining the chromaticity coordinates of a color are summarized here (Ref. 19). Specific details, including the necessary tables of spectral tristimulus values, are available in numerous sources (Ref. 18). Note that tables for the 1931, 2-degree observer are used for color areas smaller than 4 degrees and tables for the 1964, 10-degree observer are used for larger color areas.

The starting point for calculating chromaticity coordinates is the spectral distribution of radiant energy in the color, which can be expressed in either absolute or relative units. In this example, relative values are obtained by multiplying the relative radiant energy of the display (R_λ) by the transmittance of the imagery (T_λ) at each wavelength across the visible spectrum. Each of the three tristimulus values, X, Y, or Z, is then calculated by multiplying the product, $R_\lambda \cdot T_\lambda$, by the corresponding spectral tristimulus value, $\bar{x}_\lambda$, $\bar{y}_\lambda$, or $\bar{z}_\lambda$, and summing over wavelength, λ; this is equivalent to taking the area under the curve in the figure. The summation is usually carried out at wavelength intervals of 5 or 10 nm (Ref. 20). Finally, the tristimulus values X, Y, and Z are normalized, using the equations at the bottom of the figure, so that the resulting chromaticity coordinates, x, y, and z sum to unity.

Since the three chromaticity coordinates, x, y, and z sum to unity, only two are unique. It is common to state only x and y and to plot them on a chromaticity diagram as shown in Figure 5.2-9.

Note that the normalization of X, Y, and Z into x, y, and z eliminates any information about the absolute value of X, Y, and Z. A complete description of a color therefore includes one of these three, usually Y.

5.2.1.3 CIE CHROMATICITY SYSTEM (CONTINUED)

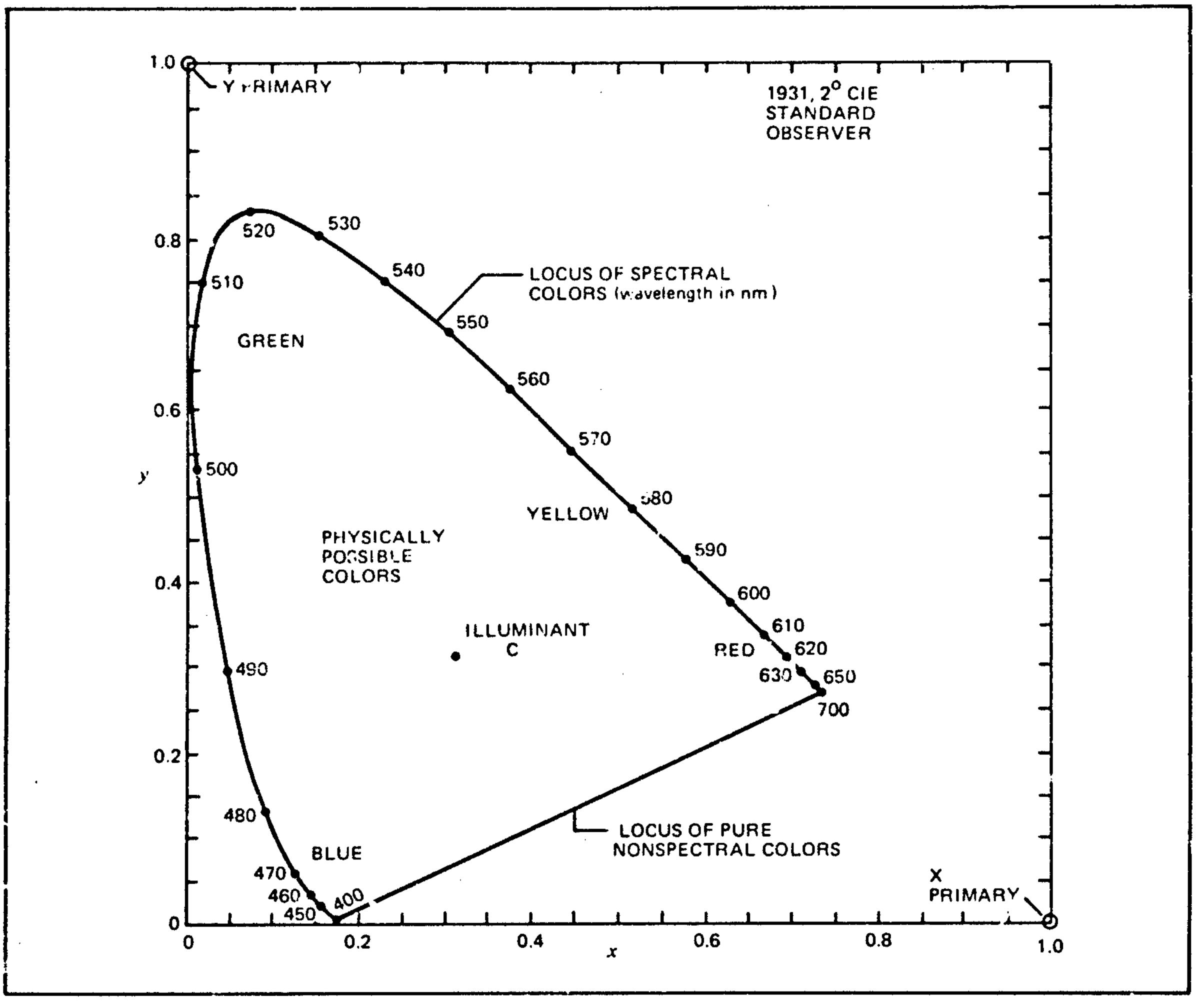


Figure 5.2-9. The CIE Chromaticity Diagram. Because x, y, and z sum to 1, only two of the three must be given to fully describe the chromaticity of a color. Most commonly, x and y are given, plotted as illustrated here on the CIE *chromaticity diagram* (Ref. 21). The redundant z axis is sometimes thought of as projecting vertically up out of the page. The two quantities, x and y, are usually known as *chromaticity coordinates*.

On the chromaticity diagram, the approximately triangular region of physically possible colors is bounded on two sides by the horseshoe-shaped line defined by the chromaticity coordinates of the spectral colors and on the third side by a line connecting the two ends of the horseshoe.

As can be seen, the chromaticity coordinates for the X and Y primaries fall well outside the region of physically possible colors.

Note that the x, y chromaticity diagram is defined by the X, Y, and Z primaries, but that the chromaticity of a particular color is calculated from spectral tristimulus values for a particular standard observer. Hence, a single color will usually have different chromaticity coordinates for the 1931 and 1964 standard observers. Similarly, the color triangle is somewhat different for the two observers. Unless noted, only the 1931, 2-degree observer is used in this handbook.

5.2.1.3 CIE CHROMATICITY SYSTEM (CONTINUED)

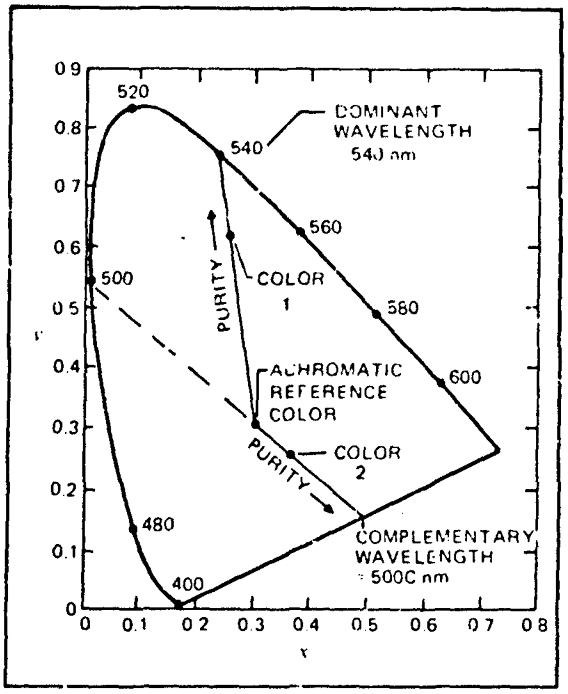


Figure 5.2-10. Dominant Wavelength and Purity. The chromaticity coordinates of a color serve to define two parameters, dominant wavelength and purity, which correspond loosely to the subjective parameters hue and saturation described in Figure 5.2-4. Dominant wavelength and purity are defined, as is illustrated here, in terms of a reference achromatic color (Ref. 22). This is usually one of the standard illuminants, A, B, or C, described in Figure 5.2-13.

The dominant wavelength of a color is determined by the intersection with the spectrum locus of a line passing through the chromaticity coordinates of that color and of the reference color. In this figure, the dominant wavelength of Color 1 is 540 nm. For nonspectral colors, such as Color 2, the line is extended to determine the dominant wavelength of the complementary color, which is usually given as a negative value or followed by a C. Hence, the dominant wavelength of Color 2 is -500 nm, or 500C nm.

Purity is the relative location of a color along the solid line connecting the achromatic reference color to the spectrum or nonspectrum locus. The purity of Color 1 in the figure is about 70 percent, and the purity of Color 2 is about 30 percent.

5.2.1.3 CIE CHROMATICITY SYSTEM (CONTINUED)

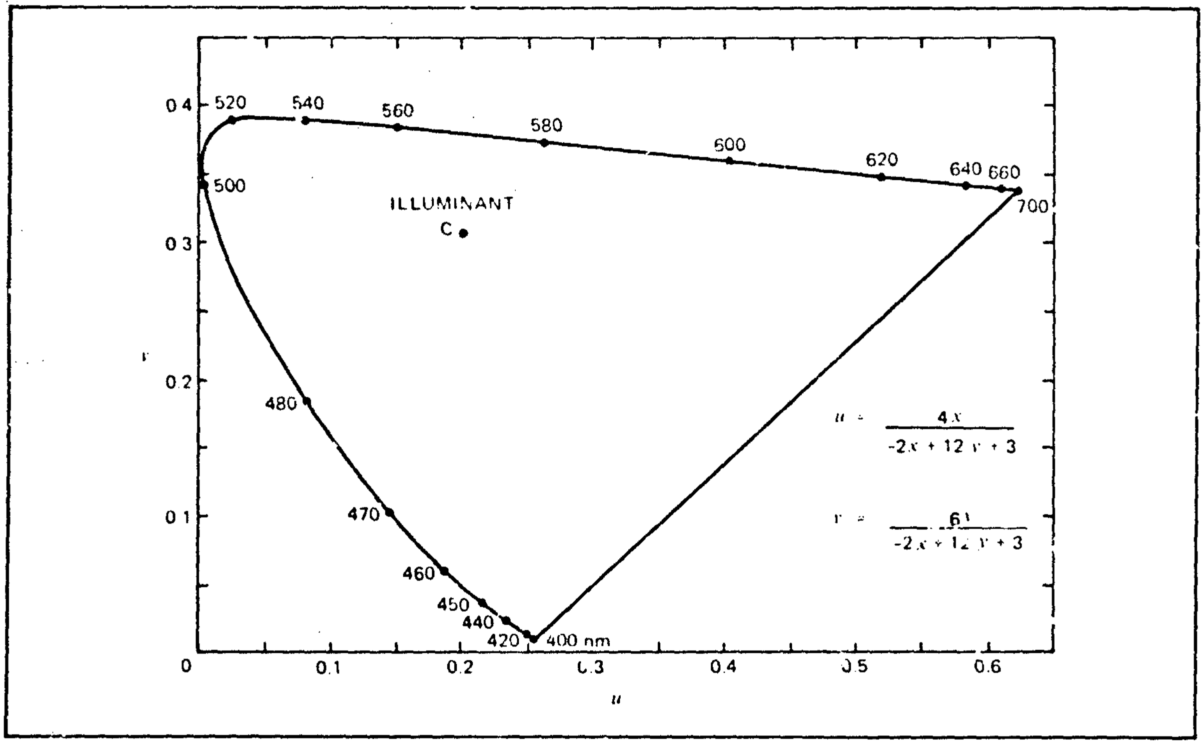


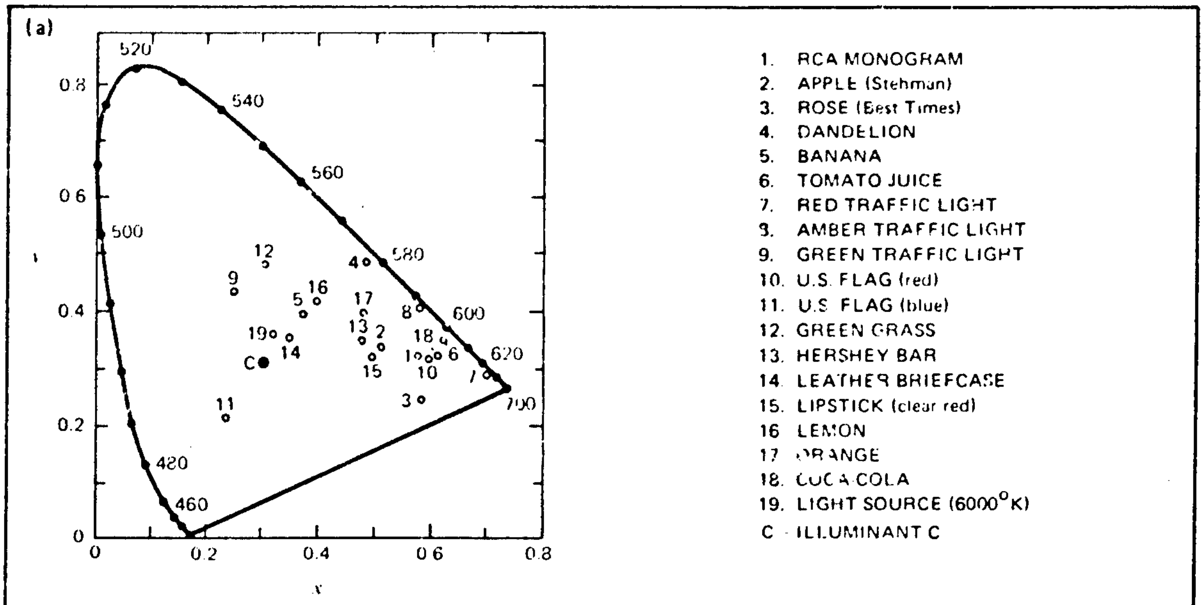
Figure 5.2-11. The 1960 CIE Uniform Chromaticity Spacing (UCS) Diagram. One of the difficulties with the CIE chromaticity diagram, shown in Figure 5.2-10 to illustrate color space, is that the smallest discriminable difference between two colors is much larger in some regions than in others (Figure 5.2-27). For many purposes, such as estimating the contribution of chromaticity to the contrast between a target and its background, a more uniform representation is desirable. Numerous systems have been developed for this purpose (Ref. 23). The one illustrated here was adopted by the CIE in 1960 as the best available compromise between accuracy and simplicity (Ref. 24).

Although the *u*, *v* chromaticity diagram is appreciably nonuniform in some regions, it is apparently as close to uniform as any two-dimensional representation can be, and in view of the relatively large variation in color sensitivity among color-normal individuals, it is sufficient for most situations (Ref. 25).

5.2.1.4 CHROMATICITY OF TYPICAL COLORS

As an aid in understanding the CIE chromaticity system, the chromaticity coordinates of a number of common materials and illuminants are illustrated in this section.

Figure 5.2-12 also illustrates the need to include lightness, or the luminance factor, as part of the description of many colors.



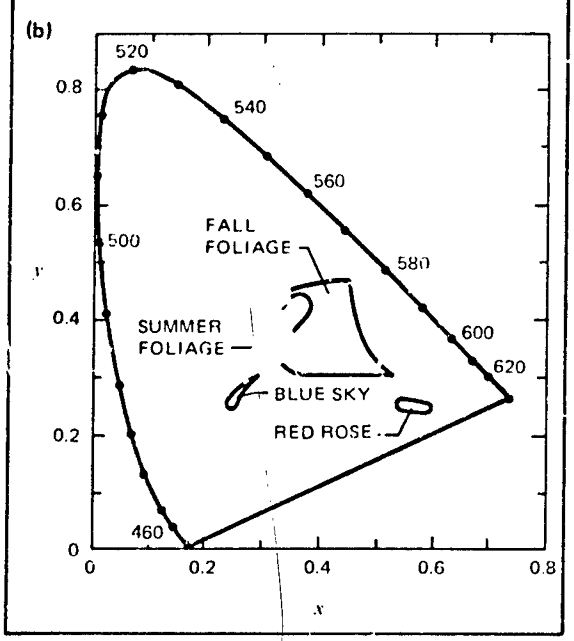


Figure 5.2-12. Chromaticity of Common Materials. The chromaticities of several common materials and illuminants are shown here (Ref. 26,X). Part (b) of the figure also serves to illustrate the variation in chromaticity that occurs from sample to sample. This variation should be kept in mind when using chromaticity values from part (a), or from some other source.

Part (a) of this figure also serves to illustrate how describing colors only in terms of chromaticity, without including luminous reflectance or some comparable quantity, can be misleading. Note, for example, how close the chromaticity of the low-reflectance chocolate bar (13) is to the chromaticity of red lipstick (15). Coca-cola (18) stands in a similar relationship to RCA red (1) and tomato juice (6).

5.2.1.4 CHROMATICITY OF TYPICAL COLORS (CONTINUED)

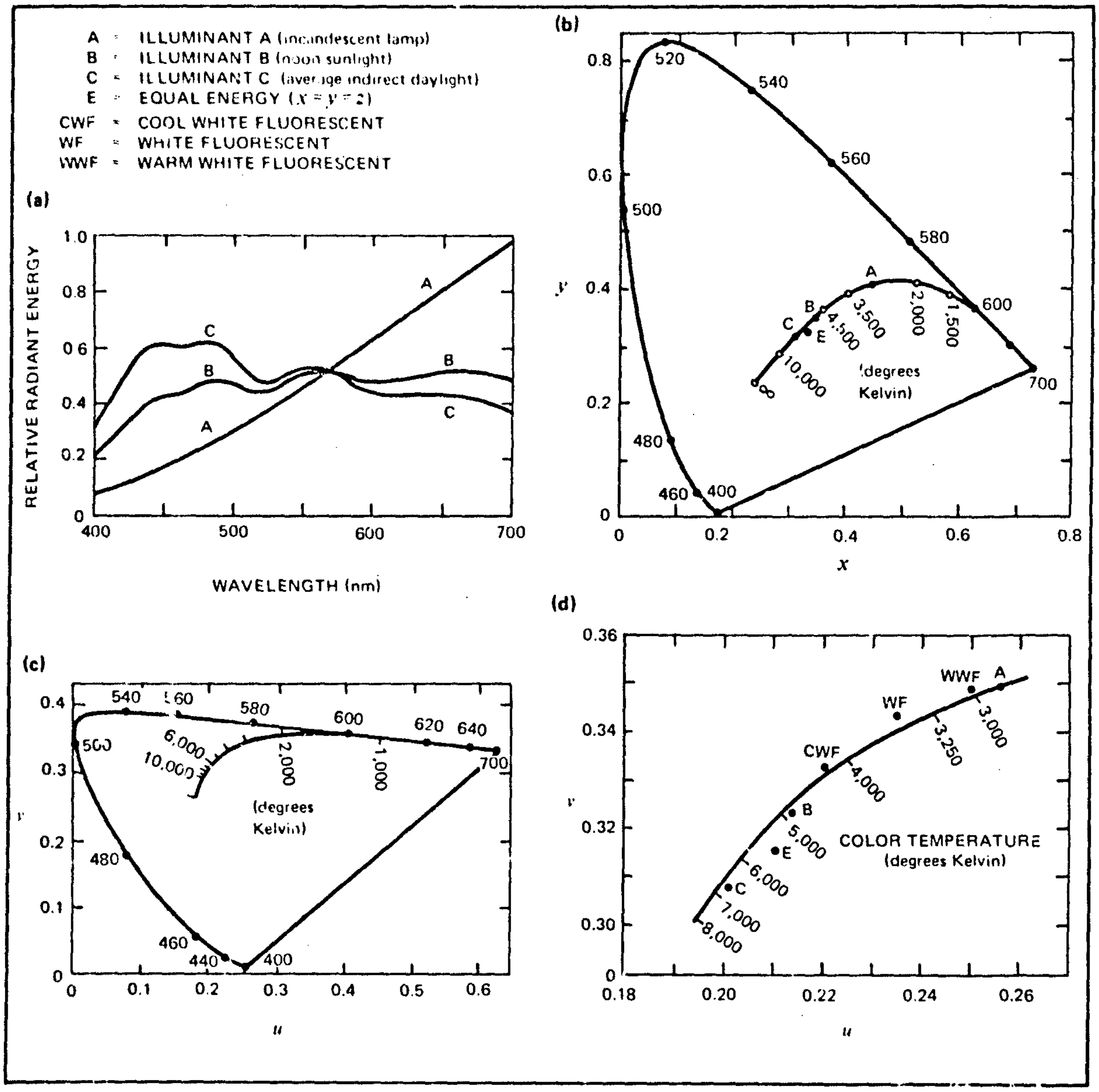


Figure 5.2-13. Chromaticity of Typical Illuminants. This figure illustrates the chromaticity, both x, y and u, v, for the CIE standard illuminants A, B, and C, and for several other common illuminants (Ref. 27). Part (d) of the figure is an enlargement of a portion of (c). The temperature scales are calibrated in *color temperature*, which provides a very accurate method of characterizing incandescent lamps and is useful but only approximate for sources such as fluorescent lamps.

One of the reasons that illuminant chromaticity is important in display design is that it determines the saturation range available for any particular hue in the material being viewed (Figure 5.2-10). For example, (b), (c) and (d) illustrate that illuminant C would provide more room for discriminating different saturations of yellow than would illuminant A.

5.2.1.4 CHROMATICITY OF TYPICAL COLORS (CONTINUED)

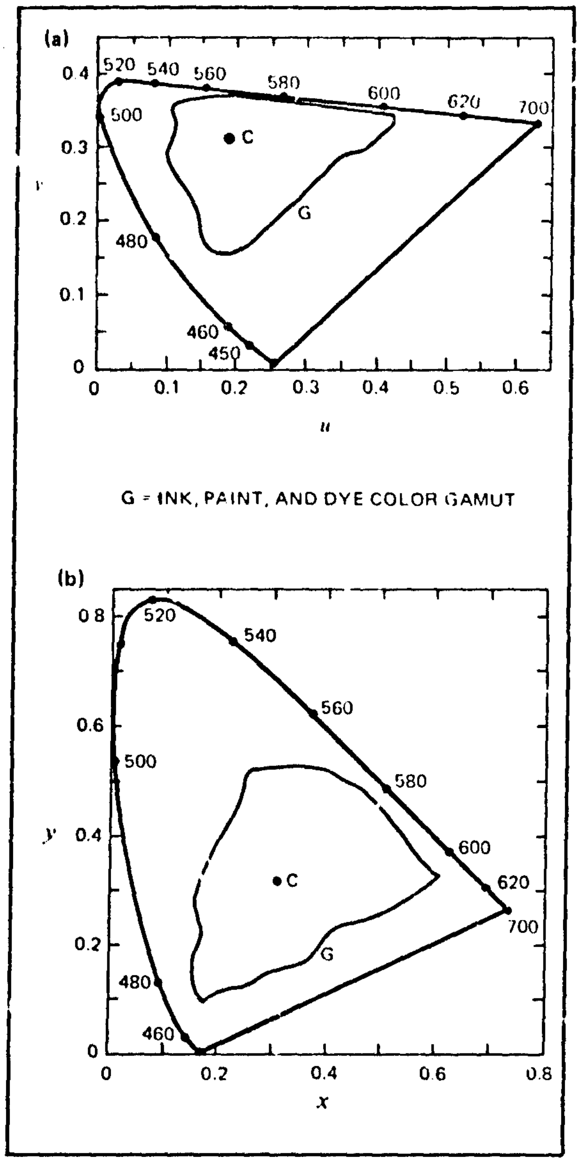


Figure 5.2-14. Surface Color Limits. The range of colors that can be obtained with a particular set of primaries is frequently referred to as a *gamut*. The gamut of surface, or reflective, colors shown here includes all those available with printing inks, plus all those included in three popular color notation systems, the Munsell, the Ostwald, and the Textile Color Card Association (TCCA) (Ref. 28). This figure was published in 1951. It is possible that currently available printing dyes, particularly fluorescent dyes, exceed these limits slightly.

Although available surface colors can match only a portion of the region on the chromaticity diagram bounded by the spectral colors, they include most colors that occur in nature (Figure 5.2-12).

5.2.1.4 CHROMATICITY OF TYPICAL COLORS (CONTINUED)

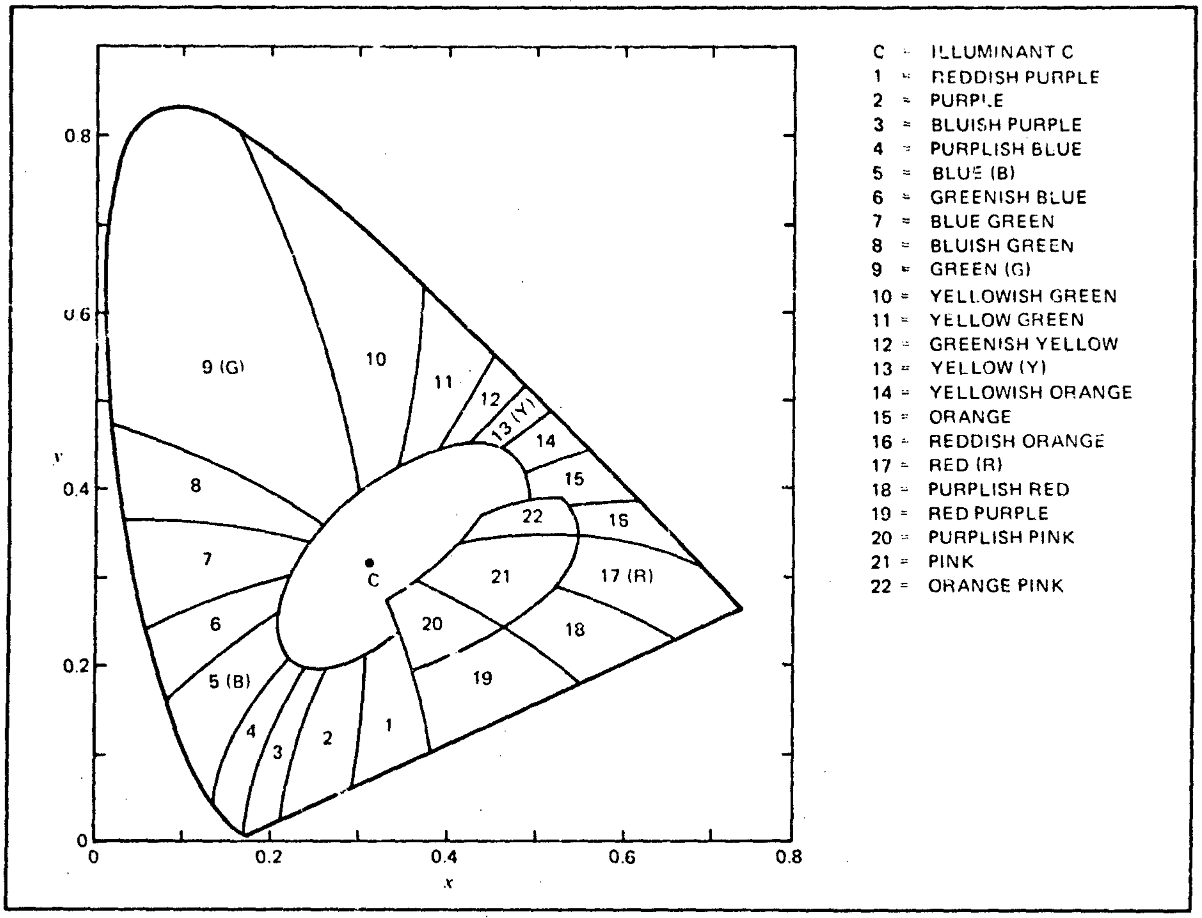


Figure 5.2-15. Color Names for Self-Luminous Surfaces. A set of color names proposed in 1943 for self-luminous surfaces, primarily signal lights, is illustrated here (Ref. 29). Although these names have not evolved into a recognized standard, they provide another useful means of illustrating the appearance of different areas on the chromaticity diagram.

These names apply to high lightness surfaces. A very low lightness surface falling in area 22, for example, would appear brown (see item 13 in part (a) of Figure 5.2-12).

5.2.1.5 COLOR SPACES FOR ELECTRO-OPTICAL DISPLAYS

In most color electro-optical displays, each color is produced by adding together the required amount of three primary colors. At some point in the display system, then, there must be three separate signals one for each of the three primaries.

The designer needs a convenient and easily understood method of specifying these signals and of visualizing the color they will produce in the display. Subjective techniques (Section 5.2.1.2) are inconvenient and imprecise. CIE chromaticity plus luminance is an essential method of describing the color of the display to individuals not working directly with the display; for example, in a scientific report or as part of a contract specification. However, chromaticity plus luminance are not particularly convenient, nor is their relationship to the three display primaries immediately obvious. For this purpose, a color space defined by the three display primaries, as is illustrated in Figure 5.2-16 below, is likely to be the most appropriate.

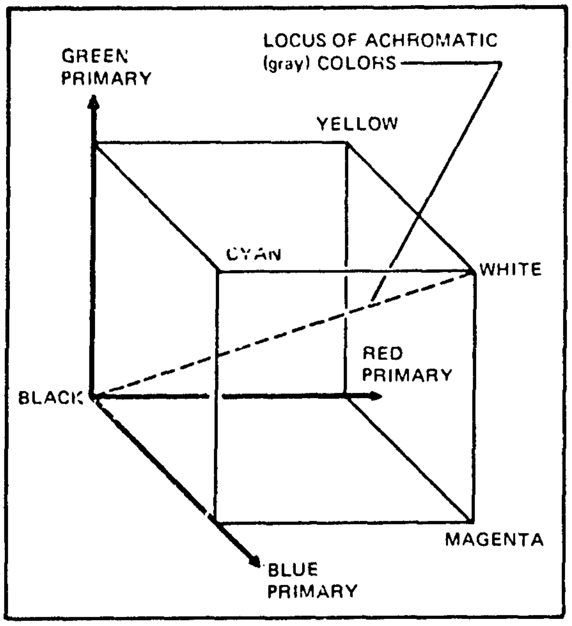


Figure 5.2-16. Three-Dimensional Color Space for an Electro-Optical Display. A color space convenient for use with an electro-optical display is illustrated here. The three arrows represent the quantity of each of the three primary colors present (Ref. 30). These serve to define a three-dimensional color space similar in many ways to those in Sections 5.2.1.2 and 5.2.1.3.

Distance in this color space can be used to represent any one of three distinct quantities:

- The strength of the signal controlling the primary
- The amount of radiant energy produced by each primary
- The perceptual strength of the radiant energy produced by each primary, in a unit such as number of discriminable steps

This color space has an advantage over those in Sections 5.2.1.2 and 5.2.1.3 because it gives the designer a more direct indication of the strength of each of the three primaries. However, it suffers from the fact that it is unique to the particular display or laboratory, making it more difficult to utilize published information on color.

5.2.1.6 METAMERISM

Metameric colors are identical in appearance but different in spectral distribution, while *isomeric* colors are identical both in appearance and spectral distribution. When considering whether two colors are metameric, it is common for appearance to be defined in terms of CIE tristimulus values, X, Y, and Z (Ref. 31). Only if two matching colors are produced by materials having nearly identical physical characteristics are they very likely to be isomeric rather than metameric.

The impact of metamerism depends on the situation. Because surfaces that are metameric with one illuminant spectral distribution are unlikely to match with a different illuminant spectral distribution, it is necessary to exercise strict control over the illuminant. Similarly, individual differences in spectral sensitivity from one observer to the next can result in disagreement about whether two metameric colors match.

Whenever possible, matches should be isomeric rather than metameric. For example, if the colors of targets on color film are to be determined by visual matching against a set of reference colors, then isomerism could be achieved by producing the reference colors on the same kind of color film as is used for the color imagery.

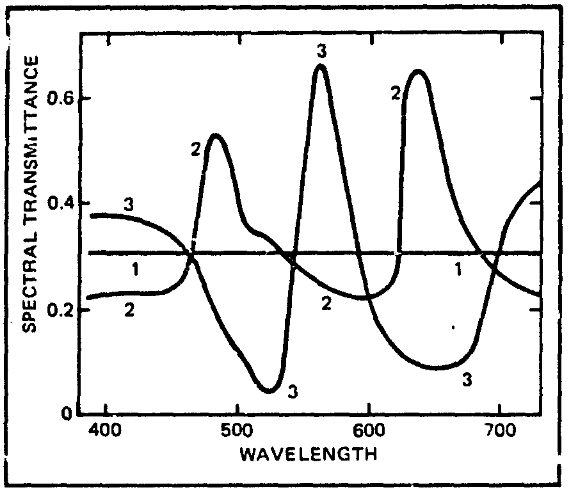


Figure 5.2-17. Metameric Spectral Distributions. This figure illustrates three hypothetical spectral transmittance distributions that are metameric with respect to illuminant C and the 1931 standard observer (Ref. 32). With a different illuminant or observer, these would probably not match. For example, changing to an illuminant with a radiant energy output concentrated at 570 nm would obviously affect the three distributions differently, with the result that they would no longer match.

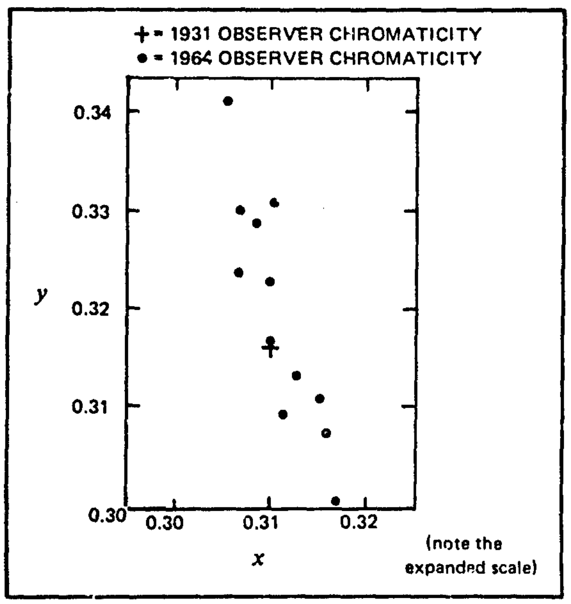


Figure 5.2-18. Metameric Colors As Seen by Different Observers. Colors that are metameric for one observer may not match for a different observer. This is illustrated here for two CIE standard observers, the 1931 observer defined for the appearance of a 2-degree test field, and the 1964 observer based on a 10-degree test field (Ref. 33).

Twelve spectral distributions were computed. All of these appeared, to the 1931 observer, as the color indicated by the cross (+) in the chromaticity diagram. For the 1964 observer these same spectral distributions yielded 12 different colors, indicated by the 12 dots (•).

5.2.2 COLOR VISION TESTING

The information summarized in this section (Ref. 34) leads to the conclusion that there is currently no test available that can be used with confidence to determine whether a particular individual has the color vision skills required to make full use of color in an imagery display. Much of this problem stems from the fact that color vision is not a single skill but is made up of several partially independent dimensions. As a result, an individual who performs well on one test of ability to discriminate differences in color may not perform well on a test designed for the same purpose but constructed differently.

This is not to imply that there are not a number of tests available that can detect gross color defects, and it may be sufficient in some instances that the display must be usable by anyone who passes such a test. However, if the display user must make extremely precise color judgments (Section 5.2.2), then he should probably be selected from the population of potential users on the basis of his ability to make such judgments. The tests described in Section 5.2.2.2 below can be used for this purpose, but the very limited data available for these tests suggests that the improvement over random selection will not be great.

Effective selection of display operators will require a test designed around the specific color discrimination tasks to be performed (Ref. 35). Since it is likely that some individuals are more sensitive than others to the variables described in Section 5.2.4 that interfere with making a color match, such as differences in size of the colored areas and differences in background, the test should include at least some items that incorporate these kinds of differences.

Existing color vision tests fall into two general categories, each of which demands a different kind of ability; for the second category, color discrimination, a somewhat different skill is required for each specific test. The two categories, which are considered in detail in Sections 5.2.2.1 and 5.2.2.2 below, are as follows:

- Color defect, or "color blindness" tests, designed to determine if an individual perceives colors in the same way as an average observer

- Color discrimination tests that measure ability to distinguish between different colors, usually by requiring the subject to order, match, or name a series of color samples

When considering color vision requirements, it is important to note that many individuals with a color defect can make color discriminations just as precisely as color-normal individuals (Ref. 36). Therefore, they may be as suitable as color normals for many image interpretation tasks involving color, especially if the task and display are properly designed. A minimal requirement if they are to perform color matching, for example, is that the reference colors be isomeric relative to the color of the targets (Section 5.2.1.6). Also, they should be required to demonstrate color matching skill with a test based on normal work activities.

5.2.2.1 COLOR DEFECT TESTING

A color-deficient individual is usually defined as one who cannot pass a color defect test. These are tests designed to determine whether an individual perceives colors the same as an average individual perceives them. Color defect tests trace their origin to Lord Rayleigh, who in 1881 showed that a mixture of red light (lithium red, 671 nm) and green light (thallium green, 535 nm) could produce a light which matched yellow (sodium, 585 nm) (Ref. 37). He noted that different observers did not use the same proportions of green and red to obtain yellow. Later, an instrument known as an anomaloscope was developed to determine an individual's "Rayleigh equation." The way people performed on this test could be grouped, and these groupings became the basis for categorizing color defects. That is, people who match yellow with the proportions of red and green that most people use are classified normal. Those who use other proportions, or who can accept a wide range of proportions as a match to yellow, are said to have a color defect. The different categories of color defect and the population incidence within each category are summarized in Figure 5.2-19.

Most color defect tests are limited to assessing perception of the red-green continuum by matching a mixture of these two colors against a yellow standard. However, some recent tests also measure yellow-blue perception (Ref. 38). Defects in yellow-blue perception are extremely rare; according to Figure 5.2-19, they occur in only 0.07 percent of the color defective population.

In general, anomaloscopes are fairly consistent in placing color defectives in the same categories. Although no direct measurements of the reliability with which anomaloscopes discriminate among color normals are known, one report provides data than can be used to obtain an indirect estimate (Ref. 39). The measure used to represent degrees of deviation from normal in the proportion of red and green mixed to make yellow is called the anomaly quotient (AQ). The *reliability* of the AQ for the Nagel anomaloscope was found to be 0.59 for color-normal individuals.

Pseudo-isochromatic chart (PIC) color tests provide a second method of detecting a color defect. The test items in a PIC are made up of dots of various colors that form one pattern for individuals with normal color vision and a different pattern for individuals with a color defect.

Pseudo-isochromatic color tests appear to have been developed as a substitute for anomaloscopes. They can be administered by less-skilled persons, in a shorter time, and with less investment. The earliest test charts of this type were developed by Stilling, of Germany, and somewhat later were improved by Ishihara, of Japan. When these sources were cut off during World War II, a version known as the H-R-R was developed in the United States (Ref. 40). Other tests of this type include the Freeman Illuminant Scale, the Rabkin, the Bostrom, and Dvorine.

Pseudo-isochromatic tests are considered to be measuring color defects properly if they can place a test subject in the same color defect category as the anomaloscope (Ref. 41). Because of the way they are constructed, they also provide some measure of color discrimination ability, but only an approximate indication and only for a very limited range of colors. Even the most similar colors used in pseudo-isochromatic tests differ by 18 National Bureau of Standards (NBS) units, which corresponds to about 9 times the *just noticeable difference* in hue or saturation (Ref. 36). Irregularities in the illumination under which the test charts are viewed or in their location relative to the illumination source can make these differences even larger.

Reliability statistics for pseudo-isochromatic tests are generally low and suggest that except possibly for eliminating individuals with extreme color deficiencies, they are of limited use in selecting individuals for tasks that require good color vision. In the opinion of some users, the Ishahara test is considerably more effective in detecting color defectives than is the H-R-R test (Ref. 42). In some applications it may be most useful to administer both.

5.2.2.1 COLOR DEFECT TESTING

PREFERRED DESIGNATION: BY NUMBER OF COMPONENTS	PREFERRED DESIGNATION: BY TYPE	COLOR DISCRIMINATIONS POSSIBLE *	INCIDENCE IN POPULATION (percent): MALE	INCIDENCE IN POPULATION (percent): FEMALE
TRICHOMATISM (3) (normal or color weak)	NORMAL	L-D, Y-B, R-G	—	—
	PROTANOMALY (red weak)	L-D, Y-B, WEAK R-G	1.0	0.02
	DEUTERANOMALY (green weak)	L-D, Y-B, WEAK R-G	4.9	0.38
DICHROMATISM (2) (partial color blindness)	PROTANOPIA (red blind)	L-D, Y-B	1.0	0.02
	DEUTERANOPIA (green blind)	L-D, Y-B	1.1	0.01
	TRITANOPIA (blue-yellow blind)	L-D, R-G	0.002	0.001
MONOCHROMATISM (1) (total color blindness)	CONGENITAL TOTAL COLOR BLINDNESS (cone blindness)	L-D	0.003	0.002

*L-D = LIGHT-DARK
Y-B = YELLOW-BLUE
R-G = RED-GREEN

Figure 5.2-19. Color Defect Categories. One classification of color defects, or color blindness, is illustrated here, along with congenital (as opposed to acquired) incidence data (Ref. 43,X).

Protanomaly is considered to involve red weakness because more than a normal amount of red light is required to match a yellow standard. Similarly, *deuteranomaly* is considered to involve green weakness because more than a normal amount of green is required.

Monochromats have visual problems in addition to their color defect, such as poor visual acuity (Ref. 44). As a result, they are extremely unlikely to appear in a population required to perform visually difficult tasks.

5.2.2.2 COLOR DISCRIMINATION TESTING

Tests developed to measure color discrimination ability fall into two categories, according to their purpose. Some, such as the Holmgren Wool Sorting Test and the New London Lantern Test, were designed to determine ability to perform a specific task. There are no known color discrimination tests developed specifically for tasks involved in interpreting color imagery. Perhaps the closest approach is the Burnham-Clark Color Memory Test (BCCMT), which was developed as a means of identifying individuals who could judge the quality of color in commercial photographic prints (Ref. 45).

The Burnham-Clark Color Memory Test measures hue discrimination as it is affected by memory. A subject is given 20 test chips, one at a time, whose match he must find from a set of 43 comparison chips arranged in a color wheel. The color wheel is covered so that only one comparison chip appears under an opening view at a time. After viewing a standard chip for 5 seconds, it is covered and a 5-second wait is enforced. The subject then turns the color wheel to select the comparison chip most like the test chip. The test-retest reliability is estimated to be only 0.64 (Ref. 45).

The second category of color discrimination tests consists of general-purpose instruments such as the Farnsworth-Munsell 100 Hue Test (FM100); this test requires the subject to place in order a set of 85 Munsell color chips (Section 5.2.1.2 , taken 20 or more at a time, into a hue series (red to orangish-red to reddish-orange, etc.). Each chip has the same value of lightness (luminous reflectance) and chroma (saturation). Thus, the test ostensibly measures hue discrimination. The test-retest reliability is a moderate 0.82, and with a second retest it drops to a low 0.67. A considerable increase in scores occurs between successive administrations (Ref. 46).

Another general-purpose color discrimination test is the Inter-Society Color Council Color Aptitude Test (ISCC-CAT). Like the FM100, it uses Munsell color chips that are all of the same lightness. This test requires the subject to match a color chip of a given hue to a color patch on a panel containing various colors of that hue which differ in saturation. Thus the test ostensibly measures saturation discrimination. The total-score test-retest reliability of the ISCC-CAT is reported as only 0.53 (Ref. 45). The correlations among the four different subtests (four hues) vary between 0.20 and 0.30 (Ref. 45), which suggests that the subtest scores by themselves are virtually useless. Nevertheless, this test is quite often used in industry, perhaps because it is so difficult for persons tested to achieve high scores.

The correlation among different color discrimination tests is relatively low, indicating that each measures different aspects of color discrimination ability. For example, in one study, the BCCMT correlated only 0.34 with the ISCC-CAT and 0.42 with a lesser known test, the Woods Color Aptitude Test (Ref. 45). In another study, the three color discrimination tests described above, the FM100, the ISCC-CAT, and the BCCMT, plus an anomaloscope, were administered along with tests of cognitive (mental) skills and personality to a group of individuals with normal color vision (Ref. 36). The correlations among the four color tests were very low, and a factor analysis indicated that they shared about as much variance with the cognitive skills and personality tests as with each other.

Although it is not normally used as a color discrimination test, the repeatability of a subject's settings on the anomaloscope provide an indication of his discrimination ability, at least along the red-green dimension, and the blue-yellow if it is tested. A limited amount of this type of data is available (Ref. 36).

5.2.3 DETECTION OF COLORED TARGETS

It is assumed in this section that the chromaticity of target objects and their surroundings differ and that these differences provide chromaticity contrast that adds to the luminance contrast the targets would have in black and white imagery, thereby making them more likely to be found by the display user (see introduction to Section 5.2). The display, therefore, should provide the maximum chromaticity contrast possible from the imagery, and it should provide a viewing situation in which the user is as sensitive as possible to differences in image chromaticity and luminance.

For imagery in the form of film, the only way the designer can affect image chromaticity is by changing illuminant spectral distribution. This topic is covered in Section 3.2.9 and is reviewed briefly here. For electronic imagery, the techniques for changing chromaticity that are available to the designer are considerably different, but the goals are essentially the same.

First, the chromaticity gamut of the displayed image should be made as large as is compatible with achieving the necessary image luminance. The use of an illuminant consisting of three narrow spectral bands centered on the peaks of the three film dye layers will yield the maximum chromaticity gamut (Ref. 47), but the filtering required may reduce the luminous efficiency to an unacceptable level. Whether the improvement in chromaticity gamut over ordinary illuminants, with broader spectral distributions, is of practical significance has not been tested. A good compromise might be a fluorescent lamp with the phosphors selected to concentrate the radiant energy at the desired wavelengths.

Second, a wide range of illuminant chromaticities will appear white (Figure 5.2-13, Section 5.2.4.6), but some may yield better chromaticity contrast than others. As Figure 5.2-10 illustrates, the purity of a color in the displayed image will range from zero, at the chromaticity of the illuminant, to a maximum set by the combination of the illuminant and the spectral transmission of the imagery. When this range, expressed in perceptual units such as those provided by the u, v diagram of Figure 5.2-11, is a maximum, the largest number of chromaticity steps can be discriminated by the display user at that dominant wavelength. Assuming that target and background chromaticities are randomly distributed in the imagery, or that they are not known, then it is most reasonable to choose an illuminant chromaticity near the center of the chromaticity gamut thereby giving all spectral regions an approximately equal number of discriminable steps. However, if colors in some spectral regions are more important, it may be useful to shift the illuminant spectral distribution in this region. (For an example, see Section 5.2.4.7.)

An additional restriction on illuminant spectral distribution is useful if the imagery spectral distribution of important target objects and their typical backgrounds are known. As is discussed in Section 3.2.9, this information can be used to select an illuminant that will yield maximum chromaticity and luminance contrasts.

5.2.4 VISUAL COLOR MATCHING

RECOMMENDATIONS:

Design the color matching viewing situation so that the following features of the target and reference colors are as equivalent as possible:

- **Size of colored area**
- **Luminance of colored area**
- **Luminance of surrounding area**
- **Hue and saturation of surrounding area**

Make both the target and reference colored areas at least 1 degree in size.

Make it easy for the operator to shift his vision between the target and the reference colors. Ideally, provide a split-field viewer so that the two colors can be seen next to each other.

Eliminate highly luminous areas that might affect adaptation; this applies both to the visual field when looking at one of the colors and while shifting from one to the other.

Allow each color to be viewed with both eyes, or at least, by the same eye, instead of presenting the target to one eye and the reference colors to the other.

Control the spectral distribution of the illuminant used for both the target and the reference colors.

To reduce the impact of illuminant spectral distribution and of individual differences in spectral sensitivity (Section 5.2.2), use reference colors on materials with the same spectral characteristics as the target color; in most instances, this means they should be on color film. In particular, because of their different appearance, avoid using reflective colors, such as paint chips to match colors in a film transparency.

Provide a neutral (gray) surround.

Use a high-color-temperature illuminant in order to facilitate discrimination among colors in the yellow region. The preferred value is 7500°K, with a minimum of 5000°K.

It may be necessary to quantify the color of an object seen in an imagery display in order to include the color in a report or as an aid to identification. Color can be quantified using physical measurements or by visual matching against a set of reference colors. This section describes probable sources of error when using the latter method. The potential for color errors because of the normal variations in imagery collection and processing is not considered here.

It is common to report the results of visual color matches in terms of the principal quantitative color designation technique, the CIE chromaticity system; that convention is generally used here. However, there is limited evidence (see Section 5.2.4.3) that this method of presentation can affect the results obtained, or at least the conclusions.

A third option, in addition to physical measurements or color matching, is for the display user to simply assign a name to the color from memory, without reference to any standard color materials. Unless extensive training is provided, the number of colors that can be distinguished consistently in this fashion does not exceed a dozen or so (Ref. 48), and borderline colors will often receive different names from different observers. If this level of precision is adequate, then the size of the color shifts caused by many of the factors described in the remainder of Section 5.2.4 will, by comparison, be insignificant.

5.2.4 VISUAL COLOR MATCHING (CONTINUED)

It is common to think of the color of an area in terms of some function of the spectral distribution of the radiant energy arriving at the eye from that area. While this is usually the predominant factor, color also varies with the following factors:

- The size of the area being viewed; smaller areas generally appear less saturated (Section 5.2.4.1).
- The luminance of the area being viewed; darker areas generally appear less saturated and there is a shift in apparent hue with luminance (Sections 5.2.4.2 and 5.2.4.4).
- The luminance of the surrounding area; changing from a light to a dark surround generally increases the lightness and decreases the saturation (Sections 5.2.4.3 and 5.2.4.4).
- The hue and saturation of the surrounding area; there is a shift in color toward a color complementary to the surround (Section 5.2.4.5).
- Prior visual experience, both in terms of spectral distribution and luminance; because of adaptation, sensitivity to colors previously seen is reduced and sensitivity to complementary colors is enhanced (Section 5.2.4.6).
- Variation among individuals; sensitivity to different regions of the spectrum varies among individuals (Section 5.2.3).
- Expectations; knowledge that an object should have a certain color may influence the results of color matching.

In most cases, the test results summarized in the sections listed above show only the direction and general size of the shift in color caused by a change in a particular parameter, such as surround luminance. They usually do not allow setting quantitative limits on a viewing situation that will ensure that the color shift does not exceed some permissible value.

The topics covered in Sections 3.2.8 and 3.2.9 are also relevant to the problems discussed here.

5.2.4.1 TARGET SIZE

Smaller targets appear less saturated and sometimes appear shifted in hue relative to larger targets. Ability to discriminate between colors is also reduced, particularly along the blue/yellow continuum. If the field is too small, this ability may be lost entirely, a phenomenon known as *small-field tritanopia* (Figure 5.2-19). Some of the reported effects (Ref. 49) are:

- Ability to discriminate blue from yellow was generally lost with field diameters smaller than 20 arc minutes (Ref. 50).
- Starting with a 5 arc minute square field, size increases to 7, 10, and 16 arc minutes each caused successively larger increases in saturation and shifts in hue (Ref. 51). The shifts were generally along the blue/yellow continuum.
- Saturation was increased slightly and there were some shifts in hue as field size increased from 2 to 12 degrees (Figure 5.2-20).
- The 1931 CIE Standard Observer is based on viewing a 2-degree color field. Changes in appearance of the colored area as it increased to 10 degrees led to the establishment of the 1964 CIE Supplementary Standard Observer for 10-degree fields (Ref. 13).

At least part of the variation in perceived color as the colored area increases in size beyond a few degrees is related to the decrease in the density of the color receptors, the cones, and perhaps also to the increase in the density of the rods outside the fovea (Figure 3.5-6).

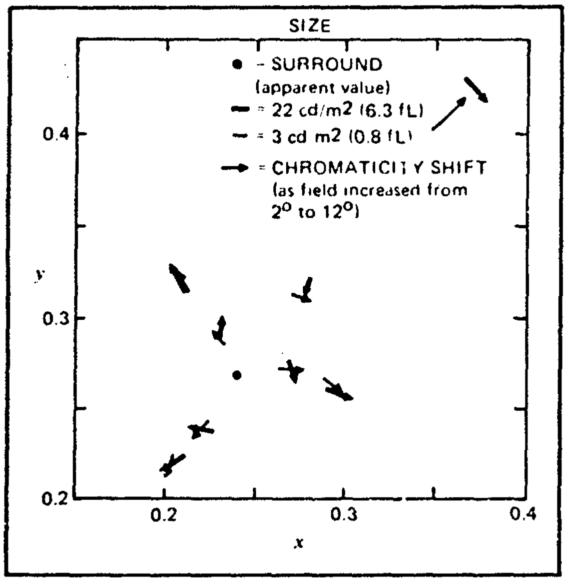


Figure 5.2-20. Impact of Target Size on Color. The arrows in this figure show the shift in apparent chromaticity of a test area as it was increased in size from 2 to 12 degrees (Ref. 52,C). Each arrow is based on 12 settings by each of eight subjects.

Although these shifts show considerable randomness, the tendancy is for the test area to move further from the surround as it becomes larger.

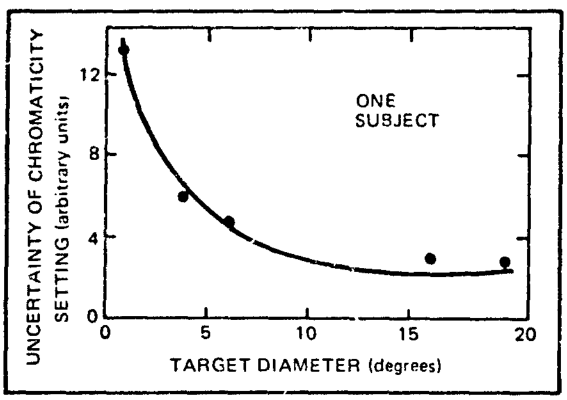


Figure 5.2-21. Impact of Target Size on Matching Precision. As this figure illustrates, chromaticity matching precision is improved considerably by increasing target size (Ref. 53,X). The change is greatest below about 5 degrees.

5.2.4.2 TARGET LUMINANCE

Changes in target luminance cause changes in both the saturation and the hue of the target. Representative data are summarized in the next two figures (Ref. 49).

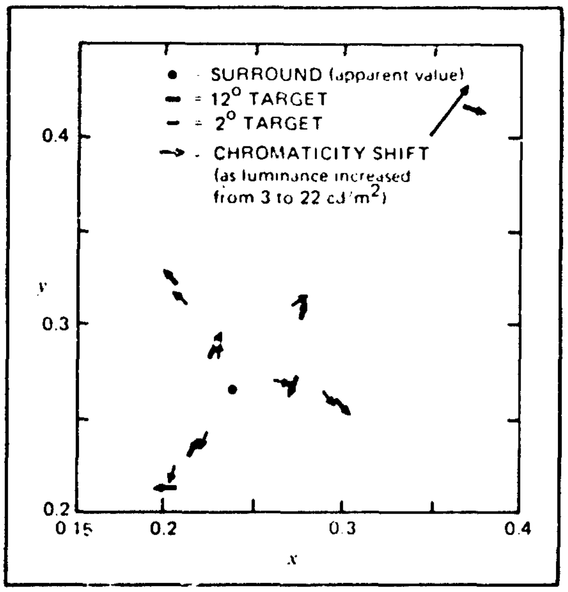


Figure 5.2-22. Impact of Target Luminance on Color. In the study illustrated here, which is from the same source as Figure 5.2-20, increasing target luminance from 3 to 22 cd/m^2 (0.8 to 6.3 fL) caused shifts in both hue and saturation (Ref. 52,C). In many cases the shifts were slightly larger for the smaller targets.

As with the size increase in Figure 5.2-20, the luminance increase tended to cause the apparent chromaticity of the target area to move away from the apparent chromaticity of the surround.

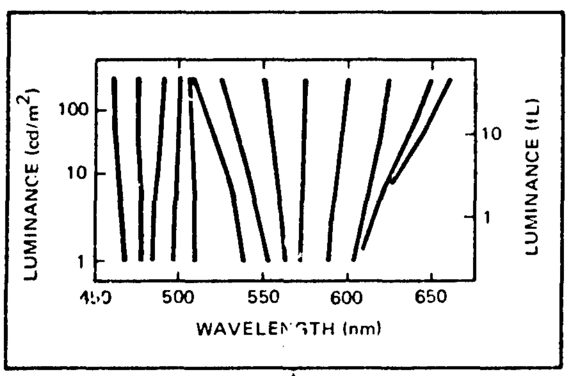


Figure 5.2-23. Impact of Target Luminance on Hue. This figure illustrates wavelengths perceived as having constant hue as the luminance was changed (Ref. 54,C). This is often referred to as the *Bezold-Brücke phenomenon.* It is larger for smaller target sizes (Ref. 55).

(The luminance scale in this figure is a conversion from retinal illuminance, in trolands, and is therefore not exactly logarithmic.)

5.2.4.3 SURROUND LUMINANCE

In several studies, increasing the luminance of the area surrounding a target decreased the brightness and increased the saturation of the target (Figures 5.2-24 and -25 and Ref. 56). In another study, changes in brightness but not in saturation were observed, possibly because color space was quantified perceptually, as in Figure 5.2-5, rather than in terms of apparent location on the chromaticity diagram (Ref. 57,X). Although this evidence is not conclusive, it suggests that the chromaticity diagram must be used with care when describing the result of visual color matching.

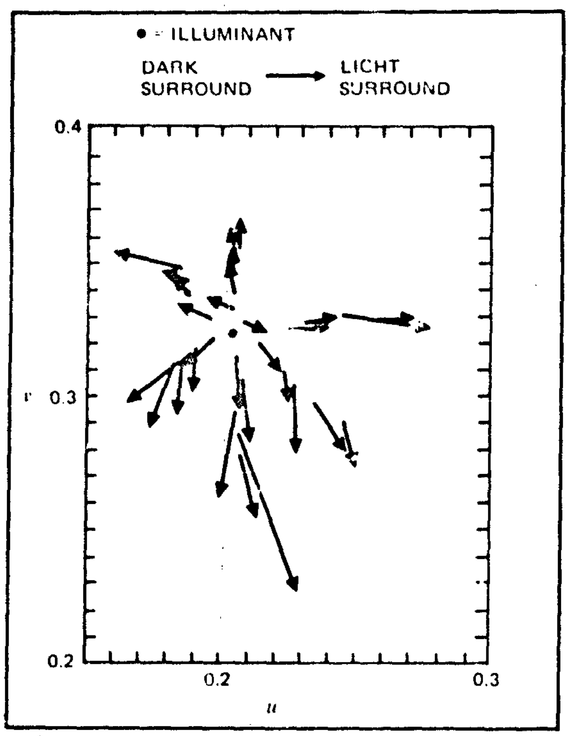


Figure 5.2-24. Impact of Surround Luminance on Color. The arrows in this figure illustrate the change in appearance of 7- by 10-degree targets of constant spectral radiance as the surround changed from extremely dark to 250 cd/m^2 (73 fL) (Ref. 58,B). The arrows are generally pointed directly away from the chromaticity of the illuminant, indicating that the increase in surround luminance caused an increase in saturation but no shift in hue. There was also a considerable decrease in target brightness with increasing surround luminance that is not illustrated here.

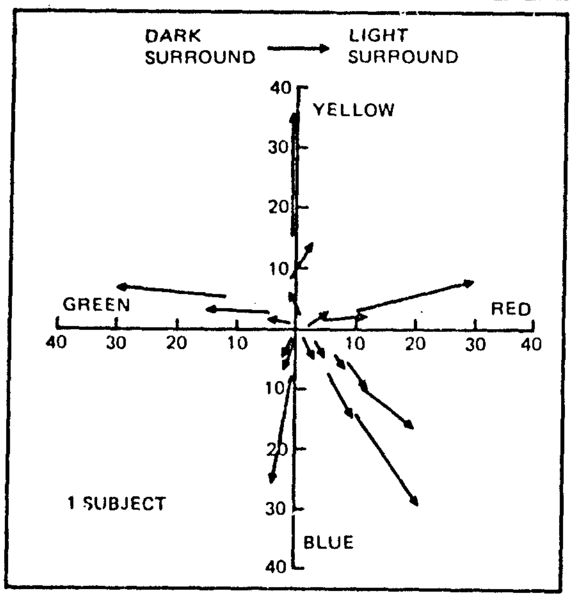


Figure 5.2-25. Impact of Surround Luminance on Judged Color. In another study, the hue and saturation of the targets in Figure 5.2-24 were not determined by matching (Ref. 59,X). Instead, the saturation of each was judged against a mental scale that ranged from 0 for colorless, or gray, to 100 for the maximum saturation the subject could imagine at each hue.

The result of increasing surround luminance was essentially the same as in Figure 5.2-24.

5.2.4.4 TARGET AND SURROUND LUMINANCE

The effect of changing target and surround luminance simultaneously is similar to changing the luminance of either one individually. As the next figure shows, it causes large changes in chromaticity and some shift in hue.

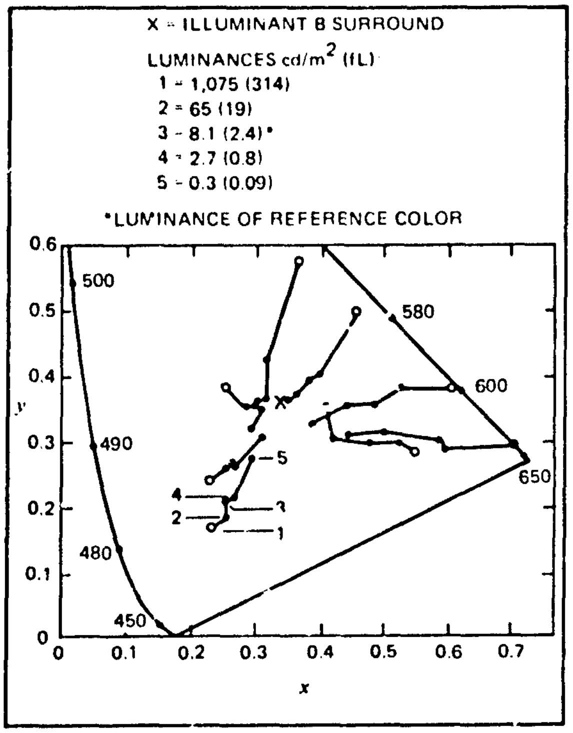


Figure 5.2-26. Impact of Target and Surround Luminance on Judged Color. In this study, the 1-degree-diameter test color was viewed against an equiluminous neutral surround provided by illuminant B, and the luminance was set to one of the five values listed (Ref. 60,C). For each test scene luminance, the chromaticity of a 1-degree-diameter reference color viewed against an illuminant B surround with a fixed luminance of 8.1 cd/m² (2.4 fL) was adjusted to match the test color. The single test subject viewed the test field with one eye and the reference field with the other in order to eliminate adaptation effects. The resulting measurements show that each decrease in the luminance of the test target and its surround caused it to appear less saturated or, particularly at low saturations, to shift in hue.

The experiment described here is similar to the situation a display user will face, in that the luminance of the unknown color and its surround will change together. However, because he will be looking back and forth between the unknown and the reference, he will probably adjust them to be much more equal in luminance than most of the test conditions used here, with a corresponding reduction in the chromaticity shift.

5.2.4.5 SURROUND HUE AND SATURATION

Almost every text that treats the perceptual or artistic aspects of color includes a discussion, and often a demonstration, of how the color of a small target is shifted by the saturation and hue of the surrounding color, generally toward the complement of the surround. There has been some effort toward quantifying this effect (Ref. 61).

5.2.4.6 ADAPTATION

To a large extent, the visual system responds to change rather than to steady-state conditions. Hence, if a uniform, moderately saturated surface fills the visual field, the saturation of the initially perceived hue will decrease and the surface will eventually be seen as achromatic. This phenomenon, known as *adaptation*, involves reduced sensitivity for colors with hues similar to the one being viewed, which makes them appear less saturated. It also involves increased sensitivity for colors of complementary hue, which makes the latter appear more saturated.

Adaptation also occurs when viewing a nonuniform surface, but because the eye is almost constantly moving, the effect of adaptation is usually noticed only when an afterimage is produced by a particularly intense source or after deliberately staring at one point for a period of time.

Adaptation is also a primary reason why subjective colors tend to remain relatively constant over wide changes in illuminant color and, hence, in physically measured color.

For most situations an illuminant should not appear to have any hue. Terms typically applied to this condition are achromatic, neutral, gray, and, if the luminance is sufficient, *white*. The viewing situation has a major effect on the range of spectral distributions that will appear achromatic, with the result that authors have written at length on the questions, "What is white?" (Ref. 62). Because of color adaptation, a wide range of different spectral distributions will appear white if only one is present in the visual field. Typical examples are warm white and cool white fluorescent lamps (Figure 5.2-13), both of which are generally considered white. However, when viewed side by side, the warm white lamp will appear slightly orange pink, and the cool white lamp slightly blue. Either by itself would generally be acceptable for making many kinds of color judgments (however, see Sections 5.2.4.7 and 5.2.1.6), but using one to illuminate the reference colors and the other to illuminate the unknown would likely result in a significant error in the color match.

Although adaptation to hue and saturation is generally more important when making color matches, the visual system also adapts to luminance (Section 3.2) and even to certain image details such as the spatial frequency of a grating (Ref. 63).

Adaptation occurs only in the eye being stimulated. One way of demonstrating this is to place complementary color filters, such as red and green, over the two eyes for a period of time. After removing the filters, striking differences in the sensitivity of the two eyes to different colors can be seen by alternately opening one eye and then the other. A simpler though less impressive demonstration results from covering one eye and exposing the other to a bright surface for a period of time.

The fact that adaptation occurs only in the eye receiving the light is useful in experimental situations. For example, to measure the impact of luminance on apparent chromaticity, the test subject matches a high luminance color seen by one eye against a low luminance color seen by the other. Figure 5.2-26 illustrates a typical study. This technique, of one color to each eye, is not appropriate when the goal is to quantify a color seen in an imagery display.

Several restrictions can help eliminate adaptation as a source of error in color matching. First, both eyes, or the same eye if only one eye can be used, should view both the target and the reference color. Second, to ensure that the visual scene experienced during the transition between the target and the reference color display does not affect adaptation and possibly influence the match, it should have low luminance and it should be achromatic.

5.2.4.7 ILLUMINANT SPECTRAL DISTRIBUTION

Unlike the topics in the other parts of Section 5.2.4, which only affect perceived or subjective color, a change in illuminant spectral distribution can also change physically measured color. Whether this change introduces any error into the color match depends on the spectral characteristics of the colored materials being matched.

The simplest situation occurs when the target and the reference colors are on the same material, such as a particular kind of color film. Then, if both are illuminated by the same source, changes in the illuminant spectral distribution will cause the same color change in both. As a result, the designer has more freedom to use an illuminant with a spectral distribution selected to provide other benefits, such as maximum separation among the colors of interest. (See the discussion of the color contrast discrimination index in Section 3.2.9).

If the target and reference colors are on different materials, then colors that match visually are almost certain to be *metameric* (Section 5.2.1.6) and each must be provided with the proper illuminant spectral distribution in order to obtain valid results. For example, Munsell color chips are designed for viewing under *illuminant C*, and an illuminant with any other spectral distribution will shift the color of each chip. It is unlikely that identical shifts would occur in as dissimilar a material as color film.

There is as yet no standard for illumination of color imagery when the goal is to determine the color of an area on the imagery by visual matching. The closest thing to a standard that exists is the American National Standards Institute (ANSI) standard for viewing color transparencies, which specifies an illuminant with a *color rendering index* of 90 and a correlated *color temperature* of 5000°K (Ref. 64). Although the specific basis for these values is not given in the standard, they are apparently intended to ensure that amateur and commercial snapshots will have a pleasant appearance. Another ANSI standard intended for appraising color quality and uniformity in graphic arts materials may be more relevant (Ref. 65). It requires a 5000°K illuminant for comparing original artwork against first proof prints, but requires a much bluer light, with a color temperature of 7500°K, in order to enhance discrimination of the yellow ink when final production prints are being compared with approved samples. Figure 5.2-13 illustrates how higher color temperature illuminants provide more color space in which to discriminate among different yellows.

An illuminant used to display color imagery in order to make color matches should meet several criteria:

- Lamps, and filters if required, should be readily available commercially.
- Consistency among units should be sufficient that the user would not need to make spectral output measurements on each new lamp.
- Output intensity should be sufficient to provide the desired image luminance with standard displays (see Sections 3.2.6 and 3.2.8).
- Color temperature should be at least 5000°K, with a preferred value of 7500°K, in order to provide good discriminations of colors in the yellow region.
- It should provide maximum discriminability between colors in the imagery, possibly by concentrating the energy into three narrow bands centered on the transmission peaks for the three dye layers in the color imagery (see Section 5.2.3). A high color rendering index (Section 3.2.9) is an alternative, though not a good one, to selecting an illuminant on the basis of discriminability.

5.2.4.8 COLOR MATCHING PRECISION

Any color matching situation involves a certain amount of error. The MacAdam ellipses covered in Figure 5.2-27 provide one estimate of the minimum error achievable under ideal conditions. Any applied situation is bound to be less than ideal and to cause a corresponding increase in measurement error. Whether this is significant will depend on the importance of the color information and on the amount of error introduced in other stages, such as the processing of the film or the several stages of signal processing in an electro-optical display.

These ellipses provide a good estimate of the minimum size chromaticity matching errors to be expected, and of how large a chromaticity difference is needed to provide a discriminable step in a pseudocolor display (Section 5.2.5). However, they must be used with caution. Among other limitations, they are based on a single observer. While some observers are quite similar, others differ widely (Ref. 66). MacAdam, in fact, has suggested that it is generally inappropriate to average responses from different observers (Ref. 67).

When using the data in Figure 5.2-27 below, it is important to remember that they apply only to chromaticity. Similar data are available for application where it is desirable to add the third color dimension, luminance (Ref. 68). In addition, an excellent summary of the data in this area published prior to 1967 is available (Ref. 69), and several other studies have recently been published (Ref. 70).

5.2.4.8 COLOR MATCHING PRECISION (CONTINUED)

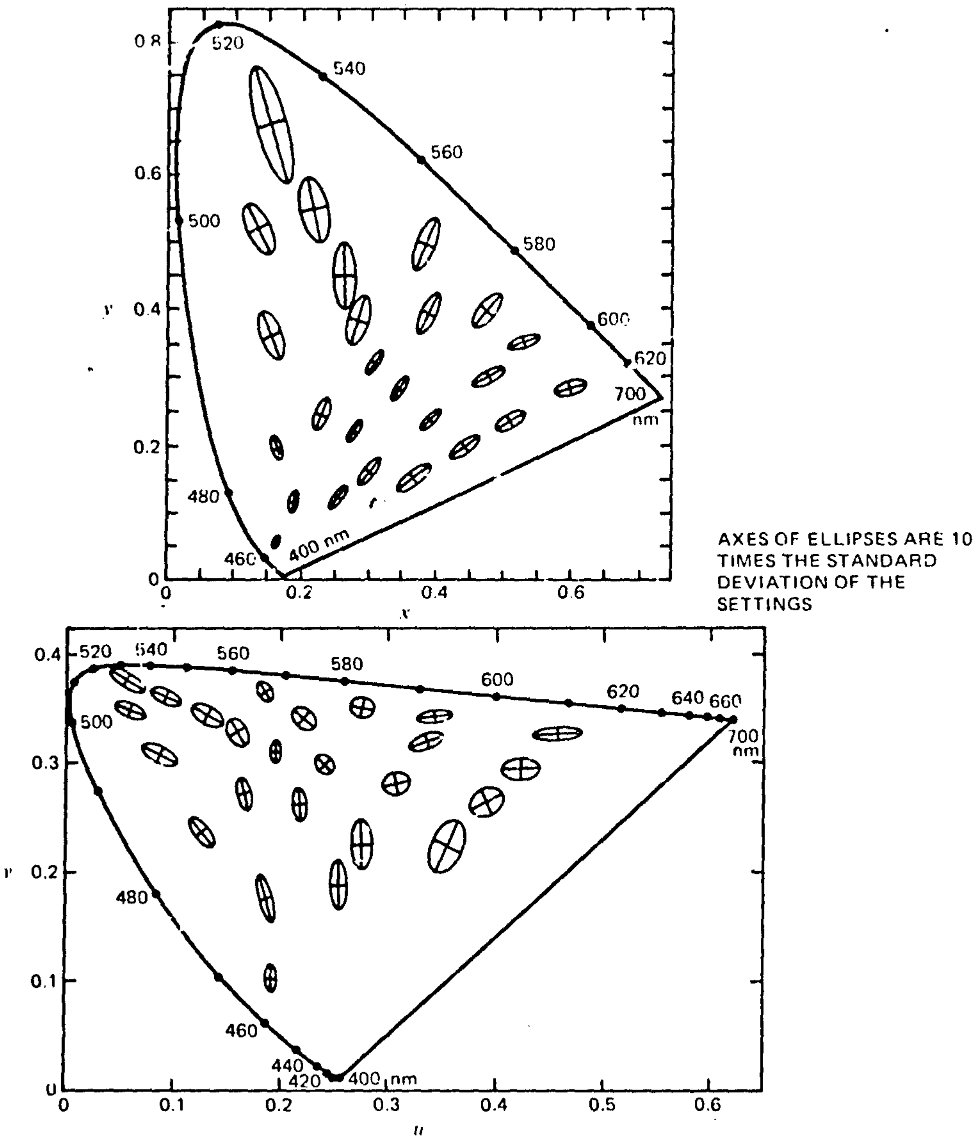


Figure 5.2-27. Chromaticity Matching Under Ideal Conditions. The ellipses in these two figures, known as the MacAdam ellipses, illustrate the adjustment precision possible when chromaticity matches are made by a single observer under ideal conditions (Ref. 71,B). The split field containing the two colors to be matched was 2 degrees in diameter and had a luminance of 50 cd/m^2 (15 fL). It was surrounded by a 21-degree illuminant C field at half this luminance. The axes of the ellipses are 10 times the *standard deviations* of the settings made.

MacAdam has estimated that the threshold, or minimum detectable chromaticity difference, is three times the standard deviations (Ref. 72).

The reduction in the range of ellipse sizes when they are plotted in the *u, v* as opposed to the *x, y* chromaticity diagram illustrates the considerable improvement in color space uniformity the former provides. (However, see the discussion with Figure 5.2-11.)

5.2.5 PSEUDOCOLOR

Pseudocolor is the use of variations in hue and saturation to display information not normally experienced as color, such as radar signal strength or the shades of gray in achromatic imagery. Pseudocolor provides one means of displaying more signal strength levels than would be discriminable on an achromatic, or black and white, display. The number of physically discriminable signal strengths is, of course, a function of the *signal-to-noise ratio* and *dynamic range* of the sensor system (Sections 4.3.3 and 4.3.4).

Various estimates have been made of the number of discriminable elements in chromatic as opposed to achromatic color space. For example, it has been suggested that several million combinations of luminance, hue, and saturation can be distinguished, while only a few hundred levels of luminance may be available in a practical display situation (Ref. 73; also see Figure 4.4-19.)

Although the practical limits on chromatic displays make the effective gain in discriminable levels less than this, there is no question that pseudocolor can be used to increase the number of signal levels that can be discriminated by the display user. If the user's only concern is in determining signal strength, for example in a narrow wavelength-band image of the sun, then pseudocolor is probably useful and should be relatively easy to implement. For more common imagery interpretation tasks such as search and target identification, there are restraints on the effective use of pseudocolor which can make design of an effective display very difficult.

Although pseudocolor displays are a perennial topic in electro-optical trade journals (Ref. 74), the only known published information on their usefulness consists of demonstration photos rather than user performance test data. As a result, the discussion in this section is limited to general concepts.

The increase in number of discriminable signal strengths with pseudocolor display is not without penalties in other dimensions. Visual acuity is generally lower when the target and background differ only in hue and saturation and not in luminance (Ref. 75). Whether this increase in size of the smallest visible target when the target is defined only by hue and saturation differences is significant depends on how important it is to see small details. In general, it means that the designer must allow for an increase in display magnification and a corresponding reduction in the ground area visible at any one time. It should be noted that luminance differences are very difficult to eliminate in this kind of test situation and may have contributed to misleading results in some experiments.

Without the object size limitation mentioned, there is no question that for an object yielding one signal strength, surrounded by a uniform background at a single slightly different signal strength, more signal strength differences will be discriminable if signal strength is encoded with hue and saturation as well as luminance.

Unfortunately, for most real objects a range of signal strengths is obtained across the object and another range is obtained across the background. If these are displayed as different luminances, they present no problem because luminance is a single dimension, easily interpreted by the visual system as such, and because single objects typically include a range of luminances. As a result, an aircraft wing is seen as a single object, even though the luminance ratio along the length of the wing may be several times as large as the luminance ratio between the wing and the background.

When hue and saturation are added, the visual system must contend with three dimensions rather than only one, and there is no assurance that the signal level gradient along the wing will be interpreted correctly. In particular, if the assignment of color to signal level is such that the wing appears in several distinctly different colors and the background also appears in several distinctly different colors, then the observer may be less able to perceive the wing as a single object. As a result, the wing may be less visible than when it was displayed achromatically, even though the effective contrast of the edge of the wing to the background has been increased. This problem is likely to be more severe in the presence of quantization effects in digital electro-optical systems than in analog systems.

To avoid this problem, a basic requirement imposed on the relationship between signal strength and color for a pseudocolor display is that when any two colors, either representing adjacent or widely separated signal strengths, are compared, it should be immediately obvious which represents the higher and which the lower signal. (This idea is also treated in Figure 5.2-28 below). Ideally, this goal should be reached for observers

5.2.5 PSEUDOCOLOR (CONTINUED)

unfamiliar with the color encoding scheme used; in practice, a certain amount of training may be both necessary and acceptable.

In a loose sense, the difference between a pseudocolor and an achromatic display can be likened to the difference between a topographic map and a shaded relief map. There is no question that the topographic map provides more detail, nor that it can be interpreted successfully by an experienced user. However, for most users, the shaded relief map makes general contours more immediately obvious.

Color space for pseudocolor displays is discussed briefly in Section 5.2.1.5.

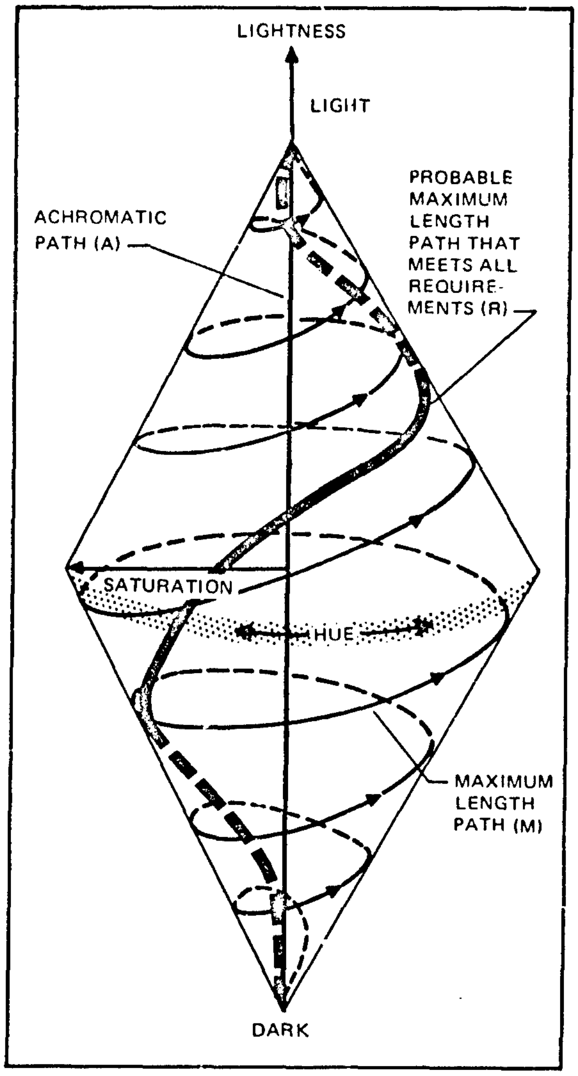


Figure 5.2-28. Pseudocolor Display Color Mapping. A pseudocolor display generally involves the mapping of a one-dimensional parameter into a three-dimensional color space. The three color dimensions can be the perceptual dimensions brightness (lightness), hue, and saturation—illustrated here as a double cone—or their approximate physical equivalents, luminance, dominant wavelength, and purity. Alternatively, the mapping can be carried out in the color space defined by three primaries, as in Figure 5.2-16, or in the color space defined by the CIE chromaticity coordinates, x and y and luminance, Y (Section 5.2.1.3).

Two requirements should be imposed on this mapping. First, it should include as many visually discriminable steps as possible within the dynamic range of the display (see Section 5.2.4.8). Second, the relative value of different signal strengths should be obvious to an observer with normal vision and minimal training. This applies both to adjacent and to widely separated signal strengths. For example, a spiral path that makes several revolutions through the available hues in passing from dark to light, such as path M in the illustration, might yield the maximum number of discriminable steps, each of which stands in an obvious greater or lesser relationship to its immediate neighbor. However, the relative value of two widely separated signal levels that differed in hue would probably not be obvious, making path M a poor choice. The longest path that would meet all these requirements might be something like R in the illustration. One approach to determining path R is a computer-generated random walk through the color space. The rules to impose on such an approach must be chosen with care.

The simplest path, of course, would be A, which follows the achromatic portion of the color space.

5.2.6 IMAGE DISPLACEMENT DUE TO COLOR

CAUTION:

Under some viewing conditions, colored details in the image can appear displaced from their true location. Variations in display interpupillary distance (IPD) adjustment can have a large effect on the amount and direction of the displacement.

Under certain conditions, strongly colored details in an image will be seen displaced laterally from their true locations. This effect is most easily seen with highly saturated colors that have dominant wavelengths near the ends of the visual spectrum, such as red and blue.

Although this phenomenon has been measured a number of times (Ref. 76), the mechanism involved is not yet fully understood. It is certainly related to the large *chromatic aberration* of the eye. As Figure 3.4-4 illustrates, the refractive power of the eye is more than 2.5 diopters greater at 400 nm (blue) than at 700 nm (red); the difference is 1 diopter over a range of 470 to 630 nm, which is easily obtainable with Wratten filters and is sometimes used in experiments on this phenomenon (Ref. 77).

The rest of the explanation varies from author to author. For example, the eye pupil is normally not quite centered and it can be shown experimentally with the eye (Ref. 78) or by ray tracing through an optical system with chromatic aberration that a decentered pupil will cause light of different wavelengths to arrive at different locations on the retina. Other explanations, which may be equally valid so long as the natural eye pupil is being used, involve the fact that the visual and optical axes of the eye differ by several degrees (Figure 3.1-1), and this may have a direct impact or it may serve to effectively decenter the eye pupil (Ref. 79).

When the lateral displacement of an image is large enough, it can be observed with only one eye. It is easier, however, to use a binocular viewing situation where the displacement is in opposite directions in the two eyes and is therefore perceived as a difference in depth. The usual measurement procedure is to have the subject move a vertical bar of one color closer or farther away until it appears to be at the same distance as a bar of a different color. Any constant error is taken as the total lateral displacement due to color in the two eyes and is known as the color stereoscopic effect, or more recently, as *chromostereopsis.*

There is considerable variation among individuals in chromostereopsis while viewing with the natural eye pupil, some reporting that red is nearer and others that blue is nearer (Ref. 80). In one study, 61 subjects yielded responses that were approximately *normally distributed* around a mean of zero chromostereopsis (Ref. 81). The direction of chromostereopsis for a single individual can reverse with a large change in size of the natural pupil, such as would occur with a large change in scene luminance (Ref. 82,B). Because of these variations, it is impossible to predict with certainty whether red near or blue near responses will predominate in any particular situation.

The amount of chromostereopsis when using the natural pupil can be quite large. In one study, the lateral displacement for a red (650 nm) target relative to a blue (450 nm) target was about 2 arc minutes for each of four subjects (Ref. 79,C). Two saw red nearer and the other two saw blue nearer. Other studies have reported much smaller values (Ref. 83). The available data are not adequate to provide a good estimate of the distribution of chromostereopsis in the population.

Chromostereopsis can be especially troublesome in binocular displays with small exit pupils, such as a typical microscope. The amount of image displacement due to color increases rapidly as a small artificial pupil is moved away from the center of the eye pupil, as would occur if the interpupillary distance of such a display was not properly adjusted. Typical values, expressed in arc minutes of lateral displacement per millimeter of movement of the artificial pupil across the eye pupil, are as follows:

- 4 to 5.5 arc minutes/mm, for a blue of 450 nm and a red of 650 nm (Ref. 79,B)
- 2.6 to 3.2 arc minutes/mm, for a blue of 470 nm and a red of 633 nm (Ref. 77,B)

5.2.6 IMAGE DISPLACEMENT DUE TO COLOR (CONTINUED)

To put these values in context, the threshold for the perception of depth is less than 0.5 arc minute (Sections 3.7.4.4, and 5.1.3).

A pair of artificial pupils, either those in a binocular microscope or simply small holes cut into two cards, provide an easy means of demonstrating chromostereopsis. As the two artificial pupils are moved closer together, blue objects will appear nearer, and as they are separated, red objects will appear nearer. This demonstration works best for objects viewed against a dark background, apparently because the low light level causes an increase in eye pupil size and allows greater displacement of the artificial pupils.

If image displacement due to color causes any serious imagery display problems, they are likely to be in the area of color *mensuration*, and particularly color stereo mensuration. Section 5.3.7 suggests techniques by which the comparator user, if he understands the principles involved, can avoid such problems.

For most other imagery display applications, this phenomenon should not contribute more than an occasional interesting illusion, which may be very puzzling unless the display user understands what is causing it. A description and demonstration of chromostereopsis should therefore be included in any color interpretation training. This training should emphasize the proper adjustment of eyepiece interpupillary distance as a means of reducing chromostereopsis.

Because chromostereopsis will only be large when highly saturated colors with large wavelength differences are involved, it is unlikely that it can effectively enhance the visibility of colored targets. However, it is conceivable that this could occur for targets so small that the sensation of color is nearly lost (Section 5.2.4.1).

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5. Figure 5.2-1 is based very loosely on p. 73 of Hunt, R. W. G. *The Reproduction of Colour.* Wiley, New York, 1967.

   Also see Ref. 3.

6. Figure 5.2-1 is adapted from *Radiometry and photometry for the electronics engineers*. Photometry/Radiometry Application Note 4, Tektronix Co., Beaverton, Oregon, 1972. The color names are from p. 56 of Ref. 3.

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5.3 COMPARATORS

5.3.1 Units

5.3.2 Pointing Precision

5.3.3 Magnification

5.3.4 Field Size

5.3.5 Image Translation

5.3.6 Backlash

5.3.7 Color

5.3.8 Reticles

5.3.9 Warning Labels

SECTION 5.3 COMPARATORS

In the context of this document, a *comparator* is a device that combines an imagery display with a mechanism for measuring distances on the imagery being displayed. Therefore, most of the design recommendations for a comparator are included in Section 3.0, on optical imagery displays, or in Section 4.0, on electro-optical imagery displays. In addition, Section 3.10, on image translation, includes an analysis of translation requirements based specifically on a comparator.

This section covers features unique to displays that are not included in Section 3.0 or 4.0 and describes some possible exceptions to the conclusions presented in those sections. It is assumed in much of the discussion in this section that the comparator is used only for measuring targets that have already been located using a regular imagery display, thereby eliminating the need to use the comparator for ordinary image interpretation functions such as search.

5.3.1 UNITS

The units commonly used when discussing dimensions in a comparator are described in Figure 5.3-1 below.

It is unfortunately common in the literature on comparator research for authors to report dimensions only in micrometers and to neglect to report the magnification used. This makes it impossible to determine the *visual angle* subtended by the reticle or by the object being measured and sometimes precludes meaningful comparisons between studies or with data on visual performance such as that contained in Section 3.1.

5.3.1 UNITS (CONTINUED)

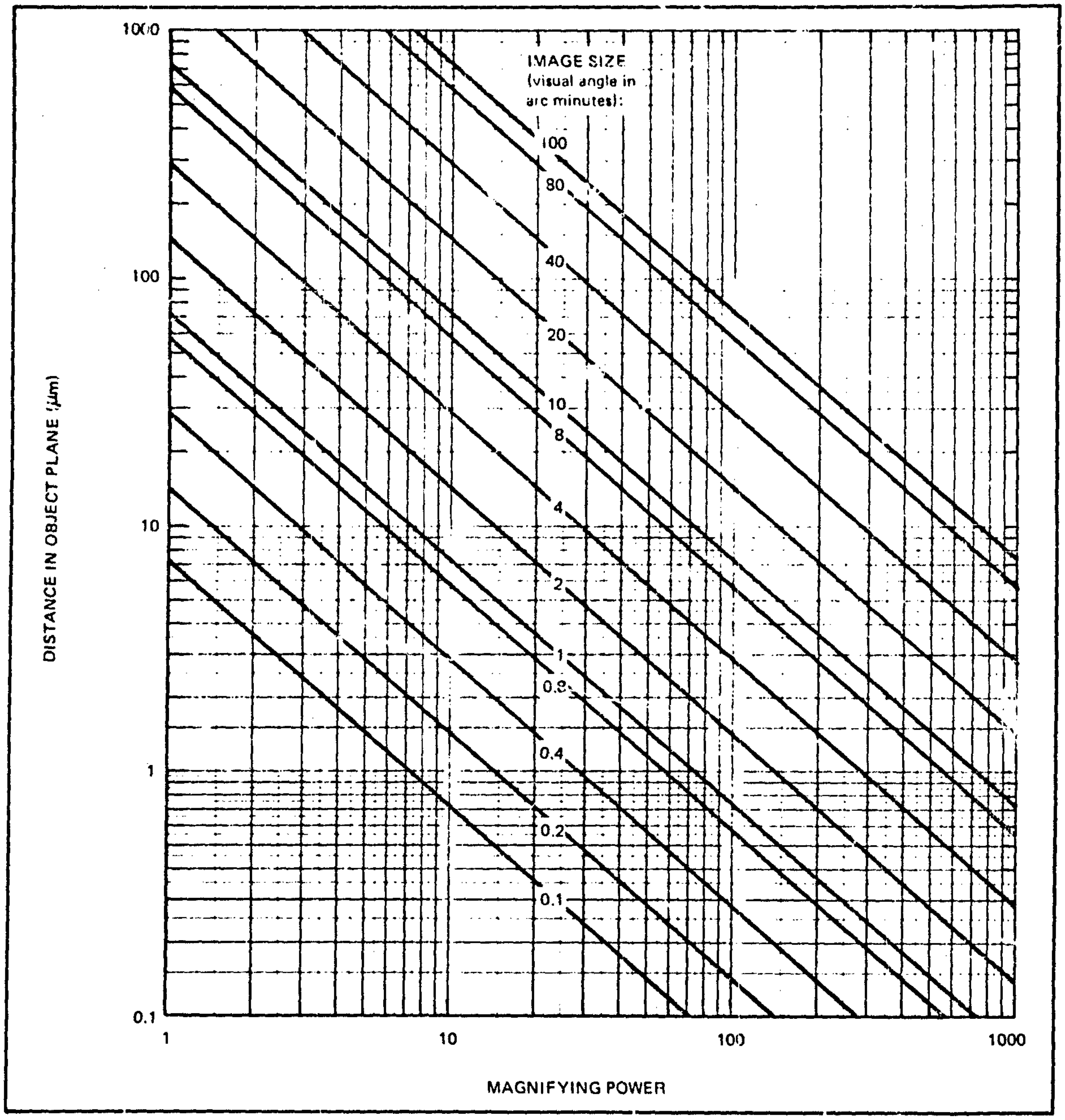


Figure 5.3-1. Relationship of Object Size, Image Size, and Display Magnifying Power (Ref. 1). Dimensions in a comparator are usually expressed as linear distance in micrometers (μm, formerly called microns). This figure shows the conversion from this linear distance to visual angle in the displayed image.

In a microscope-type display the magnifying power for the imagery is usually the magnification engraved on the display by the manufacturer (Figure 3.6-1). The reticle, however, is probably in the object plane of the eyepiece, making the magnification of the eyepiece the appropriate value to use in this figure.

5.3.2 POINTING PRECISION

The term "pointing" refers to the action of a comparator operator, often called a photogrammetrist, in aligning the comparator reticle with an edge in the displayed image. This section summarizes information on the precision with which this task can be performed with high-quality imagery and modern high-quality comparators.

Two terms used in an exact sense in this section are "accuracy" and "precision." These are defined as follows:

- "Accuracy" refers to how closely a measurement, or the average value of several measurements, matches the true value. In order to assess the accuracy with which a particular operator using a particular comparator can measure a dimension on a piece of imagery, it is necessary to know the true value of the dimension.

- "Precision" refers to the consistency within a set of measurements. If several measurements of a dimension yield the same value, they are very precise, even though they may contain a large constant error.

With artificial targets, considerable higher pointing precision than reported in Figure 5.3-2 below is possible. For example, values on the order of 1 μm and 0.02 arc minute have been reported (Ref. 2,C).

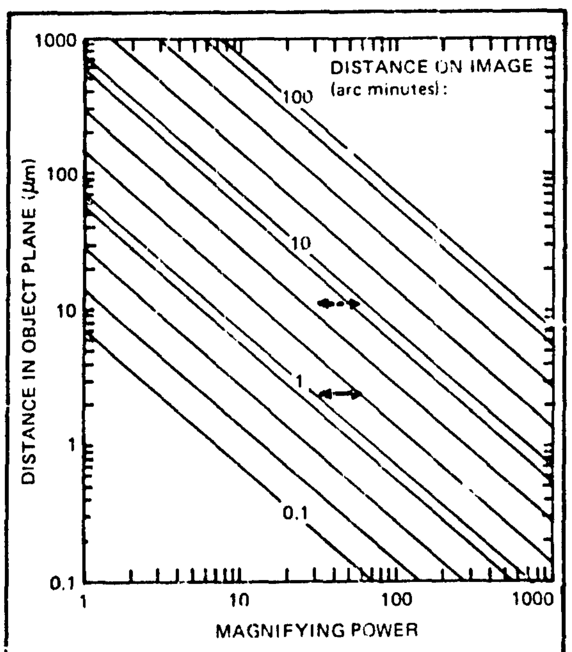


Figure 5.3-2 Sources of Pointing Variability. The purpose of the study summarized here was to determine the relative contribution of two sources of error in a realistic imagery mensuration situation (Ref. 3,B). These were:

- Between-operator variability—This was the variability among the average values obtained by the different operators as they each measured a single target dimension. It was assumed to result primarily from differences in what each operator defined as the edges of a target. (continued)

Figure 5.3-2 (continued)

- Within-operator variability—This was the variability within the set of values obtained by a single operator as he repeatedly measured a single target dimension. It was assumed to represent the individual operator's uncertainty about the location of the edge of the target, plus any pointing variability caused by the comparator.

The study involved 12 operators experienced in using comparators, three high-quality comparators and 18 linear target dimensions such as building length, aircraft wingspan and oil tank diameter. The 18 targets were distributed across several types of aerial photography.

The data were analyzed as follows:

- Within-operator variability, 2.5 μm, was the average of the *standard deviations* calculated for each set of five measurements made by a single operator on a single target with a single comparator.

- Between-operator variability, 11 μm, was the average of the standard deviations calculated for the average lengths obtained by the 12 operators on a single target with a single comparator.

These values are shown here in a copy of Figure 5.3-1, along with the range of magnification used. The position of the lower arrow shows that the within-operator variability corresponded to a distance in the image of 1 to 2 arc minutes.

These results imply that measurement precision, and presumably accuracy also, can be increased more by improving the ability of comparator operators to decide where the edges of a target are located than by improving the capability of a comparator to repeat a pointing precisely.

The three different comparators had little impact on the results, even though they differed widely in design. For example, two had opaque reticles, and one had a luminous dot reticle.

5.3.3 MAGNIFICATION

The topic of magnification requirements for displays is discussed in Section 3.3.1.

It is probable that just as excessive magnification of an edge decreases the luminance gradient on the retina to the point where the edge is less visible (see Figures 3.1-34 and -36), it also reduces the comparator operator's ability to determine the true location of the edge and as a result, his accuracy. However, the operator may not be aware of this loss in accuracy because grain and other irregularities in the imagery will be greater, and if these help him to repeat his pointing, his precision may actually increase with magnification. (The difference between precision and accuracy is discussed in Section 5.3.2.) With the exception of the studies discussed in this section, there is no known test data on this topic.

The factors that affect the choice of a magnification range for a comparator are generally the same as those described in Section 3.3 for imagery displays. The primary exception is that the comparator operator has less need to reduce magnification in order to increase the area visible on the imagery.

There are no known studies in which operators were required to use specific magnifications in order to assess the effect on mensuration performance. (However, see Ref. 4.)

In the study summarized in Figure 5.3-2, the magnification chosen by the operators ranged generally from 33X to 60X. The effect of magnification was not specifically tested, but there was no effect that was sufficiently large that it was obvious to the experimenters as they analyzed the data.

In a study that followed this one, accuracy of measuring targets on high-quality imagery was determined (Ref. 5). The operators could use any magnification within the available range of 10 to 150X. About 90 percent of the measurements were made using a range of 30 to 80X. The *correlation* between the accuracy achieved and the magnification used was only 0.08, indicating that there was no significant relationship.

5.3.4 FIELD SIZE

RECOMMENDATION:

Provide a minimum comparator image field size of 30 degrees, with a preferred value of 40 to 45 degrees.

Unlike the image interpreter, the comparator user has no need for a large display field to aid him in searching an extended area on the imagery or in placing some target object in context with its surroundings. Instead, his goal is simply to determine the true location on the imagery of the edge of some object and to align this imagery point with a reticle. A display field larger than the minimum size necessary to avoid any unpleasant sensation of tunnel vision may be of help to the operator in locating the target object he is to measure. Insofar as is known, there are no data on the impact of display field size on the performance of such a task. (See Section 3.5 for a more extensive discussion of the possible impact of display field size and for a summary of the units used to describe field size.)

The best available recommendation is to incorporate as large a field as possible without significantly increasing the cost of the comparator or reducing the image quality. Microscope eyepieces that provide an image field of 40 to 45 degrees are routinely available; this size is a good choice, though there is no evidence that it is significantly better than the more typical microscope field sizes of 20 to 35 degrees.

5.3.5 IMAGE TRANSLATION

RECOMMENDATION:

Refer to Section 3.10, and particularly Section 3.10.5, for recommendations on image translation.

The image translation control mechanism on a comparator must not limit the precision with which the imagery can be aligned with the reticle, and it should allow the operator to traverse the entire film stage in a reasonable period of time. Following an analysis based on these two requirements in Section 3.10.5, it is concluded that the most suitable control for most comparators is a *displacement joystick* that controls stage velocity, preferably in a nonlinear fashion (see Figure 3.10-14) combined with a crank/handwheel that controls stage position. This also happens to be the control configuration on many commercially available comparators.

Quantitative requirements for translation control parameters are also discussed in Section 3.10.5. When designing any control mechanism, it is important to remember that the control parameters, such as the ratio between control setting and stage velocity, can be as important as the type of control. (Also, see the brief discussion of this topic in the introduction to Section 6.2.)

Because of mechanical difficulties in providing the entire range of velocities that should be provided, comparator users are particularly likely to be dissatisfied with the maximum velocity available. This dissatisfaction will be increased if the control configuration does not make it obvious when the maximum control setting has been achieved. As is discussed in Section 3.10.4, force joysticks are less effective in providing such information to the operator than are displacement joysticks. However, force joysticks that incorporate a small amount of movement and thereby provide the user with this kind of feedback are available (Ref. 6).

5.3.6 BACKLASH

RECOMMENDATION:

Limit backlash to the minimum amount possible.

Ideally, the device that converts comparator stage position to a numerical value will have no backlash, or free play. Though some sophisticated optical devices may achieve this ideal, mechanical devices cannot, and comparator operators have generally learned to always approach the target from the same direction when making a pointing. As a result, the primary impact of a moderate amount of backlash is to increase operating time and to increase training requirements.

No quantitative data on the permissible amount of backlash are known. For a manually operated crank-type translation system, some of the considerations included in the analysis of focus controls in Section 3.8.2 may be relevant.

5.3.7 COLOR

RECOMMENDATION:

Before incorporating a colored reticle in a comparator, evaluate the possibility that it will contribute to mensuration errors.

Because display interpupillary distance (IPD) adjustment can contribute to measurement errors associated with color, make a special effort to provide good IPD adjustment capability, a precise and accurate IPD scale, and a means of locking the IPD so no change will occur during a series of measurements.

Color can have one important effect on comparator operation. As is discussed in Section 5.2-6, the apparent location of a colored object may be shifted laterally from its true location. This occurs for some individuals when they are using their *natural pupil*, and for most when they are using a small *artificial pupil* that is displaced laterally from the center of the natural pupil. The cause of this shift in location is apparently the chromatic aberration of the eye (Figure 3.4-4), which results in shorter wavelengths of light being refracted more strongly than the longer ones, in combination with the difference of several degrees between the optical and visual axes of the eye (Figure 3.1-2).

If both eyes are in use and the direction of the shift is in opposite directions in the two eyes, as is the usual case, then the result is a lateral disparity between objects of different colors that makes them appear to be at different distances. The usual term for this phenomenon is *chromostereopsis*.

The amount of displacement due to color varies widely among individuals and can be quite large. Measurements on four individuals using natural pupils yielded a maximum of 1.0 arc minute in each eye over a spectral range of 450 nm (blue) to 650 nm (red) (Ref. 7). However, it is much larger if an artificial pupil, either a physical aperture or the exit pupil of a microscope, causes the light to enter the eye through the periphery of the natural pupil. In this type of situation, target displacements of 5 to 6 arc minutes per millimeter across the eye pupil have been measured (Ref. 8). Referring to Figure 5.3-1, 1 arc minute corresponds to 7.3 μm at 10X and 0.7 μm at 100X.

In order to reduce the chance of mensuration errors, the peak of the spectral distribution of the light from a luminous reticle should be approximately the same as for the light used to illuminate the imagery. If a different reticle color is used, a check should be made to see if it might introduce any measurement error. To do this, the user simply watches for any shift in the relative position of the image and the reticle as he shifts his head laterally. If there is none, there is no problem.

If it is the imagery that is colored, absence of relative motion eliminates any impact on pointing precision but leaves the possibility of a constant error when measuring the distance between differently colored objects. That is, a pair of objects might appear to be farther apart when the one with shorter wavelength is on the left than when it is on the right. This is also easy to check by simply rotating the imagery 180 degrees on the comparator stage and measuring the distance between the two objects a second time.

Additional discussion of image displacement due to color appears in Section 5.2.6.

5.3.8 RETICLES

RECOMMENDATION:

Because they are easier to locate visually, self-luminous reticles are preferred.

There must be no parallax, or movement of the reticle relative to the displayed image, as the operator's head is moved.

A reticle is a fixed reference mark that the comparator operator aligns with the edge being measured. It can be located at any one of several different positions in the optical train of the comparator, but it must be at the same optical distance as the imagery so that both will be seen in focus.

The size and shape of an opaque reticle are necessarily a compromise between making the reticle sufficiently large that it is easy to find and sufficiently small that it does not obscure the edge of the target; the limited data available on these topics are summarized below. A luminous reticle is much more complicated to build into a comparator than an opaque reticle, but it can easily be made both small enough to not obscure the target edge and bright enough to be found easily.

For most applications involving measurements on imagery of a ground scene, the reticle does not set the limit on pointing precision, and the designer has considerable latitude in his selection. For example, in the study summarized in Figure 5.3-2, there were no differences in pointing precision among the three comparators, even though the reticle in one was a luminous dot while in the others it was a 5-μm opaque dot centered in an opaque segmented cross.

Reticle size and style becomes more important as imagery resolution increases, and it can be important for special kinds of targets. For example, precision in aligning a dot with another dot is two to three times better than is possible when aligning a dot with an X-shaped reticle (Ref. 9, C). If the circular target is high quality and only slightly larger than the reticle—and if the positioning mechanism is adequate—precision of 0.02 arc minute is possible (Ref. 10,B). This is two orders of magnitude better than in the study described in Figure 5.3-2 and is several times better than possible with either *vernier* or *stereo acuity*.

The available test data on the minimum size of opaque object that can be seen is not very helpful in the design of an opaque reticle because it is all based on a uniformly luminous background. With such a uniform background and relatively high luminance, the minimum width for detection of a line at least 1 degree in length is less than 0.1 arc minute, and the minimum diameter for detection of a dot is approximately 0.5 arc minute (Ref. 11). However, when an opaque disc is viewed against the density irregularities in imagery, plus the inevitable dirt particles, it can be very difficult to find. A minimum size for a simple opaque dot reticle cannot be established precisely, but in one case a 3-arc-minute reticle, six times the minimum detectable size, was occasionally difficult to locate against a photograph (Ref. 12). Opaque dot reticles smaller than this should probably be avoided.

A frequent complaint about binocular comparators incorporating an opaque dot reticle, particularly stereo comparators, is that the dot is difficult to fuse vertically. Correct vertical alignment of the reticle in each optical train to within the limits in Section 3.7.5.1 is essential to minimize this problem. In addition, it is likely that part of the problem results from the fact that the dots are a much weaker stimulus for fusion than the imagery. As a result, no matter how well the two dots are aligned vertically, if one member of the stereo pair is shifted vertically relative to the other, the operator's eyes will tend to follow the imagery and keep it fused rather than the dots.

One way to determine if this is the cause of complaints about reticle alignment is to observe which dot is higher when they separate. Unless one is consistently higher, changing reticle alignment will not correct the problem. Explaining this to the comparator operator may help because he will then realize the importance of aligning

5.3.8 RETICLES (CONTINUED)

the imagery carefully. Once he understands the problem he should be able to fuse the two dots simply by moving one piece of imagery vertically. Otherwise, it will be necessary to strengthen the reticle as a fusional stimulus by making it larger or by adding horizontal lines. A third alternative is to add noncoincident horizontal lines, as in the lower part of Figure 5.3-3, in order to provide the user with a means of checking vertical alignment.

A final requirement for the reticle is that it not show any *parallax* relative to the image as the operator shifts his head position relative to the comparator. It is also desirable that the reticle not move relative to the image as focus or magnification is changed. Few designs achieve this goal completely, so most experienced comparator users have learned not to change focus or magnification within a series of measurements.

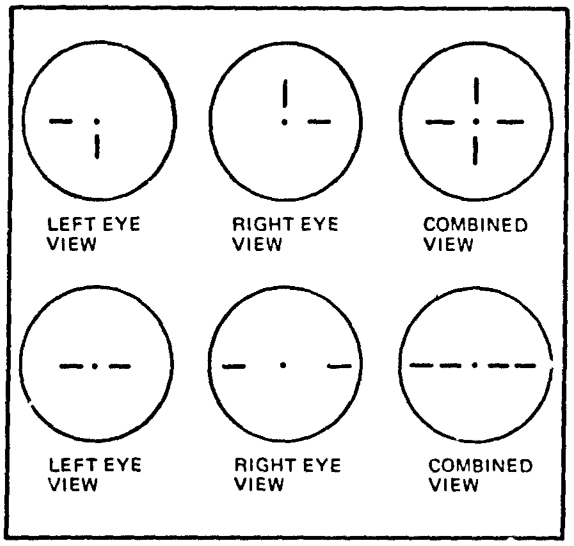


Figure 5.3-3. Addition of Lines To Make an Opaque Dot Reticle More Visible. The reticle most difficult to locate is the simple opaque dot. A dot reticle will be much easier to locate if it is at the intersection of two lines or the center of a circle. Lines used for this purpose should be at least 0.5 arc minute wide and 1 degree long. For stereo instruments, locating the lines differently in the two eyepieces, as is shown in the upper part of the figure, would reduce the requirement imposed on instrument alignment (see Section 3.7.5), but may be uncomfortable for some users.

The arrangement in the lower part of the figure would offer similar advantages plus allow the user to confirm the adequacy of his vertical alignment of the imagery. Optimum alignment and best depth perception ability would occur when the lines in the combined view were seen as exactly aligned. Again, the difference in the image to the two eyes may cause problems for some users. In general, complicated reticles such as the ones described here should be evaluated by the anticipated users prior to permanent installation.

5.3.9 WARNING LABELS

Because of their greater sophistication, comparators are more susceptible than ordinary displays to operator errors that can cause equipment damage or an incorrect output. As an example, on most comparators changing magnification or focus shifts the position of the reticle relative to the imagery. If such a change is made within a series of pointings, an error will result.

The need to provide labels warning of these hazards depends on the personnel who will be operating the comparator. If it is operated only by a small number of highly experienced individuals, each of whom uses it often enough to remain familiar with it, then labels of this kind are generally unnecessary. On the other hand, if many operators will be only occasional users, then warning labels should be provided, even if they detract from the appearance of the device.

SECTION 5.3 REFERENCES

1. Object size in μm is (250,000/M) tan (α/60), where α is image size in arc minutes.

2. See Ref. 9 and 10.

3. Dean, R. D. and Fallis, R. F. *Relative Accuracy of Mensuration.* Document D2-114242-1, The Boeing Company, Seattle, Washington, 1968.

4. Ahrend, M. Analysis of photogrammetric errors. *30th Photogrammetric Weeks*, Carl Zeiss Co., Oberkochen, Germany, 1966, pp. 62-78. This study has been cited as showing a relationship between comparator magnification and pointing precision. Although the author says that several operators made several thousand measurements on aerial photographs, no test data are reported and he does not describe the relationship, if any, between test data and the equations he presents that use magnification to predict pointing precision.

5. Unpublished study by R. D. Dean of The Boeing Company, Seattle, Washington.

6. Mehr, M. H. President, Measurement Systems Inc., Norwalk, Conn. Personal communication, December, 1974.

   Also, see Figure 6.2-3.

7. Vos, J. J. Some new aspects of color stereoscopy. *J. Opt. Soc. Am.*, Vol. 50, 1960, pp. 785-790.

8. Owens, D. A. and Leibowitz, H. W. Chromostereopsis with small pupils. *J. Opt. Soc. Am.*, Vol. 65, 1975, pp. 358-359.

   Also, see Ref. 7.

9. Helava, U. V. New significance of errors of inner orientation. *Photogram. Engr.*, Vol. 29, 1963, pp. 126-129.

10. O'Connor, D. C. *Some Characteristics of the Visual Process Affecting the Observation and Measurement of Pass Points.* Report AF-WP-O-DEC 64 70, GIMRADA, Fort Belvoir. Va., 1964. (Also available as AD 815 336.) This is the report that contains the best presentation of the cited data.

    O'Connor, D. C. *Visual Factors Affecting the Precision of Coordinate Measurements in Aerotriangulation.* Civil Engineering Studies–Photogrammetry Series No. 6, Univ. of Illinois, Urbana, 1967. (Also available as AD 663 821.)

    The task in these studies, centering one circular object on another circular object, is not a visual acuity task in the usual sense of the term. However, it is directly relevant to certain comparator operations.

11. Riggs, L. A. Visual acuity. Chapter 11 in Graham, C. H. (Ed.) *Vision and Visual Perception.* Wiley, New York, 1965.

12. Personal observation of senior author.

5.4 SEARCH

5.4.1 Magnification

5.4.2 Techniques for Ensuring Complete Search [redacted]

5.4.3 Display Field Size

5.4.4 Organization of the Search Operation

The term search, as it is used in this document, refers to the act of looking at imagery for the purpose of finding targets whose location is not known. This usually, though not necessarily, means previously unreported targets. A typical sequence of activities involved in search is described in Section 1.5.

The design features that must be considered in a display to be used for search are essentially the same as those covered in Sections 3.0 and 4.0, but with increased emphasis in certain areas.

Most imagery collection systems are characterized by the production of a large quantity of imagery and searching this imagery for new targets is likely to require many interpreter manhours. The length of the search task, plus the fact that in many cases interesting new targets will not occur frequently, increases the need to provide a display that will help keep the interpreter comfortable and alert after many hours of use. One of the potential advantages claimed for screen and large exit pupil aerial image displays over small exit pupil displays, such as a typical microscope, is that the former, by eliminating the need for the user to maintain a fixed head position, are more comfortable to use over an extended period of search. The opinions expressed by some interpreters who have used screen displays for search imply that for them at least, screen displays are more comfortable, but there is no known test data on this question.

Topics that require special consideration in an imagery display intended for search are magnification (Section 5.4.1 below and Section 3.3.1), techniques for ensuring that all the imagery is viewed during search (Section 5.4.2 below), display field size (Section 5.4 3 below and Section 3.5), and the organization of the search task (Section 5.4.4 below). Also, because search usually involves looking at such a large amount of imagery, a good imagery translation system is even more important than in a display not intended for search. The discussion and recommendations in Section 3.10 are the best available on this topic.

During search, the eye is *fixated* on one point in the image for a few tenths of a second and is then moved rapidly to another fixation point. The effective visual field, at least for small details, extends only a couple degrees from each fixation point (Figures 3.5-10, -11, and -12). Successive fixation points may be chosen at random or according to a pattern chosen by the searcher. A systematic pattern is generally more successful than a random one (Ref. 1).

The searcher's next fixation point is also influenced by objects seen peripherally. In general, the more similar in shape size, color, and brightness an object is to the target being sought, the more likely it is to be fixated (Ref 2.A).

The amount of time expended in searching a given area on the imagery is increased by blurring or reducing the contrast of the imagery (Ref. 3), by increasing the number of objects that can be confused with targets (Ref. 4), by making the background less uniform (Ref. 5 and Section 3.1.10), and by allowing the searcher more time (Ref. 6). It is likely that many of these effects are unique to the specific task, imagery content, and target type.

Searching imagery in stereo might result in more targets being found (but see Figures 4.3-16, -17, -18 and Ref. 15). Because more information is available to the interpreter in the stereo image, it is also possible that search in stereo would be slower. With a stereo pair in *chip* form that contains little distortion due to *obliquity*, and a display with a good imagery translation system that allows easy movement of one member of the stereo pair relative to the other, small areas can be searched in stereo (Ref. 7; also see Section 5.1). However, search over areas larger than a few fields-of-view of the display will require a display that automatically maintains the registration, or "correlation," of the two members of the stereo pair during imagery translation. In the absence of such a display, there is no way to determine if stereo can make a significant contribution to search performance.

Because the techniques used for search are so highly individualized, it is unlikely that any single display design will be satisfactory for all interpreters. Therefore, a display intended for search should provide as many different user options as are compatible with the need to keep the display simple, easy to operate, and reliable.

5.4.1 MAGNIFICATION

RECOMMENDATIONS

Provide higher magnification for close inspection of targets than for search. Refer to Section 3.3.1 for the best available discussion of specific values.

Allow magnification changes to be made rapidly and with a minimum of effort.

A zoom device for changing magnification is preferred.

Keep the same imagery area centered in the display field as magnification is changed.

The magnification used during search is a compromise between two factors. First, the image must be enlarged enough that the kinds of targets that may be present will be visible. (See Figure 5.4-1 and the data in Sections 3.1.4 through 3.1.10.) However, because the display user's effective visual field for seeing small details is only a few degrees, and because each fixation lasts for a finite period of time, lower magnification means that the imagery can be searched faster.

In most situations the interpreter will use higher magnification to inspect objects in the imagery that are suspected of being targets than he will use during search. The result is that relatively large changes in magnification, by a factor of perhaps 2 to 6 times, will occur frequently. It must be possible for the display operator to make these changes in magnification easily and rapidly. There are no data on the maximum allowable time to complete a magnification change, but anything over 2 or 3 seconds is likely to meet with complaints from the user. In an unpublished evaluation of a prototype display, a duration of 10 seconds was judged much too long by most interpreters who used the display for search.

Changing magnification with a zoom system, rather than in discrete steps, is preferable for two reasons. First, it allows infinite control of the magnification, eliminating the possibility that the interpreter might need a magnification value midway between two of the discrete steps. Second, it allows the interpreter to continue viewing the object as the magnification is changing, and this saves a small amount of time and a potential source of confusion. The available test data are not adequate to determine whether any of these advantages justifies the usually greater cost of a zoom system. In the one known experiment which compared search performance using the two techniques for changing magnification, there was no significant advantage to either (Ref. 8,C; also see discussion of this study in Section 3.3.1). However, because most interpreters are accustomed to the convenience of a zoom system, it should not be replaced by a discrete system without strong justification.

It is essential that changes in magnification not displace an object in the center of the display field significantly from its location. This should not be much of a problem except in complex displays where different optical systems provide the different magnifications. An example would be a display in which a rear projection screen is used at low magnification for search, and a microscope is used for inspecting suspect targets at high magnification.

5.4.1 MAGNIFICATION (CONTINUED)

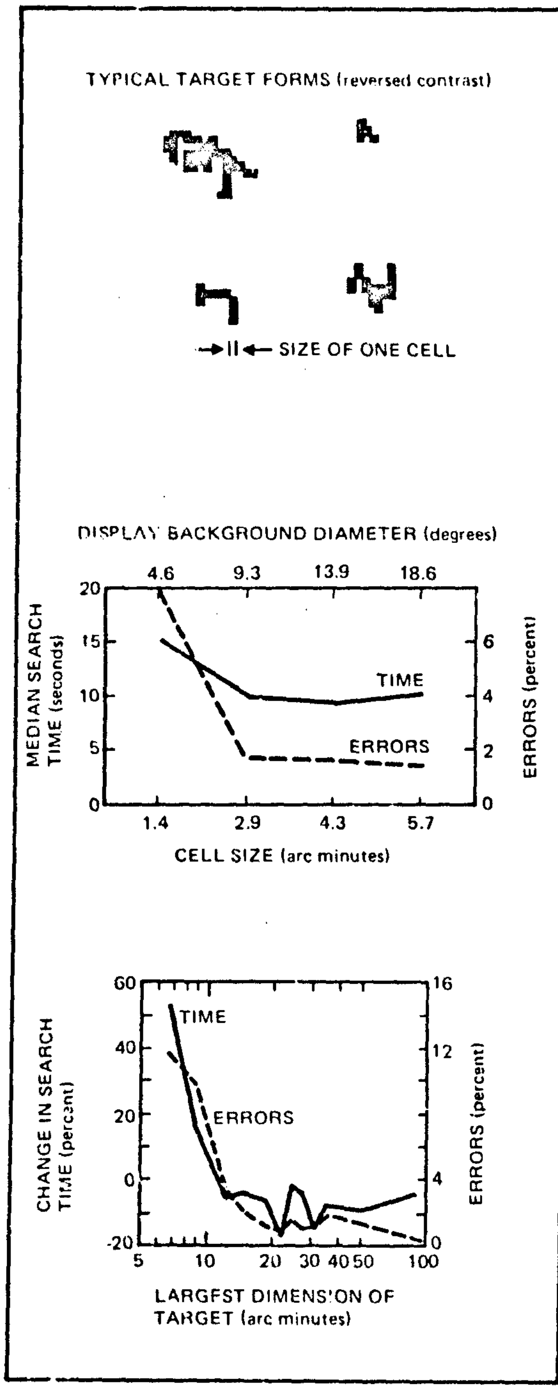


Figure 5.4-1. Effect of Target Size on Search. In this study, subjects searched for 1 of 24 target forms of the type illustrated, in a scene made up of 184 similar high-contrast forms viewed against a dark background (Ref. 9,C). In each case, the target form being sought was shown in correct orientation above the display area, which had a diameter of 4.6 to 18.6 degrees. The forms were viewed with various amounts of defocus, so that under worst case conditions a single square cell looked much like a circle.

The subjects were under considerable pressure to perform both rapidly and accurately. Referring to the middle part of the figure, performance reached a maximum when the square cells making up the forms reached a size of 2.9 arc minutes. For the bottom graph, the results from the four display sizes were pooled and then segregated according to the distance across the largest dimension of the target. In this situation, performance reached a maximum with a target of size of 12 to 20 arc minutes.

Normally, the orientation of the target form matched the copy of the target displayed just above the search area. In a second study, when the two orientations did not match, search time doubled and the number of errors increased by a factor of 5. It is unlikely that such a large increase would appear with a well known target, such as an aircraft or a ground vehicle.

5.4.2 TECHNIQUES FOR ENSURING COMPLETE SEARCH

RECOMMENDATION

Provide an optional, easily removable rectangular reticle as an to achieving a uniform search pattern in a display with a circular field.

Provide an automatic method of keeping track of what part of a frame has been searched and of automatically moving the imagery past the display field, if these can be provided economically and if they meet all the requirements described in this section.

In most imagery search situations, it is desirable to ensure that the interpreter actually looks at all of the imagery. There are two aspects to this problem:

- Does the interpreter actually look at each point on the imagery that passes through the display field?
- Does all of the imagery pass through the display field?

The eye movement pattern used during search has a major effect on how much area is overlooked. A random pattern is likely to result in large areas being missed and in some areas being looked at many times (Ref. 1). A search pattern based on regular eye movements will result in more complete coverage. Typical patterns are up and down, left and right, and a spiral.

Although training can help ensure a regular eye movement pattern during search, a more certain approach is to incorporate some device into the display that essentially forces the user to follow the desired pattern. As Figure 5.4-2 illustrates, the use of a small aperture, subtending only a few degrees, as a guide to ensure that the searcher looks at each area in the display image field does not appear useful.

A spiral pattern is efficient for a static display (Ref. 10), but for searching moving imagery, eye movements along straight lines perpendicular to the direction of image motion are more appropriate. If the display has a circular field, the user may find it difficult to follow such a pattern consistently. One solution is to add an aperture that makes the field rectangular, thereby providing the user with a guide for directing his eye movements. The insertion of a rectangular aperture into a display with a circular field would of course cause a considerable reduction in the imagery area visible. Whether this reduction is compensated by an improvement in search performance has not been tested.

The reduction in display field with an aperture can be avoided by use of a rectangular reticle pattern. Again, there is no known test data to indicate that this will actually result in improved search. In the absence of such data, it is a desirable option for those search displays where it can be provided inexpensively.

When a frame of imagery is large, relative to the imagery area covered by a single display field of view, it may be difficult for the interpreter to keep track of which portions of the frame have been searched and which have not. It is common to start from one edge and work down, or across, the frame. However if the interpreter must break this pattern to inspect a suspect target or to follow a road or trail, he may lose track of where he was. One approach is to reduce the chance of confusion by using a grease pencil or marking pen to divide the frame into segments and to mark each as it is searched.

A more sophisticated, and expensive, approach is to add a device to the display that automatically keeps track of which parts of the frame have appeared in the display field and which have not. To be effective, such a device must be easy to operate, it must not slow search activity, it must be reliable, and it must not impose unreasonable demands on the search procedure used by the display operator. There is no test data available to indicate whether such a device will make a significant contribution to search performance.

An extension of the concept described in the previous paragraph is to make the device automatically move the imagery across the display field. This is sometimes

5.4.2 TECHNIQUES FOR ENSURING COMPLETE SEARCH (CONTINUED)

known as "automatic scanning," or "autoscan." The requirements imposed on an autoscan device include all those imposed on a device that just keeps track of the area searched, plus the velocity, and the overlap between consecutive paths across the frame, must be adjustable by the operator. In addition, it must be easy to override the automatic device in order to search manually, and to then return to the point on the imagery where automatic search stopped.

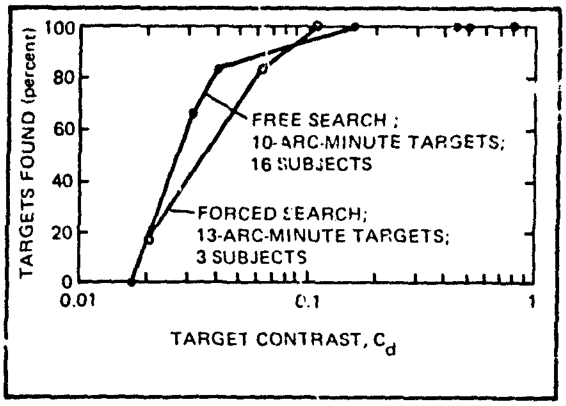


Figure 5.4-2. Automatic Control of Eye Position During Search. In the study illustrated here, experienced subjects searched a 27-degree-square aerial map display for Landolt ring targets (Ref. 11,D). In free search, subjects could use any search pattern they preferred. In the forced search condition, a different set of subjects searched a different set of aerial maps, using a 3-degree circular ring of light as a guide in directing their eyes. The ring moved across the display field in successively lower rows, jumping ahead or down 2.5 degrees each second.

The results, as plotted here from the authors' summary table, do not provide good evidence for any benefit from forced search.

(The data shown here also appear in Figures 3.1-44 and -45.)

5.4.3 DISPLAY FIELD SIZE

RECOMMENDATION

Provide a display field with a diameter of at least 36 degrees, with a preferred minimum of 45 to 55 degrees; do not exceed a diameter of 60 degrees.

The very limited data available on image field size and search performance are summarized below. The first figure suggests that the image-field diameter should be at least 9 degrees and the second suggests that it should be at least 34 degrees but probably need not be more than 54 degrees.

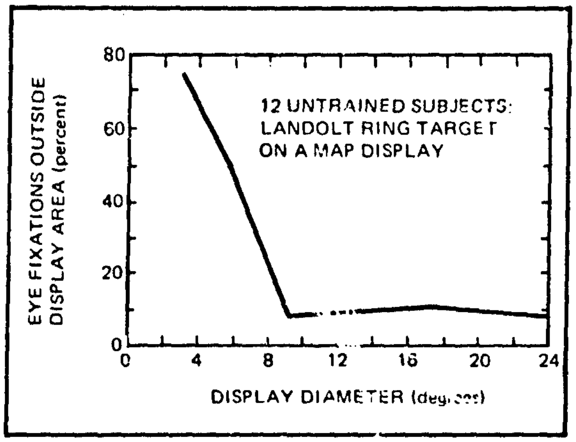


Figure 5.4-3. Visual Search Behavior with Small Display Fields. With extremely small fields, visual search efficiency may suffer because of time lost while looking outside the display area. In the experiment illustrated, this effect occurred with fields smaller than 9 degrees (Ref. 12,B).

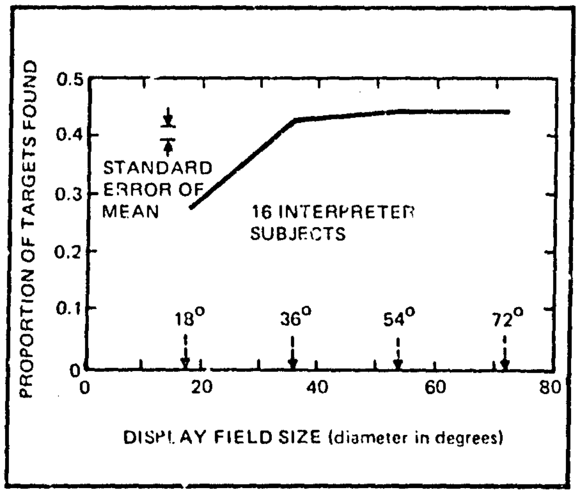


Figure 5.4-4. Field Size and Search Performance. A high quality experimental *microstereoscope* with a 72-degree image field was used to measure the impact of field size on search performance (Ref. 13,C). Sixteen interpreters searched for a range of different sized targets, such as electronic sites, transformer substations, active construction sites, missile sites, and air fields on small-scale, high-resolution imagery. The imagery was not in stereo, so two copies were made and mounted in registry on the two film stages in order to provide a binocular monoscopic viewing situation.

As the graph illustrates, there was a large increase in target detection success, from 27.6 to 42.8 percent, as the field was enlarged from 18 degrees to 36 degrees. This change was statistically significant at $P < .01$. With a further enlargement of the field to 54 degrees, performance increased to 44.2 percent, a change that was too small to be statistically significant.

The interpreters who served as test subjects in this experiment were accustomed to a microscope with an image field of approximately 45 degrees. It is possible that this experience prevented their taking full advantage of the larger fields used in the test.

The display used in this experiment incorporated an excellent manual imagery translation system, at least for the purposes of the test. Absence of an adequate imagery translation capability would probably make a large image field more important.

5.4.4 ORGANIZATION OF THE SEARCH OPERATION

When typical imagery of a ground scene is being searched, the rate of reporting objects that are targets does not change over time in the same manner as the rate of reporting false objects, or objects that are not actually targets. As Figure 5.4-5 shows, the rate of detecting new targets is highest shortly after starting to search a particular imagery area and this rate decreases with time. The rate of reporting false targets typically shows a reverse trend, increasing with time. This has led to studies showing that, for a given number of search manhours on a particular imagery area, more correct targets and fewer false targets will be reported if several interpreters search the imagery and pool their results (Ref. 14,C). It has not been determined whether the improvement justifies the increased administrative burden involved in distributing the imagery to additional interpreters and in combining their reports. Also, it is not certain that these results would still occur in work situations where a single interpreter becomes familiar with a specific ground area through viewing it in successive coverage.

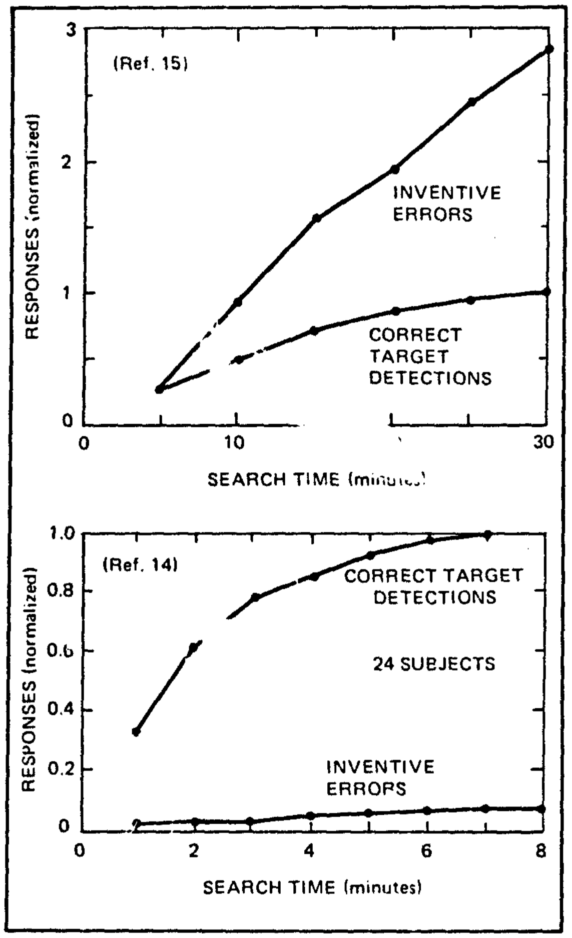


Figure 5.4-5. Relative Response Rates. When searching for targets in aerial imagery, success in reporting targets is greatest in the early parts of the test session. As search continues, the rate of correct target reports drops off but the rate of reports for objects that are not targets, sometimes called inventive errors, or errors of commission, remains relatively constant.

Both sets of data shown here are based on the performance of image interpreters searching for realistic targets in tests made up of aerial photographs. To simplify summarizing and comparing the data, it has been normalized so that the total number of correct targets reported equals 1. This does not imply that all the targets were found. In any but the simplest search situation, there are always a few, and sometimes a large proportion of the targets, that are missed.

The reversal in relative proportion of correct targets and inventive errors between these two studies is an excellent example of how heavily the results of such studies depend on specific aspects of the test situation such as target type, imagery content, experience of the subjects, and instructions to the subjects.

SECTION 5.4 REFERENCES

1. Enoch, J. M. and Fry, G. A. *Visual Search for a Complex Display: A Summary Report.* MCRL T.P. No. (696)-17-282. Mapping and Charting Research Lab, Ohio State University, 1958.

   However, also see Ref. 10.

2. Williams, L. G. Studies of extrafoveal discrimination and detection, In *Visual Search–Proc. of NRC Symposium,* 1970, pp. 77-92, Washington D.C., National Academy of Sciences, 1973.

3. Townsend, C., Fry, G. A., and Enoch, J. M. *The Effect of Image Degradation on Visual Search: Aerial Haze.* MCRL T.P. No. (696)-13-269. Mapping and Charting Research Lab, Ohio State University, 1958.

   Enoch, J. M. *The Effect of Image Degradation on Visual Search: Blur.* MCRL T.P. No. (696)-16-280. Mapping and Charting Research Lab, Ohio State University, 1958.

   Also see Ref. 1.

4. Erickson, C. W. Partitioning and saturation of visual displays and efficiency of visual search. *J. Appl. Psychol.,* Vol. 39, 1955, pp. 73-77

   Also see Ref. 6.

5. Williams, J. R. Training and stereoscopic photo–interpretation performance. *SPIE Seminar Proceedings–The Human in the Photo–Optical System.* New York, 1966.

   Smith, S. W. Display factors in visual search of complex two dimensional displays. *Proc. of Seventh Army Human Factors Conference,* 1961, pp. 53-62. (Also available as AD 267153.) Subjects searched an irregular array of circular targets for a target with a different shape. Triangular targets were found most rapidly, followed by squares, pentagons, and hexagons. Time required to find a target increased in direct proportion to the number of nontarget circles present.

6. Richman, M., Enoch, J. M. and Fry, G. A. *The Effect of Limiting the Time Allowed for Visual Search Patterns.* MCRL T.P. No. (696)-13-269. Mapping and Charting Research Lab, Ohio State University, 1958.

7. Personal experience of senior author. The situation was preparation of an imagery interpretation test involving search of small areas for military vehicles. Vehicles that were difficult to see because they were in dark shadows or partially obscured by trees were subjectively much easier to find when they were viewed in stereo. Translation across a distance equal to several fields-of-view of the display was easy, but required a small movement of one film stage relative to the other to maintain alignment. Proper rotation of the two film chips on the stages and the absence of any optical rotation of the images are essential to translating across a stereo image in this fashion.

8. Ventimiglia, D. A. *Comparison of Zoom Magnification vs. Discrete Magnification for Target Scanning Tasks.* Report RADC-TR-71-161, Rome Air Development Center, July 1971. (Also available as AD 728646.)

9. Steedman, W. C. and Baker, C. A. Target size and visual recognition. *Human Factors,* Vol. 2, 1960, pp. 120-127.

10. Erickson, R. A. Visual search performance in a moving structural field, *J. Opt. Soc. Am.,* Vol. 54, 1964, pp. 399-405.

11. Townsend, C. A. and Fry, G. A. Automatic scanning of aerial photographs. In Morris, A. and Horne, E. P. (Ed.), *Proc. of Armed Forces/NRC Symposium on Visual Search Techniques,* Washington, D. C. 1959. Also see Publication 712, National Academy of Sciences, 1960, pp. 194-210. (Also available as AD 234502.) One of the conclusions in this article that was not supported by the data, at least as it is summarized in Figure 5.4-2, was that although forced search was less efficient for high-visibility targets, it was preferred for low-visibility targets.

12. Enoch, J. M. Effect of the size of a complex display upon visual search. *J. Opt. Soc. Am.,* Vol. 49, No. 3, 1959, pp. 280-286.

13. Farrell, R. J. and Anderson, C. D. *The Effect of Display Field Size on Image Interpretation Performance*. Document D180-19056-1, The Boeing Company, Seattle, Washington, 1975.

14. Klingberg, C. L., Gonzalez, B. K. and Jones, H. H. *Effects of work pacing and teaming on interpreter performance.* Document D2-114076-1, The Boeing Company, Seattle, Washington, 1967. The interpreter test subjects searched for military ground vehicles in photographs of an army training camp.

15. Zeidner, J., Sadacca, A. and Schwartz, A. I. *Human factors studies in image interpretation: The value of stereoscopic viewing.* Technical Research Note 114, TAG Research and Development Common, U.S. Army, 1961. The newly trained interpreter test subjects searched for militarily significant targets in aerial photographs of a variety of ground scenes.

SECTION 6.0
WORKSTATION DESIGN

6.1 WORKSTATION

6.2 CONTROLS

6.3 CONTROL/DISPLAY

6.4 SECONDARY DISPLAYS

6.5 LABELS

6.6 ACOUSTIC NOISE

6.7 COMPUTER INTERFACE

6.8 SAFETY

6.9 MAINTAINABILITY

6.10 MANUALS

SECTION 6.0 WORKSTATION DESIGN

Many of the human engineering factors that should be considered in the design of an imagery display are not unique to imagery displays, but instead apply to any work situation. Among the factors in this category that are considered here are the physical configuration of the workstation, the selection and use of controls and secondary displays, the effects of acoustical noise, safety, and maintainability.

6.1 WORKSTATION CONFIGURATION

6.1.1 Anthropometric Data

6.1.2 Fixed Eyepoint Workstation Dimensions

6.1.3 Eyepiece Elevation Angle

6.1.4 Visual Work Area

6.1.5 Manual Work Area

6.1.6 Console Dimensions

This section provides data and design recommendations on workstation size and shape. While these data can be very helpful, they do not eliminate the need for a mockup in order to adequately evaluate a workstation design.

Special attention is paid in Section 6.1.2 to image interpretation workstations that require the user to keep his eyes positioned in a relatively small area in front of the eyepiece.

6.1.1 ANTHROPOMETRIC DATA

Proper layout of a workstation requires the designer to consider the population that will be using it and which physical body dimensions of that population are relevant to the design. This section presents anthropometric data of special importance to the design of a workstation involving a relatively fixed eye position. It represents only a small portion of the published data (Ref. 1).

Use of this type of data in design situations is complicated by the fact that the correlation between many body dimensions is very low (Ref. 2,B). As an example, a very short person may have very thick thighs. When possible, therefore, the design should allow for the population extremes in each of the body dimensions involved.

Workstations must accommodate an adequate range of operator body sizes. It is usual to design for 5th through 95th percentile personnel, though other limits can be used. Section 6.1.1 includes 1st, 5th, 50th, 95th, and 99th percentile values for the body dimensions of most importance in display design. Data on other body dimensions are summarized in several sources (Ref. 1).

Whether the large or small size limit for a particular body dimension is the relevant value depends on the application. Workstation dimensions such as clearances must be sized for the largest anticipated operator. Other dimensions, such as reach distance to controls, and the separation between the seat and a fixed eye position, must be sized for the smallest anticipated operator. Because of the very low correlation between many body dimensions (Ref. 2), it will often be necessary to allow for a minimum value of one dimension and a maximum value of another in the same design. The result of such a requirement can be seen in Section 6.1.2.

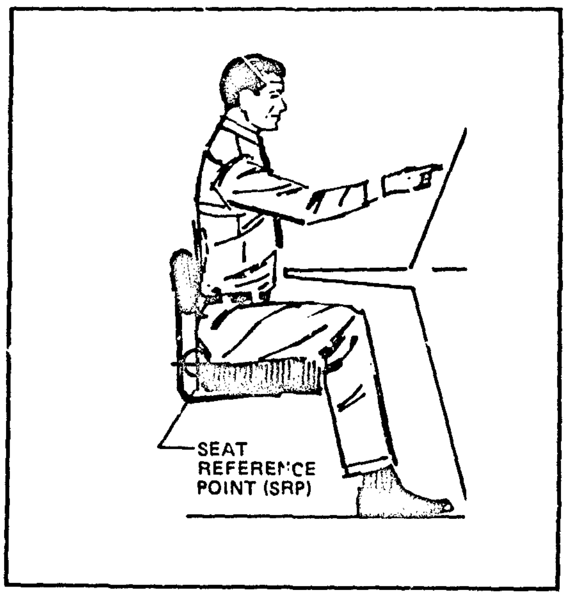


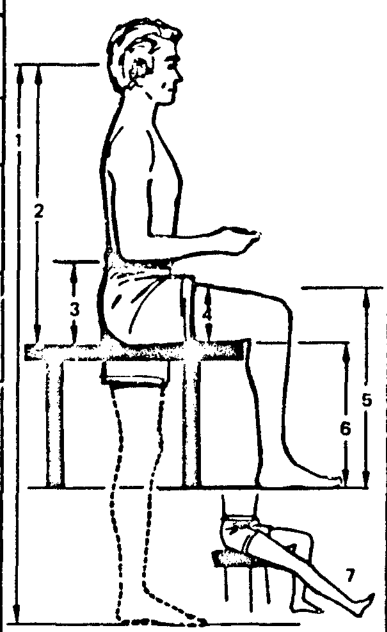
Figure 6.1-1. Reference Point for Seated Operator Dimensions. Anthropometric dimensions for a seated operator are usually measured relative to the intersection of the seat bottom surface and backrest. This location is known as the seat reference point (SRP). Since a rigid, flat seat surface is normally used, measurements on any chair for a workstation should be made relative to the seat surface when compressed by the weight of the operator.

6.1.1 ANTHROPOMETRIC DATA (CONTINUED)

Dimension [a]	Group	Original Source (Ref. 3,8)	Percentile				
			1	5	50	95	99
1 Standing Eye [b] Height, Relaxed	Male						
	AF Flight Personnel	1	148.3	152.4	162.3	172.2	176.5
	Female						
	AF Nurses (Estimated Values)	3	135.6	139.2	148.1	168.2	162.8
2 Seated Eye [c] Height, Relaxed	Male						
	AF Flight Personnel	1	68.3	70.9	75.9	81.0	83.3
	Aviators	2	-	69.6	-	82.0	-
	Ground Troops	2	-	68.6	-	80.5	-
	Female						
	AF Nurses	3	64.0	66.5	71.6	76.2	79.0
	Unspecified Military Personnel	2	-	66.0	-	75.9	-
3 Elbow Rest Height	Male						
	AF Flight Personnel	1	16.8	18.8	23.1	27.4	29.2
	Aviators	2	-	18.8	-	29.5	-
	Ground Troops	2	-	17.5	-	27.9	-
	Female						
	Civilian (Age 25-34)	4	15.5	18.8	23.6	28.2	30.2
4 Thigh Clearance Height	Male						
	AF Flight Personnel	1	11.4	12.2	14.2	16.5	17.3
	Aviators	2	-	12.4	-	18.8	-
	Female						
	Civilian (Age 25-34)	4	10.2	10.7	13.7	17.5	19.6
5 Knee Height	Male						
	AF Flight Personnel	1	49.5	51.1	55.1	59.2	61.0
	Aviators	2	-	49.0	-	59.9	-
	Ground Troops	2	-	49.8	-	58.7	-
	Female						
	AF Nurses	3	45.0	46.0	49.5	52.8	54.6
	Unspecified Military Personnel	2	-	43.7	-	51.6	-
6 Popliteal Height	Male						
	AF Flight Personnel	1	38.9	39.9	43.2	46.2	47.8
	Aviators	2	-	38.4	-	47.8	-
	Ground Troops	2	-	40.6	-	50.0	-
	Female						
	Civilians (Age 25-34)	4	33.5	35.8	40.1	44.4	46.2
7 Buttock-Heel Length (Diagonal)	Male Aviators	2	—	263.9	—	305.8	—

DIMENSIONS IN CENTIMETERS

(inches on next page)



[a] ALL OF THESE DATA ARE BASED ON NUDE BODY MEASUREMENTS AND SHOULD BE CORRECTED AS REQUIRED FOR CLOTHING MEASUREMENTS, PARTICULARLY FOR SHOE HEIGHT

[b] ERECT DIMENSION IS APPROXIMATELY 2.0 cm GREATER

[c] ERECT DIMENSION IS APPROXIMATELY 4.1 cm GREATER

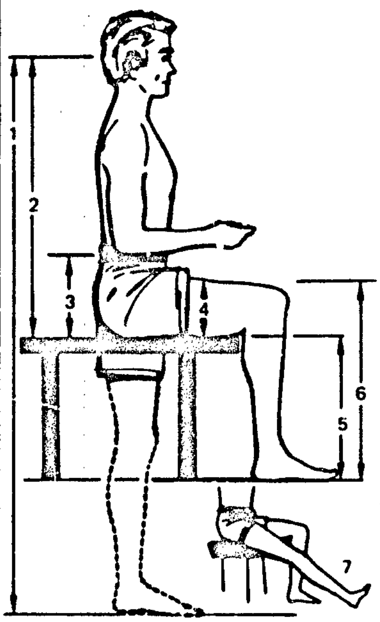
Figure 6.1-2. Selected Body Dimensions in Centimeters

6.1.1 ANTHROPOMETRIC DATA (CONTINUED)

Dimension[a]	Group	Original Source (Ref. 3.8)	Percentile 1	5	50	95	99
1 Standing Eye[b] Height, Relaxed	Male AF Flight Personnel	1	58.4	60.0	63.9	67.8	69.5
	Female AF Nurses (Estimated Values)	3	53.4	54.8	58.3	62.3	64.1
2 Seated Eye[c] Height, Relaxed	Male AF Flight Personnel	1	26.9	27.8	29.9	31.9	32.8
	Aviators	2	-	27.4	-	32.3	-
	Ground Troops	2	-	27.0	-	31.7	-
	Female AF Nurses	3	25.2	26.2	28.2	30.0	31.1
	Unspecified Military Personnel	2	-	26.0	-	29.9	-
3 Elbow Rest Height	Male AF Flight Personnel	1	6.6	7.4	9.1	10.8	11.5
	Aviators	2	-	7.4	-	11.0	-
	Ground Troops	2	-	6.9	-	11.0	-
	Female Civilian (Age 25-34)	4	6.1	7.4	9.3	11.1	11.9
4 Thigh Clearance Height	Male AF Flight Personnel	1	4.5	4.8	5.6	6.5	6.8
	Aviators	2	-	4.9	-	7.4	-
	Female Civilian (Age 25-34)	4	4.0	4.2	5.4	6.9	7.7
5 Knee Height	Male AF Flight Personnel	1	19.5	20.1	21.7	23.3	24.0
	Aviators	2	-	19.3	-	23.6	-
	Ground Troops	2	-	19.6	-	23.1	-
	Female AF Nurses	3		18.1	19.5	20.8	21.5
	Unspecified Military Personnel	2	-	17.7	-	20.5	-
6 Popliteal Height	Male AF Flight Personnel	1	15.3	15.7	17.0	18.2	18.8
	Aviators	2	-	15.1	-	18.8	-
	Ground Troops	2	-	16.0	-	19.7	-
	Female Civilians (Age 25-34)	4	13.2	14.1	15.8	17.5	18.2
7 Buttock-Heel Length (Diagonal)	Male Aviators	2	-	103.9	-	120.4	-

DIMENSIONS IN INCHES

(centimeters on previous page)



[a]ALL OF THESE DATA ARE BASED ON NUDE BODY MEASUREMENTS AND SHOULD BE CORRECTED AS REQUIRED FOR CLOTHING MEASUREMENTS, PARTICULARLY FOR SHOE HEIGHT

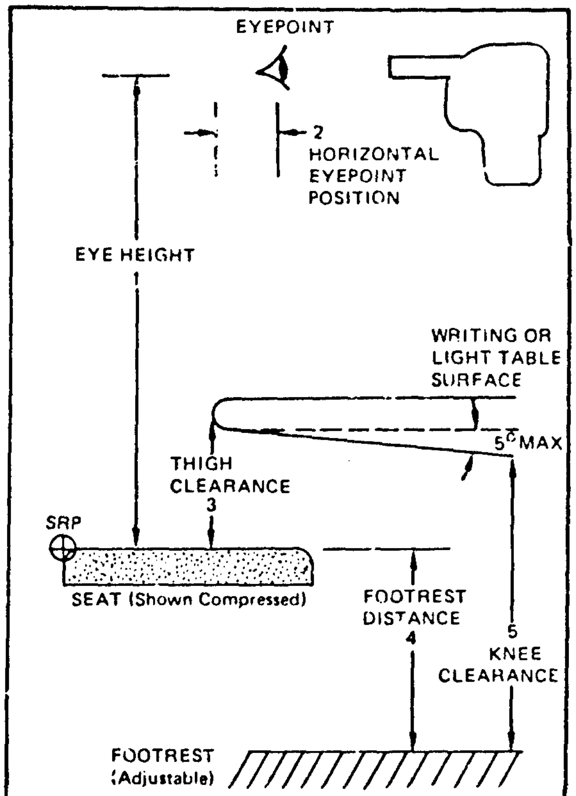
[b]ERECT DIMENSION IS APPROXIMATELY 0.8 IN GREATER

[c]ERECT DIMENSION IS APPROXIMATELY 1.6 IN GREATER

Figure 6.1-3. Selected Body Dimensions in Inches

6.1.2 FIXED EYEPOINT WORKSTATION DIMENSIONS

This section provides recommendations for dimensions in a display where the operator's *eyepoint* is fixed. A typical example is the common small-exit pupil microscope mounted on a light table.



Dimension	Recommended Value(s)	Comments
1 Eye Height for Horizontal Eyepiece	Maximum is 66.5 cm (26.2 in) 5% Female or 69.8 cm (27.5 in) 5% Male	Reduce Maximum Height to Account for Eyepiece Tilt (Section 6.1.3) and if Eyepoint Moves More than 5 cm (2 in) Beyond Edge of Table
2 Horizontal Eyepoint Position	See Text	
3 Thigh Clearance	17.8 cm (7 in)	28 cm (11 in) to cross knees
4 Footrest Distance	Adjustable from 38 cm (15 in) for 5% Female to 53 cm (21 in) for 95% Male	2.5 cm (1 in) Added for Shoes—Modern Shoe Styles May Require a Greater Correction
5 Knee Clearance	63.5 cm (25 in) Minimum for 99% Male	2.5 cm (1 in) Added for Shoes—Modern Shoe Styles May Require a Greater Correction

Figure 6.1-4. Critical Dimensions for Fixed Eyepoint Displays. Dimensions particularly important in fixed eyepoint displays are illustrated here.

The value for eye height (Dimension 1) is a maximum for a nonadjustable eyepiece, since it is easier for a tall operator to slump an extra few inches than for a short operator to stretch to reach an eyepiece that is too high. It is based on a horizontal eyepiece angle and must be reduced downward if the eyepieces are tilted (Figure 6.1-5). Because of the variation in eye height (Dimension 2 in Figures 6.1-2 and -3), adjustment of eye height should be possible. Some of this adjustment can be achieved by varying eyepiece elevation angle (Figure 6.1-5).

Dimension 2 is the displacement of the eyepoint beyond the first obstruction that limits forward movement of the operator's body, usually the edge of a light table or desk. There is little relevant data but if the 5 cm (2-in) value is not exceeded there should be no problems. Larger values are feasible, but at some point they will cause the operator's eye height (Dimension 1) to drop as his trunk bends around the obstruction. Specific values are not available and must be determined by use of a mockup if the situation is marginal. Also, see Figure 6.1-5.

The allowance for thigh clearance (Dimension 3) must be at least 18 cm (7 in), since thigh thickness is essentially uncorrelated with eye height (Ref. 2,B). In other words, short people may have large thighs. Increasing this value to 28 cm (11 in) increases freedom to position legs.

A footrest (Dimension 4) allows the thigh to be raised slightly off the seat, thereby maintaining circulation and reducing discomfort. To accommodate the necessary range of body sizes, either the chair or the footrest should be adjustable over the range indicated. The adjustment must be simple to perform. A footrest deep enough to allow fore and aft movement of the legs is preferred over a simple railing.

Although it is not included in the figure, adequate space for the user to stretch his legs (Dimension 7 in Figure 6.1-2) is highly recommended. Also, see the discussion of chairs in Section 7.2.

One aspect of viewing device use not illustrated in this figure is the tendency of most users to place their lower arms on the light table/writing surface and to use it to carry part of the weight of their upper body. Good data on the best height are not available, but for some applications the 20 to 25 cm (8 to 10 in) armrest height recommended in Figure 7.2-3 may provide useful guidance. A surface used for an elbow or armrest can be considerably higher than this so long as it extends out beyond the sides of the operator.

6.1.3 EYEPIECE ELEVATION ANGLE

A wide range of eyepiece elevation angles is in use. Some displays, particularly many older comparators, use horizontal eyepieces. The popular Bausch and Lomb Zoom 70 and Zoom 240 microstereoscopes have eyepiece elevations approximately 60° above horizontal.

The available data allow setting only very broad limits on eyepiece elevation angle. Elevation angle affects workstation design in two ways. First, as the next figure illustrates, it affects the permissible eyepoint location envelope.

In addition, eyepiece elevation angle can have an impact on the physical comfort of the display user. If the eyepieces are near horizontal, the user's weight is thrown back toward the rear of his chair and onto the chair backrest (see Section 7.3). If these are inadequate, e.g., if he is using an executive style chair with armrests that prevent moving the backrest close enough to the display, he will be unable to relax his trunk muscles while looking into the display and may therefore suffer fatigue. As the eyepiece angle raises above horizontal the user's head will drop forward, shifting his weight forward onto the front edge of his chair and onto his arms if an armrest such as the surface of a light table is available. Again, if the support surfaces are inadequate, the result may be excessive muscle tension and fatigue.

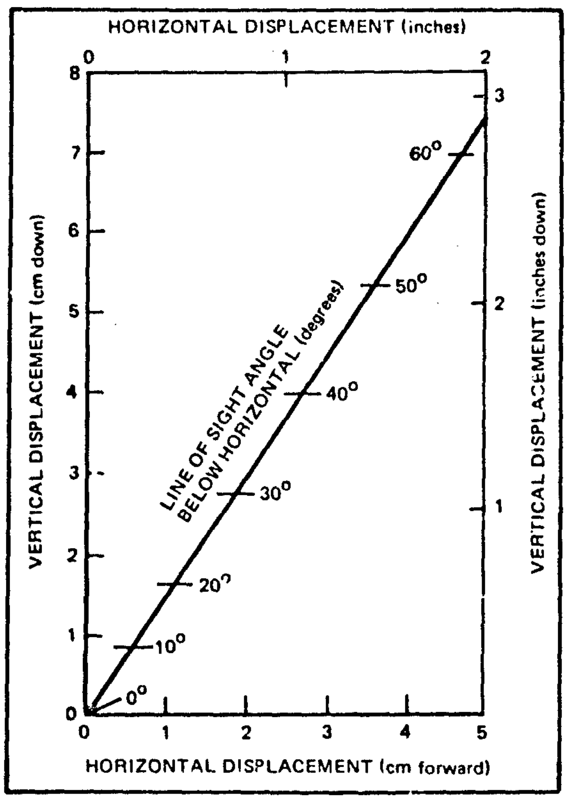
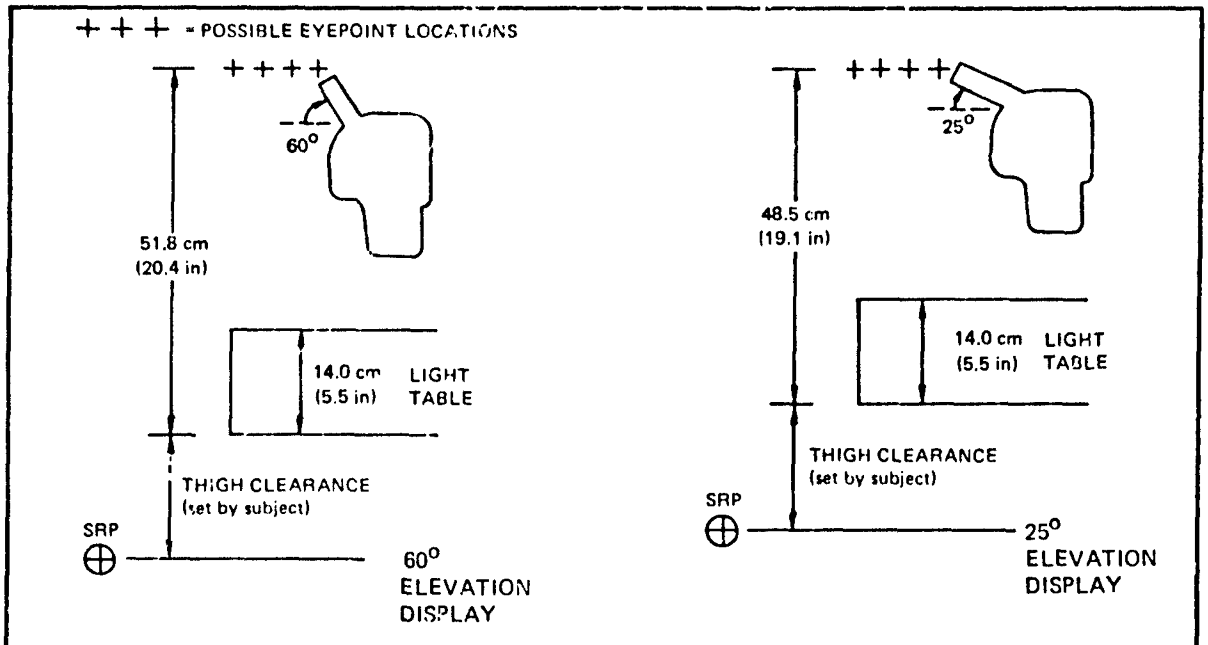


Figure 6.1-5. Eyepoint Displacement as Line of Sight Drops. The eyepoint location shown in the previous figure is for a horizontal line of sight. As the line of sight drops below horizontal, neck rotation moves the eyes down and forward by the amount illustrated (Ref. 4,C). When designing for an eyepiece angle above horizontal, this figure should be used to determine the appropriate reduction in Dimension 1, and increase in Dimension 2, that is appropriate in Figure 6.1-4.

SUBJECT	NOT COMFORTABLE	COMFORTABLE	NOT COMFORTABLE
1	0	5-60	65
2	5	10-55	60
3	5	10-60	70
4	5	10-60	70
5	15	20-60	65
6	5	10-60	65

Figure 6.1-6. Eyepiece Elevation Angle Comfort Limits. Eyepiece elevation angle comfort limits were established for six image interpreters as they used a mockup of a binocular display that allowed free adjustment of both vertical position and elevation angle (Ref. 5,D). the data suggest that while an elevation angle of 10 to 60° will be generally acceptable, a value between 20 and 55° is a safer design choice.

6.1.3 EYEPIECE ELEVATION ANGLE (CONTINUED)



SUBJECT EYE HEIGHT (percentile)	2	5	5	5	8	15	95
THIGH THICKNESS cm (inches)	15.2 (6.0)	15.2 (6.0)	13.5 (5.3)	13.7 (5.4)	18.5 (7.3)	15.0 (5.9)	16.3 (6.4)
PREFERRED ELEVATION	25°	25°	EITHER	60°	25°	25°	EITHER
SUBJECT COMMENTS	CANNOT USE 60°	CANNOT USE 60°	TABLE TOO HIGH AT 25°*	TABLE TOO HIGH AT 25°*	CANNOT USE 60°	CANNOT USE 60°	MAKES NO DIFFERENCE

*THE 25° ELEVATION MADE THE TABLE TOO HIGH TO SERVE AS A CONVENIENT ARMREST. NOTE THAT THESE TWO SUBJECTS HAD SMALL THIGHS AND THEREFORE COULD REACH THE EYEPOINT FOR THE 60° ELEVATION.

Figure 6.1-7. Preferences for 60° vs. 25° Eyepiece Elevation Angles. Several of the factors discussed above are illustrated by a study conducted to compare two eyepiece elevation angles for use on one particular microscope/light table combination (Ref. 6,C). The upper part shows the two viewing situations. Reducing eyepiece elevation angle from 60° to 25° reduced the microscope eyepoint to thigh distance by over 3 cm. Figure 6.1-5 shows that it also raised the permissible operator's eye position above the SRP by an additional 4 cm. Thus the eyepoint is effectively 7 cm further above the seat for the 60° display than for the 25° display. (This is a good example of how the equipment design and the operator's physical characteristics can interact and illustrates the desirability of using a mockup to evaluate complex designs.)

These differences are reflected in the user preference data at the lower part of the figure. Four of the six short subjects had difficulty reaching the 60° eyepieces and preferred the 25° version. Two other short subjects, both of whom had thin thighs and could therefore lower the light table relative to their chair, were able to use the 60° eyepieces and complained that the 25° angle placed the light table surface too high for convenient use as an armrest. The single large subject found both angles acceptable.

6.1.4 VISUAL WORK AREA

So long as the operator's position is not restrained, by a seat belt for example, he can change his head and body position in order to look at a display in almost any location not physically obstructed. Some locations, however, are more convenient and are therefore likely to be viewed more frequently and to result in a more rapid response to the displayed information. This is particularly true of locations close enough to the operator's normal line of sight that he can look at them without turning his head. (See Section 3.5.)

Distance to visual displays is treated in Section 3.6.

If there are controls adjacent to a display that must be adjusted, the manual workspace limits in the next section (6.1.5) apply.

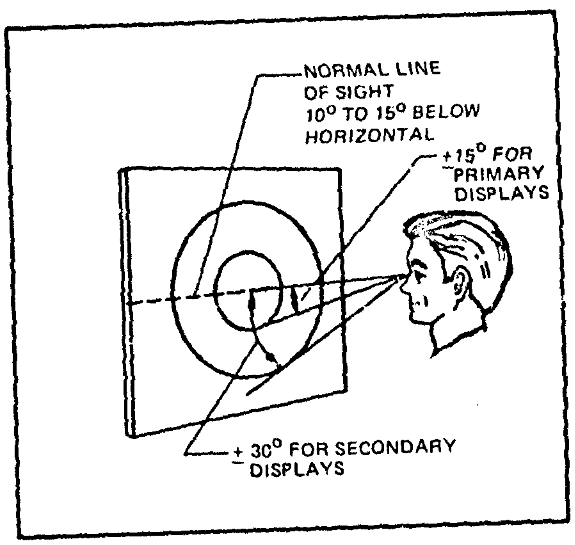


Figure 6.1-8. Preferred Visual Work Area (Ref. 7,X). The normal line of sight is usually taken as 10 to 15 degrees below horizontal. Primary displays should generally be within 15 degrees of this line and secondary ones within 30 degrees. Although some head movement accompanies nearly all eye movements, major head and neck movements occur for viewing angles of more than 30 degrees to each side. Eye elevations above the horizontal are especially fatiguing and should be avoided except for intermittent viewing. Viewing angle depressions to 45 degrees are acceptable, even though some head motion will occur.

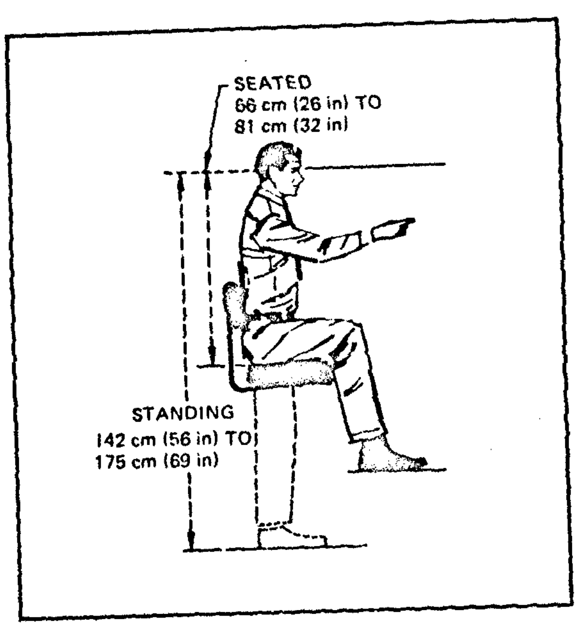


Figure 6.1-9. Eye Height for Visual Work. Eye heights for seated and standing 5th percentile female and 95th percentile male operators are from Figure 6.1-2, -3. The value for standing operators includes 2.5 cm (1 in) for shoes. Modern shoe styles may require a larger correction.

6.1.5 MANUAL WORK AREA

The most important and frequently used controls should be located where they can be operated with the greatest comfort and convenience, and all controls must be within easy reach. The data presented below provide a guide to control placement. Many additional pages of data are available (Ref. 8,B). In many situations, however, there is no good alternative to a mockup evaluation utilizing individuals with the extremes of body dimensions that will occur in the user population.

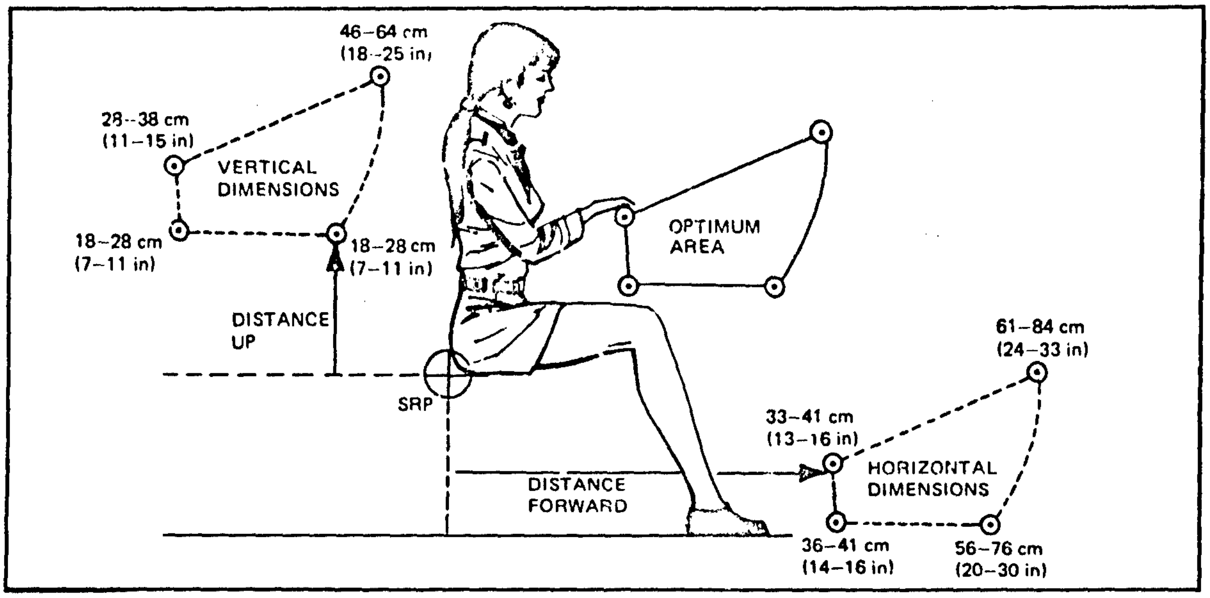


Figure 6.1-10. Optimum Manual Work Area. The optimum manual work area illustrated here results from the need to provide a comfortable lower arm position and elbow flex angle (Ref. 9,X). It is suitable for operators ranging in size from 5th percentile female to 95th percentile male.

The width of this area is approximately 60 cm (24 in).

HEIGHT ABOVE SEAT REF. PT. (cm)	ANGLE FROM STRAIGHT AHEAD REACH (centimeters)						
	0°	15°	30°	45°	60°	75°	90°
0	-	-	-	40.6	45.5	44.2	47.0
15	15.2	-	-	56.9	60.5	60.7	65.0
30	49.3	54.6	59.7	63.2	68.6	70.1	71.1
46	54.1	58.2	64.5	68.3	71.4	74.4	76.2
61	54.9	59 4	63.2	67.1	71.1	73.4	76.2
76	51.1	55.9	60.2	67.1	69.6	71.9	74.4
91	44.2	47.5	51.3	56.9	60.7	63.8	65.8
107	32.3	33.5	34.5	40.6	48.8	51.6	53.6

HEIGHT ABOVE SEAT REF. PT. (in)	ANGLE FROM STRAIGHT AHEAD REACH (inches)						
	0°	15°	30°	45°	60°	75°	90°
0	-	-	-	16.0	17.9	17.4	18.5
6	17.0	-	-	22.4	23.8	23.9	25.6
12	19.4	21.5	23.5	24.9	27.0	27.6	28.0
18	21.3	22.9	25.4	26.9	28.1	29.3	30.0
24	21.6	23.4	24.9	26.4	28.0	28.9	30.0
30	20.1	22.0	23.7	26.4	27.4	28.3	29.3
36	17.4	16.7	20.2	22.4	23.9	25.1	25.9
42	12.7	13.2	13.6	16.0	19.2	20.3	21.1

Figure 6.1-11. Functional Forward Reach for the Seated Operator. Functional arm reach (grasp distance) data for 5th percentile male military personnel are shown (Ref. 10,X).

These values are for a seated, restrained operator. They can be increased as follows:

- Shoulder extension, 10 cm (4 in) at 0° and 7.5 cm (3 in) at 45°
- Shoulder extension plus trunk rotation, 15 cm (6 in) at 0° and 10 cm (4 in) at 45°
- Complete freedom to bend forward, 40 cm (16 in) at 0°, 30 cm (12 in) at 45°, and 20 cm (8 in) at 90°

6.1.6 CONSOLE DIMENSIONS

Workstation consoles must be designed to fit the operational requirements and space limitations of the particular situation.

As an aid to this design process, Figure 6.1-12 below indicates the minimum clearances that should be provided, and Figure 6.1-13 shows dimensions for typical consoles. Additional information on this topic can be found in Reference 11.

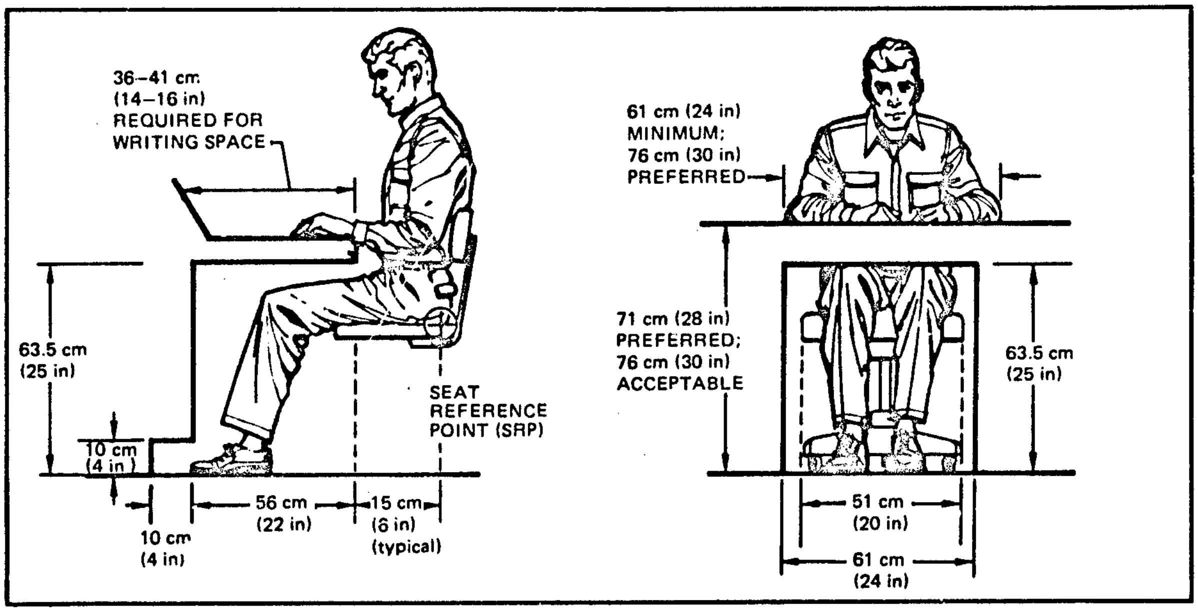


Figure 6.1-12. Minimum Leg and Foot Clearances for Consoles (Ref. 12,X).

6.1.6 CONSOLE DIMENSIONS (CONTINUED)

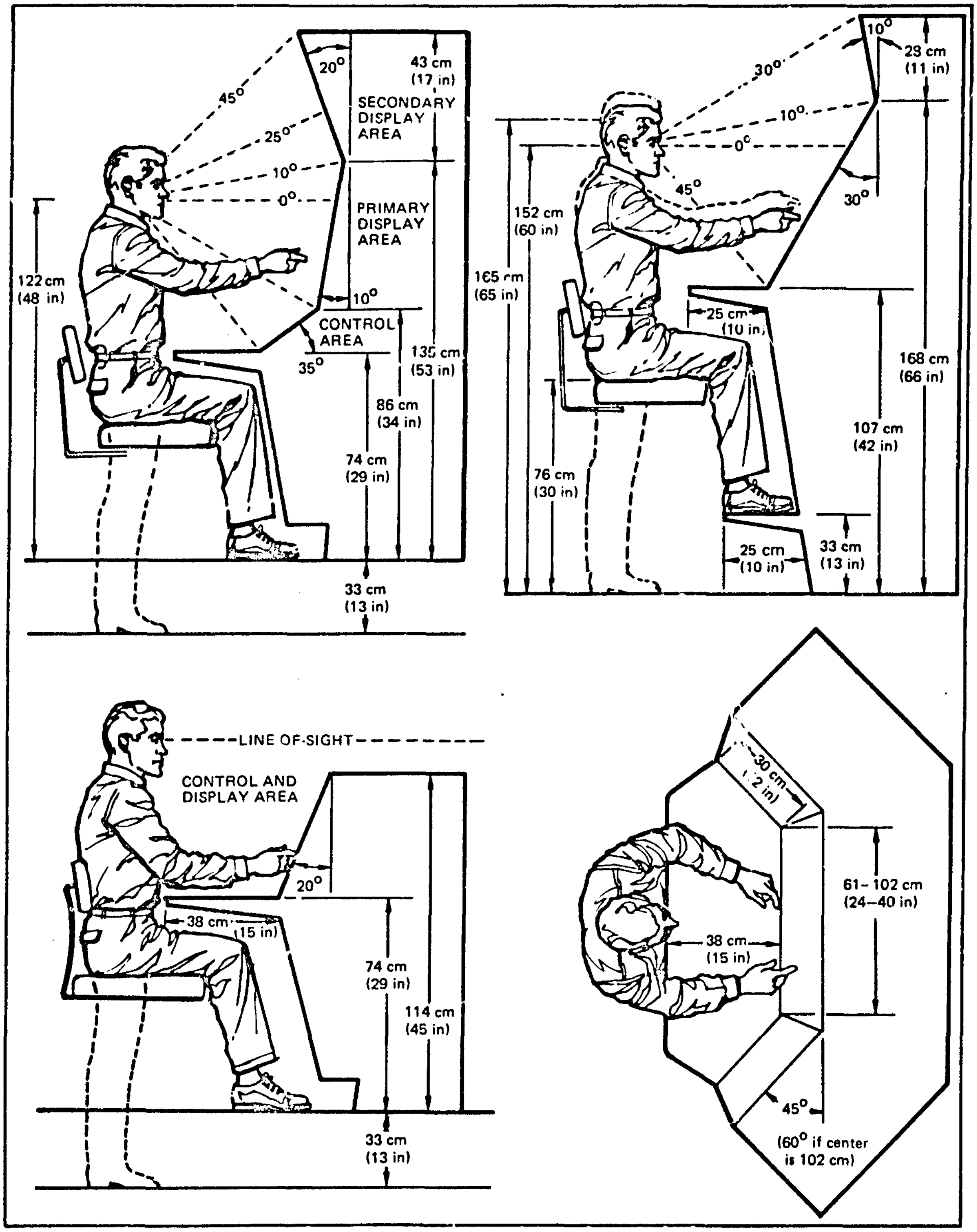


Figure 6.1-13. Typical Console Configurations (Ref. 12,X).

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(4) National Health Survey. *Weight, Height and Selected Body Dimensions of Adults: United States, 1960-62* (H. W. Stoudt, A. Damon, R. A. McFarland, and J. Roberts). U.S. Public Health Service, Washington, D. C., 1965. (Cited in Damon, A., Stoudt, H. W. and McFarland, R. A. *The Human Body in Equipment Design*. Cambridge, Harvard University Press, 1966.)

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11. See Chapters 9 and 10 of Ref. 7.

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6.2 CONTROLS

6.2.1 Continuous Controls

6.2.2 Discrete Position Controls

SECTION 6.2 CONTROLS

Recommendations for specific types of controls are summarized in this section. The more general problems of control arrangement and the association between controls and displays are treated in Section 6.3.

Much of the material in this section was extracted from design handbooks (Ref. 1), with modifications as required by personal experience in the design and evaluation of control panels. In those instances where research reports were also used, they have been referenced.

Recommended control resistances are to be measured linearly unless they are referred to specifically as torques. To be correct, force in the metric system should be specified in newtons or dynes. However, commonly available scales are calibrated in grams so this unit has been used instead (Ref. 2).

Minimum separation distances between controls usually apply also to the separation between the control and the nearest obstruction.

Increased use of integrated circuits has generated pressure to reduce control panel size and to incorporate special logic codes into control devices. The result has been miniaturized controls, multifunction controls whose effect depends on the setting of some other control, and completely new types of controls for which there are no established design recommendations. In some instances recommendations for more traditional types of controls provide guidance, but in others there is no good alternative to installing the new control in a panel and having operators try it. This topic is discussed briefly in Section 6.7.

6.2.1 CONTINUOUS CONTROLS

Continuous position controls, in contrast with controls that have a limited number of discrete positions, can be set to any position within the limits of control movement.

TYPE	FIGURE NUMBER	COMMENTS
LEVER	6.2-2	ALLOWS LARGE FORCES; INDICATES SETTING; SUBJECT TO ACCIDENTAL ACTIVATION
JOYSTICK	6.2-3	SPECIALIZED LEVER; USUALLY MOVES IN TWO DIMENSIONS; SUBJECT TO ACCIDENTAL ACTIVATION
TRACKBALL	6.2-4	EXCELLENT POSITION CONTROL WHEN A LARGE RANGE OF INPUT COMMANDS ARE NECESSARY
CRANK	6.2-5, -6, -7, -13	ALLOWS RAPID, MULTIPE TURNS; USEFUL TO OBTAIN LARGE AMOUNTS OF WORK
KNOB	6.2-8 TO -14	ALLOWS PRECISE ADJUSTMENT; INDICATES SETTING
THUMB-WHEEL	6.2-15	MINIMUM PANEL SPACE; POOR DISPLAY OF SETTING
LINEAR SLIDE	6.2-16	WASTES PANEL SPACE; EXCELLENT INDICATION OF SETTING; SUBJECT TO ACCIDENTAL MOVEMENT
FOOT PEDAL	6.2-17	USED TO OBTAIN LARGE FORCES OR WHEN BOTH HANDS ARE OCCUPIED

Figure 6.2-1. Types of Continuous Position Controls

6.2.1 CONTINUOUS CONTROLS (CONTINUED)

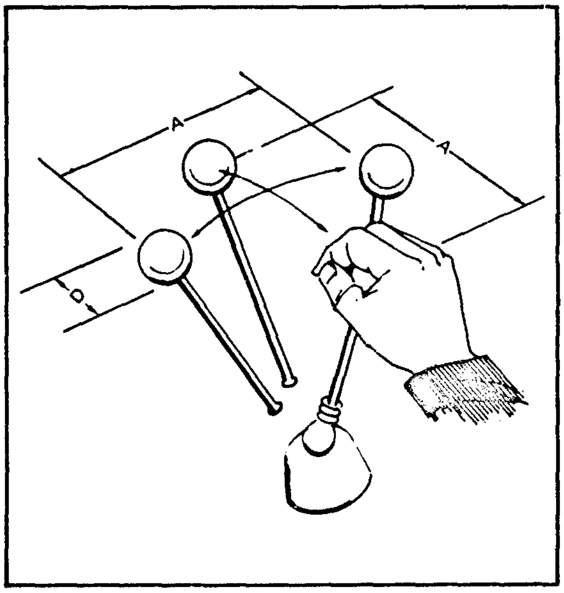

Figure 6.2-2. Levers

Parameters:

Diameter (D): 13 to 75 mm (0.5 to 3.0 in) for finger grasp and 38 to 75 mm (1.5 to 3.0 in) for hand grasp.

Displacement (A): Up to 350 mm (14 in) fore-aft and 950 mm (38 in) laterally

Separation for one-hand use: 100 mm (4.0 in) preferred, 50 mm (2.0 in) acceptable

Resistance for finger use: Up to 900g (32 oz)

Resistance for one-hand use: 1 to 14 kg (2 to 30 lb) fore-aft and 1 to 10 kg (2 to 20 lb) laterally

Design Notes:

- For fine adjustments or continuous use, provide support for the limb used

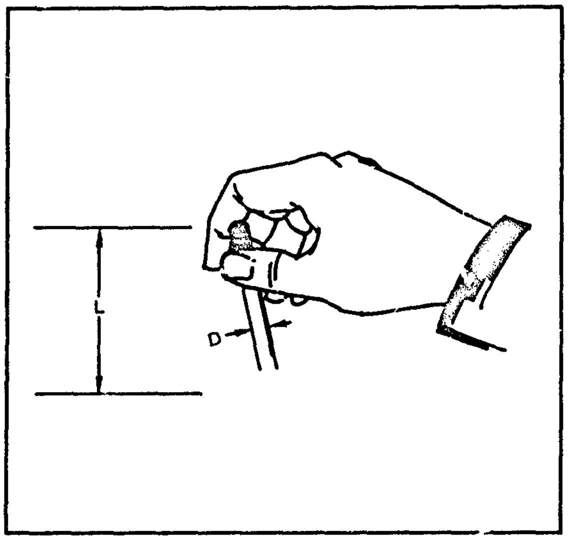

Figure 6.2-3. Joysticks

Parameters:

Diameter (D): 6 to 25 mm (0.25 to 1.0 in)

Length (L): 75 to 150 mm (3.0 to 6.0 in)

Displacement: Up to $\pm$ 45°

Resistance (at tip): 340 to 900g (12 to 32 oz)

Design Notes:

- Provide support for the body part used to manipulate the joystick. If the stick is held by the fingers, the support should be at the wrist
- Locate the pivot point below the support surface
- *Isometric* (force) *joysticks* offer performance and reliability advantages for some applications, but should be avoided for most image translation applications unless they incorporate an indication to the user when he is making a maximum input (Ref. 3). (See Section 3.10.4.)
- A *position joystick* can be set to within 1.5 steps in a 800-step display (RMS error) (Ref. 4).
- If pushbutton is added to the center of the joystick to obtain two output ranges, expect a reduction in joystick positioning precision when the pushbutton is depressed.
- See Section 3.10.5 for a discussion of a particular joystick application.

6.2.1 CONTINUOUS CONTROLS (CONTINUED)

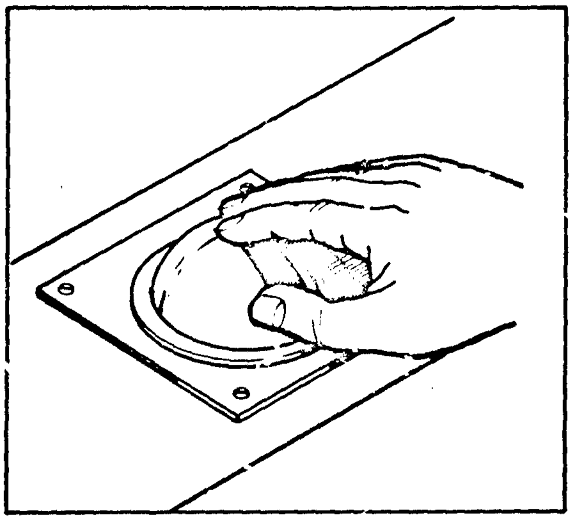

Figure 6.2-4. Trackballs

Parameters (Ref. 5)

Diameter: No operator-imposed restrictions; 75 to 100 mm (3 to 4 in) typical.

Resistance: 35 gm (1.2 oz) works well and allows easy slewing with a 90 mm (3.5 in) plastic ball; increasing resistance to 57 to 85 gm (2.0 to 3.0 oz) to eliminate movement due to vibration is acceptable but will reduce slewing and increase time to make large inputs.

Design Notes:

- Setting precision depends on how precisely the operator can position his hand along the circumference of the ball. With an adequate display, an RMS error of 0.7 mm (0.03 in), which is equivalent to 1/400 revolution of an 8.9 cm (3.5 in) diameter ball, is reasonable.

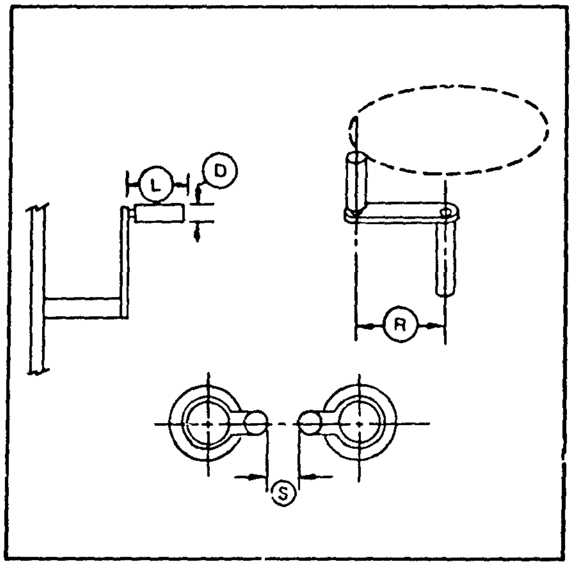

Figure 6.2-5. Cranks

	CRANK OPERATING MODE		
	HIGH SPEED LIGHT LOAD	MEDIUM TO HEAVY LOAD, MULTIPLE TURNS	PRECISE POSITIONING, LESS THAN ONE TURN
CRANK RADIUS (R)	13 TO 125 mm (0.5 to 5 in)	100 TO 500 mm (4 to 20 in)	13 TO 500 mm (0.5 to 20 in)
RESIST-ANCE AT HANDLE	0.9 TO 2.3 kg (2 to 5 lb)	2.3 TO 4.5 kg (5 to 10 lb)	0.9 TO 3.6 kg (2 to 8 lb)
HANDLE DIAMETER (D)	13 mm (0.5 in)	13 TO 25 mm (0.5 to 1.0 in)	13 TO 25 mm (0.5 to 1.0 in)
HANDLE LENGTH (L)	38 mm (1.5 in)	95 mm (3.8 in)	95 mm (3.8 in)

Separation (S): At least 75 mm (3 in)

Design Notes:

- Use a handle that rotates freely on its shaft.
- A crank handle can be combined with a knob to allow rapid slewing with the crank and fine positioning with the knob (see Figure 6.2-13).
- For large resistances, orient the rotation axis parallel to the frontal plane of the body (a vertical plane through the shoulders)

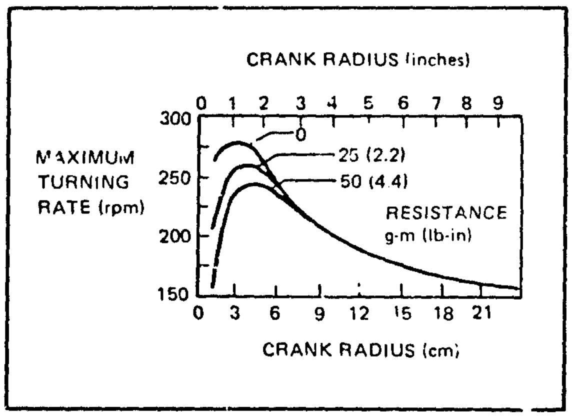

Figure 6.2-6. Maximum Cranking Speed (Ref. 6,X). With a light load the maximum turning rate is achieved with a crank radius of 3 to 5 cm. As crank resistance (expressed as torque) increases, a slightly larger crank is required in order to achieve maximum speed.

6.2.1 CONTINUOUS CONTROLS (CONTINUED)

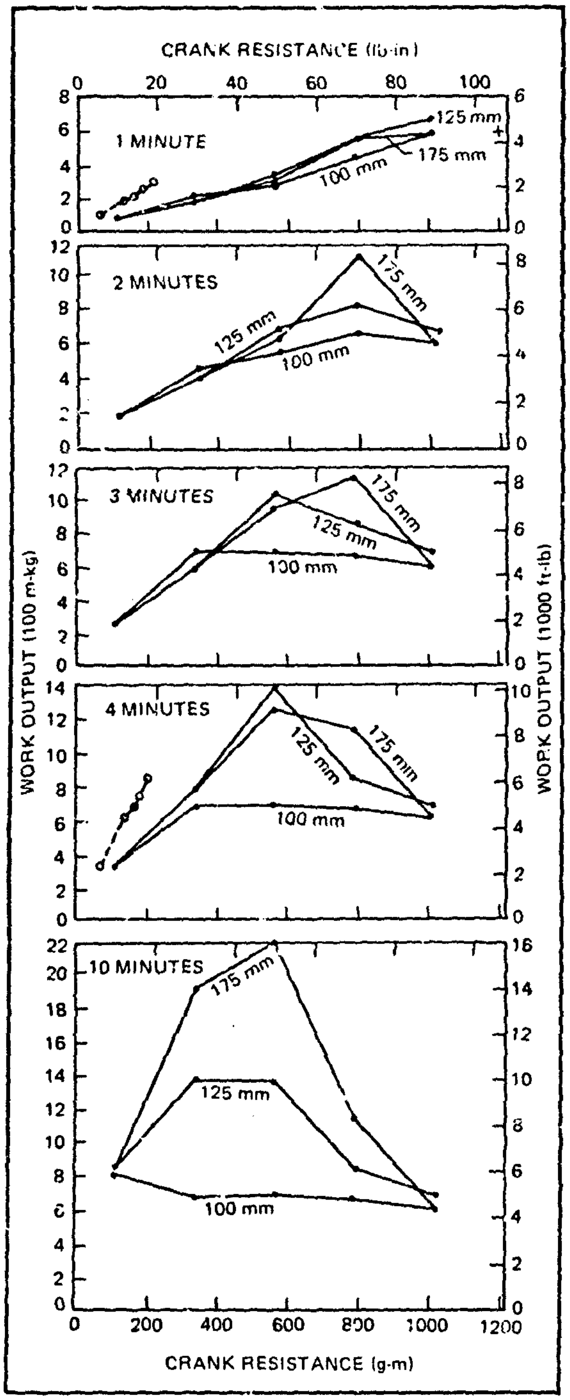

Figure 6.2-7. Work Output With Cranks. A crank may be used to enable an operator to perform work. The amount of work that can be obtained increases with the time available for the task. For infrequently performed tasks that do not contribute directly to the interpretation of imagery, such as elevating a display, a reasonable upper limit might be 2 minutes. In the absence of any test data on the user population, the designer may choose to use a different value.

These curves illustrate the maximum amount of work that might be expected as a function of crank resistance (torque) after given intervals of time. They are all based on one-hand cranking at waist height by military personnel, or the equivalent, and were collected as follows:

- •—• Average scores; maximum constant speed for maximum time (stopped at 10 minutes if still cranking; three crank sizes) (Ref. 7,C).
- o-o Average scores; maximum speed for 4 minutes; 11.5 cm (4.5 in) crank (Ref. 8,C).
- + Output by 85% of small (5 45 percentile) personnel; maximum speed for maximum time (subjects quit after about 1 minute); 19 cm (7.5 in) crank (Ref. 9,C). These data appear only in the upper graph.

The 1-minute curves at the top are directly equivalent to horsepower (0.1 horsepower is equal to 450 m-kg (3300 ft-lb) per minute.)

Heavier crank resistances increased the rate of work output, but decreased the maximum amount of work that was eventually obtained. In order to avoid the fatigue effects evident for the heavier crank resistances in the lower sets of curves, crank resistance should not exceed 560 g-m (50 lb-in). This would be equivalent to a handle resistance of 5.4 kg (12 lb) for a 100 cm (4 in) crank and 3.2 kg (7 lb) for a 175 cm (7 in) crank.

Total work output of 550 m-kg (4000 ft-lb) over a period of 2 to 3 minutes is reasonable for male personnel of military age. Some reduction should be made for female personnel; in the absence of any data, a reduction of 30% is reasonable.

6.2.1 CONTINUOUS CONTROLS (CONTINUED)

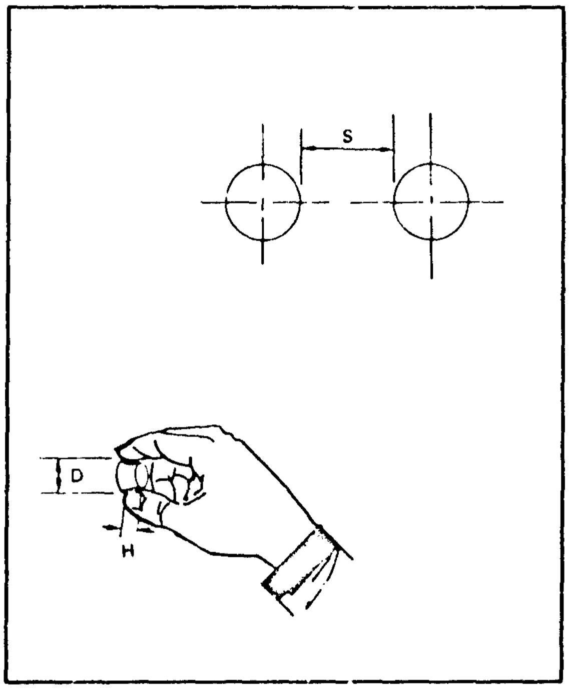

Figure 6.2-8. Continuous Position Knobs

Diameter (D): 13 to 75 mm (0.5 to 3 in); 50 to 75 mm (2 to 3 in) for heaviest resistances.

Depth (H): 13 to 25 mm (0.5 to 1 in)

Separation (S): For one hand operation, no less than 25 mm (1 in), with 50 mm (2 in) preferred. For simultaneous operation by two hands, no less than 75 mm (3 in), with 125 mm (5 in) preferred.

Resistance: Up to 4.2 g-m (6 oz-in) for small knobs or many turns; up to 11.3 g-m (16 oz-in) for large knobs and only 1 or 2 turns. (See Figure 6.2-12 and Ref. 10,D.)

Design Notes:

- Operating time is a function of the required revolutions (Figure 6.2-10) and adjustment precision (Figure 6.2-11).
- For minimum operating time, do not require adjustment to less than 1 or 2° (Figure 6.2-11). (Section 3.8 covers application of this data to focus controls.)
- If more than four revolutions are frequently required, reduce operating time by adding a handle (Figure 6.2-13).
- For a pointer at a normal reading distance, 25 to 75 mm (1 to 3 in) of pointer travel for each revolution of the knob is reasonable (Ref. 11,C).
- For the higher resistances, use a knob with a nonslip surface. Knurl small knobs and flute the edges of large ones.
- Use a bar-shaped knob (Figure 6.2-19) if the operator must know the control setting.
- Backlash of up to 20° in the control will have little effect (Ref. 11,E) if:
  - There is a good display of the control setting. (Section 3.8.2 discusses a case where this is not true.)
  - Resistance is not excessive,
  - The display movement to control movement ratio is good, and
  - Required setting precision is not excessive and does not require several reversals of the control.
- When centering a knob between stops separated by from 20 to 160°, as might be required when focusing a microscope (see Section 3.8), the expected average error is 10 to 25% of the range, and the expected variation (one standard deviation) is 10 to 20% (Ref. 12,C).

6.2.1 CONTINUOUS CONTROLS (CONTINUED)

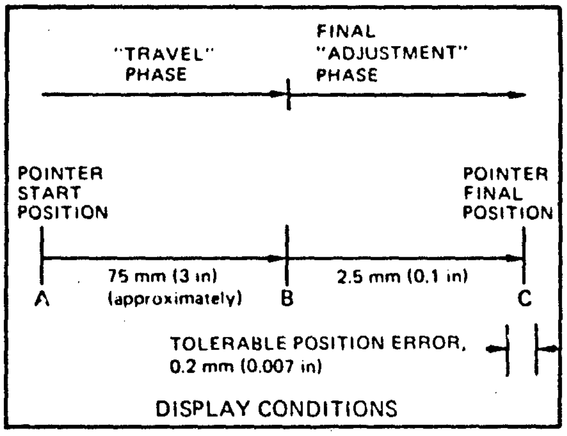

Figure 6.2-9. Display Conditions for the Knob Rotation Studies Described in Figures 6.2-10, -11, -12, and -13 Several useful numbers are available from two studies in which "travel" and "adjustment" times were measured as practiced subjects used a knob to position a pointer along a scale located at a distance assumed to be between 25 and 75 cm (10 and 30 in) (Ref. 11).

Knob diameter was generally 70 mm (2.75 in); other values, from 25 to 100 mm (1 to 4 in) did not affect the results.

In the next four figures, "travel" time is the time to move the pointer from A to B in the illustration, and "adjustment" time is the time to move it from B to C. Total time is the sum of these two.

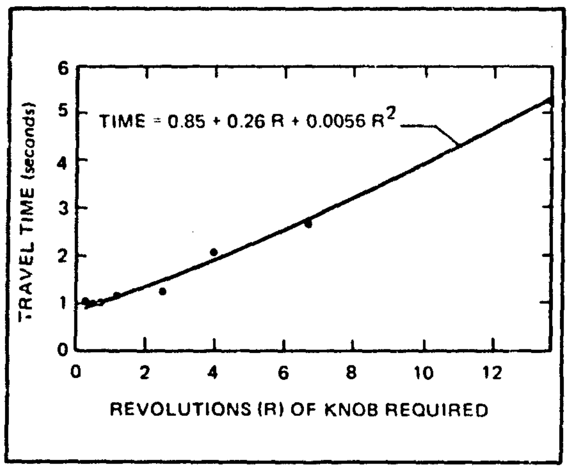

Figure 6.2-10. Time Required to Rotate a Knob. In one study with the display in Figure 6.2-9, different pointer movement per knob turn ratios necessitated different numbers of turns of the knob to complete the 75 mm (3 in) of travel. After the first turn or so, "travel" time increased almost linearly with the number of turns required (Ref. 11,C).

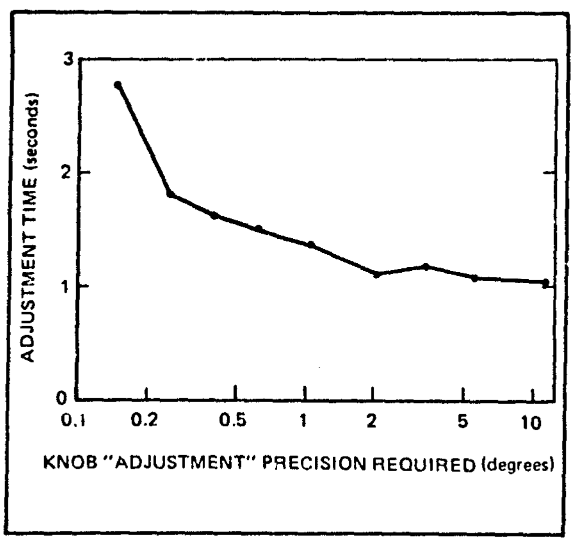

Figure 6.2-11. Time Required to Adjust a Knob. In one study with the display in Figure 6.2-9, increasing the pointer movement per knob turn ratio increased the knob adjustment precision necessary to place the pointer within the 0.2 mm (0.007 in) allowable area (Ref. 11,C). Very few incorrect settings were made, even when the knob had to be adjusted to within 0.15°. However, "adjustment" time increased when the knob had to be set to better than 2°. The authors, on the basis of the results shown in this and the previous figure, concluded that one revolution of a knob should move a scale of this type 30 to 60 mm (1.2 to 2.4 in).

6.2.1 CONTINUOUS CONTROLS (CONTINUED)

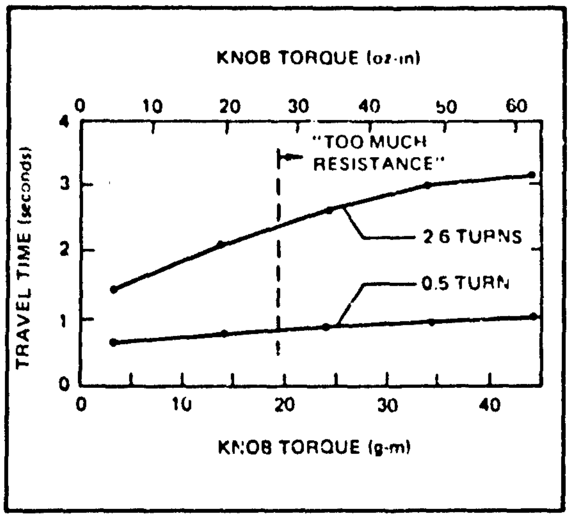

Figure 6.2-12. Influence of Knob Resistance on Adjustment Speed. In one study with the display in Figure 6.2-9, operators required more time to turn knobs that offered more resistance. They accepted a torque of 14 g-m (19 oz-in), but complained that 24 g-m (34 oz-in) was excessive (Ref. 13,C).

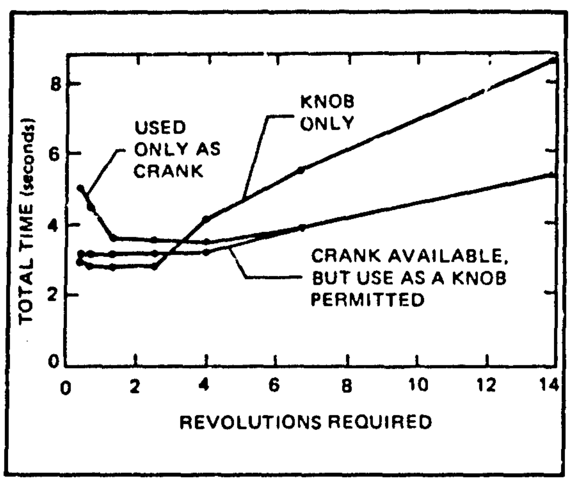

Figure 6.2-13. Addition of a Crank Handle to a Knob. In one study with the display in Figure 6.2-9, a knob was turned more rapidly through four or more revolutions when a handle was added so that it could be used as a crank (Ref. 11,C). Forcing subjects to use the handle for a small number of revolutions slowed performance.

6.2.1 CONTINUOUS CONTROLS (CONTINUED)

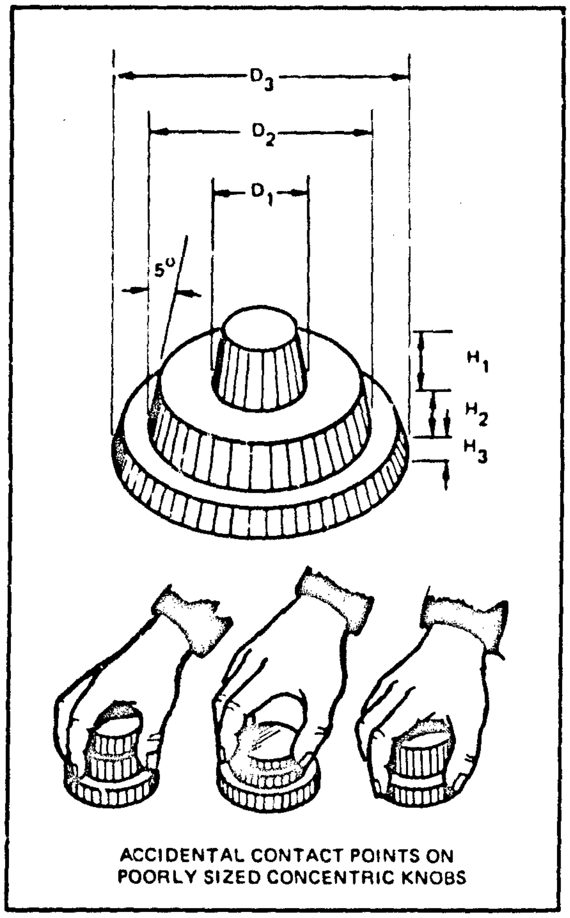

Figure 6.2-14. Concentric Continuous Position Knobs

Parameters (Ref.14):

Diameter (D_1): 13 mm (0.5 in)
(D_2): 44 mm (1.7 in.)
(D_3): 75 mm (3.0 in.)

Depth (H_1): 20 mm (0.8 in.)
(H_2): 20 mm (0.8 in.)
(H_3): At least 6 mm (0.25 in.)

Design Notes:

- Difficult to use without occasionally activating the wrong control
- Difficult to indicate to the user what is controlled by each portion of the knob (see Section 6.3)
- Limited to round knobs, which do not provide a good display of their position

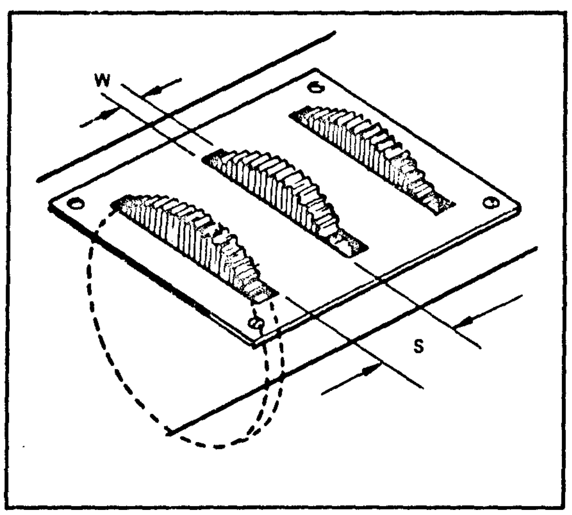

Figure 6.2-15. Continuous Thumbwheels

Parameters:

Wheel width (W):	No less than 3 mm (0.12 in)
Separation (S):	No less than 10 mm (0.38 in)
Resistance:	85 to 140-g (3 to 5 oz)

Design Notes:

- A detent is required if control has an OFF position

6.2.1 CONTINUOUS CONTROLS (CONTINUED)

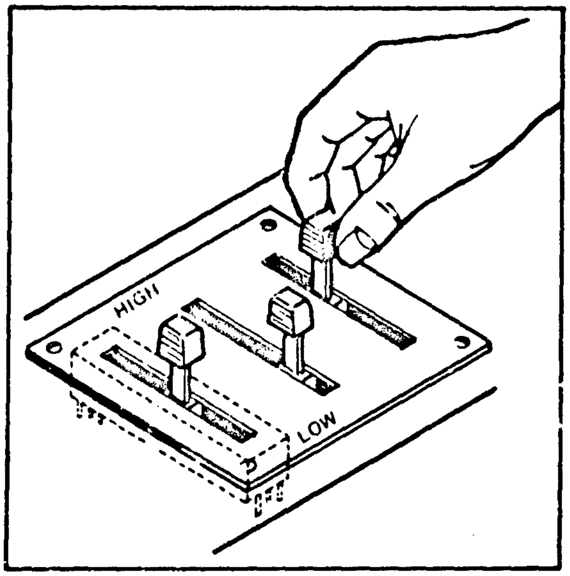

Figure 6.2-16. Linear Slides

Parameters:

None have been established. Resistance is a compromise between prevention of inadvertent movement and operator convenience.

Design Notes:

- Smooth resistance with motion is essential (and is provided by most commercially available units).

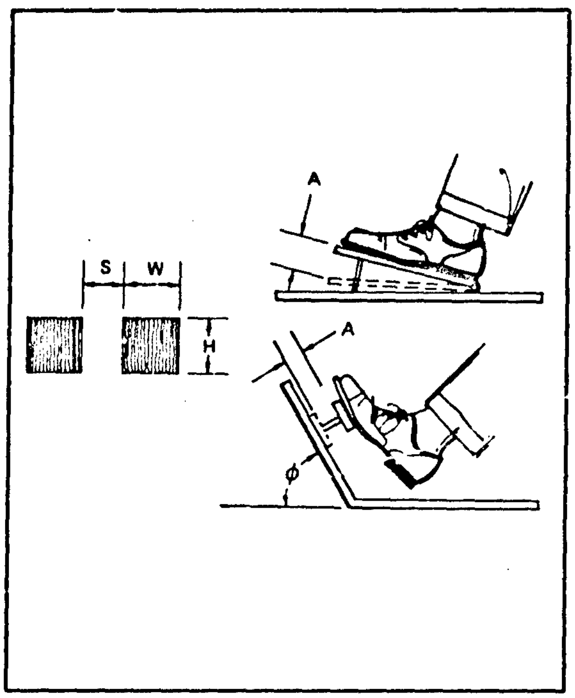

Figure 6.2-17. Foot Pedals

Parameters:

Height (H): No less than 25 mm (1.0 in)

Width (W): No less than 75 mm (3.0 in)

Displacement (A): Up to 63 mm (2.5 in) for ankle flexion and 180 mm (7.0 in) for leg movement

Resistance: Minimum of 2 kg (4 lb) if foot does not rest on pedal and 4.5 kg (10 lb) if it does; up to 4.5 kg (10 lb) for ankle flexion only and 9 kg (20 lb) for leg movement; if total leg can exert force against a secure backrest, 80 kg (180 lb) can be exerted (for male operators).

Separation (S): No less than 150 mm (6.0 in) for one-foot random operation and 100 mm (4.0 in) for one-foot sequential operations.

Slope (ϕ): Up to 60°

Design Notes:

- Pedals can serve to produce large amounts of force or displacement.
- A secure seating arrangement is necessary to obtain large forces.
- Use a heel support if the pedal is more than 20° above horizontal.
- Use non-slip surface.

6.2.2 DISCRETE POSITION CONTROLS

Discrete position controls can be set to any one of a limited number of exact positions.

A standard human engineering recommendation for discrete controls is a snap action, or detent, so that the operator has tactual and auditory feedback to indicate that the control has been actuated. Detents are clearly required with a multiposition control, such as a rotary knob or thumbwheel. With a pushbutton the need for a detent depends on the application. In general, the user should be provided with some type of feedback to indicate that he has actuated the control. This might be movement of the display, illumination of the control, or a detent. With pushbuttons that are used at high rates, as in a keyboard, a detent generally offers no advantage and may even reduce performance (Ref. 15,B).

TYPE	FIGURE NUMBER	NUMBER OF POSITIONS	COMMENTS
KNOB	6.2-19	3-24*	EASY TO ADJUST
THUMBWHEEL	6.2-20	3 OR MORE*	MINIMUM PANEL SPACE; LOW ERROR RATE (Ref. 16, B)
LEVER WHEEL	6.2-21	3 OR MORE	MINIMUM PANEL SPACE; DIFFICULT TO SET ACCURATELY WITHOUT EXTENSIVE PRACTICE (Ref. 17)
PUSHBUTTON WHEEL	6.2-22	3 OR MORE	NO DATA AVAILABLE
TOGGLE SWITCH	6.2-23	2 (3 IF CENTER OFF)	EASY TO USE; INDICATES SETTING; EASY TO ACTIVATE BY ACCIDENT
ROCKER SWITCH	6.2-24	2 (3 IF CENTER OFF)	SLIGHTLY HARDER TO USE THAN A TOGGLE; ADDS INTERVAL ILLUMINATION TO DISPLAY SYSTEM STATUS; GOOD IN COMBINATION WITH LEGEND SWITCHES
PUSHBUTTON	6.2-25	2	FAST TO USE; EXCELLENT FOR MOMENTARY INPUTS; EASY TO ACTIVATE BY ACCIDENT
LEGEND SWITCH	6.2-26	2	CONSISTS OF A PUSHBUTTON WITH INTERNAL ILLUMINATION TO INDICATE SYSTEM STATUS
KEYBOARD	6.2-27	—	CONSISTS OF A SPECIAL ARRANGEMENT OF PUSHBUTTONS FOR FREQUENT INPUTS
FOOT PUSHBUTTON	6.2-28	2	USE ONLY TO OBTAIN LARGE FORCES OR WHEN BOTH HANDS ARE OCCUPIED

*USE A 2-POSITION KNOB OR THUMBWHEEL IF IT IS NECESSARY TO ELIMINATE THE POSSIBILITY OF ACCIDENTALLY ACTIVATING A TOGGLE OR PUSHBUTTON

Figure 6.2-18. Types of Discrete Position Controls

6.2.2 DISCRETE POSITION CONTROLS (CONTINUED)

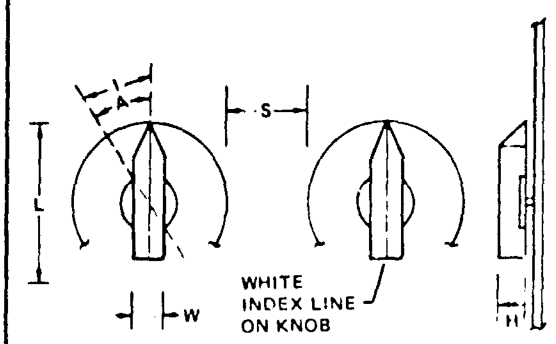

Figure 6.2-19. Discrete Position Knobs (Rotary Selector Switches)

Parameters:

Length (L): 25 to 100 mm (1.0 to 4.0 in)

Width (W): No more than 25 mm (1.0 in)

Depth (H): 15 to 75 mm (0.6 to 3.0 in)

Separation (S) for one-hand random operation: 50 mm (2.0 in) preferred, half this is acceptable

Separation (S) for two-hand operation: 125 mm (5.0 in) preferred, half this is acceptable.

Angular displacement (A): 30° preferred, 15° to 90° acceptable; choice depends on number of positions required.

Index mark displacement (I): At least 6 mm (0.25 in)

Resistance: 11 to 69 g-m (1.0 to 6.0 lb-in)

Design Notes:

- Use a knob that provides both visual and tactual indication of position. The bar shape shown is a good choice.
- Do not leave any space between the index mark and the end of the knob pointer.
- Make the knob, not the scale, move.
- Include end stops to limit travel.
- If settings 180° from each other must be used, choose a knob shape that will avoid pointer end confusion.
- Increase the setting value with clockwise rotation.
- Avoid knobs with a raised pointer that will result in parallax.

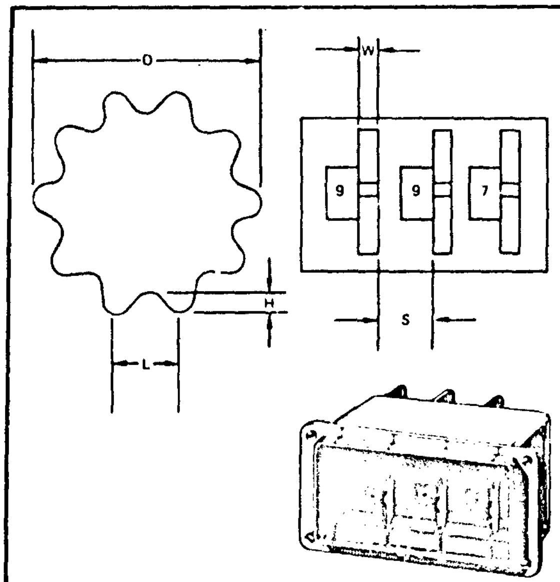

Figure 6.2-20. Discrete Position Thumbwheels

Parameters:

Diameter (D):	No less than 38 mm (1.5 in)
Trough width (L):	11 to 19 mm (0.45 to 0.75 in)
Trough depth (H):	3 to 13 mm (0.12 to 0.5 in)
Wheel width (W):	No less than 3 mm (0.12 in)
Separation (S):	No less than 8 mm (0.31 in); 10 mm (0.38 in) preferred
Resistance:	170 to 570 g (6 to 20 oz)

Design Notes:

- Adequate lighting is particularly important because numerals are partially recessed.
- Almost all thumbwheels are manufactured so that the setting increases with downward movement; see Section 6.3.3.
- Avoid small sharp tabs that can cause operator discomfort with repeated use.

6.2.2 DISCRETE POSITION CONTROLS (CONTINUED)

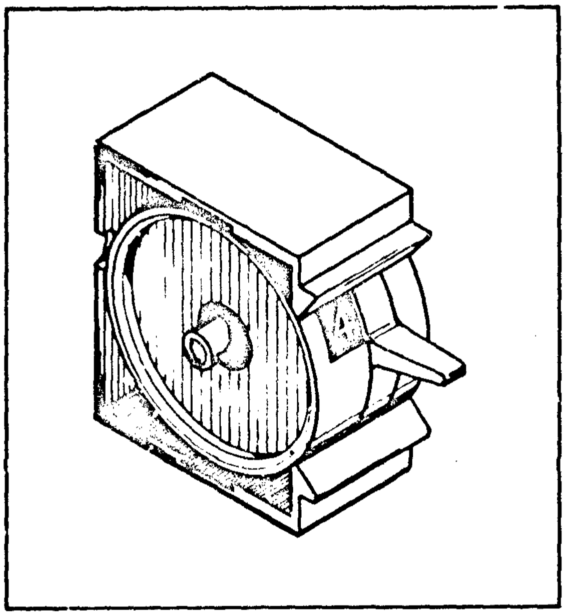

Figure 6.2-21. Leverwheels. No design parameters have been established. Because the lever must be positioned very precisely, correct positioning by inexperienced users will require several attempts (Ref. 17). With considerable experience and a good working environment, users may be able to set this control blind by moving the lever to either end stop and then moving it through the required number of detents.

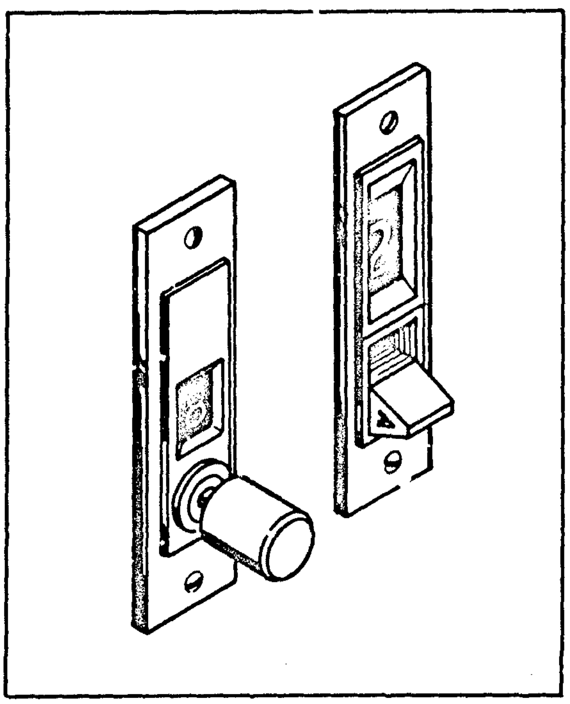

Figure 6.2-22. Pushbutton Wheels and Toggle Wheels. No design parameters have been established. Figures 6.2-23 and -25 provide some guidance. An interesting modification of this control is a version in which the operator simply touches the surface of the control and an electronic circuit causes the setting to change.

6.2.2 DISCRETE POSITION CONTROLS (CONTINUED)

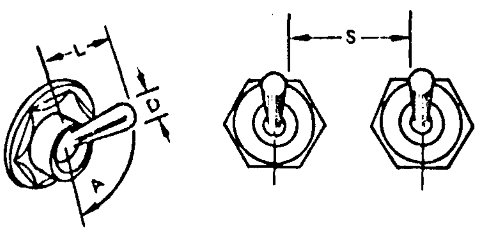

Figure 6.2-23. Toggle Switches

Parameters:

Arm length (L): 13 to 50 mm (0.5 to 2.0 in.)

Tip diameter (D): 3 to 25 mm (0.125 to 1.0 in.)

Displacement (A): minimum of 30° between positions

Lateral separation (S):	PREFERRED	MINIMUM
Single finger operation	50 mm (2.0 in)	20 mm (0.75 in)
Single finger operation of lift-to-unlock switch	50 mm (2.0 in)	25 mm (1.0 in)
Single finger sequential operation	25 mm (1.0 in)	13 mm (0.5 in)
Simultaneous operation by different fingers	20 mm (0.75 in)	15 mm (0.62 in)

Vertical separation: Depends on switch size and displacement

Resistance: 280 g to 1.1 kg (10 to 40 oz)

Design Notes:

- Orient for vertical lever arm travel unless horizontal motion is required for compatibility with the controlled functions.
- To reduce panel space requirements, arrange toggle switches in rows perpendicular to the direction of lever arm travel.
- On power switches, place OFF in the down, left or center position.
- Except for center-off controls, do not use more than two positions

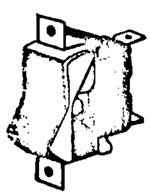

Figure 6.2-24. Rocker Switches

Parameters:

None have been established.

Design Notes:

- Use internal illumination of the depressed half of the control to make control setting more obvious.

6.2.2 DISCRETE POSITION CONTROLS (CONTINUED)

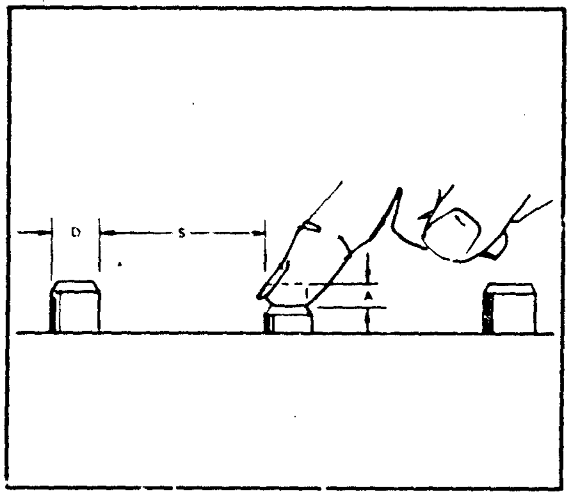

Figure 6.2.25. Pushbuttons

Parameters:

Diameter (D): No less than 13 mm (0.5 in), except for miniature devices, 9 mm (0.38 in) is acceptable

Displacement (A): 3 to 13 mm (0.12 to 0.5 in)

Separation (S):	PREFERRED	MINIMUM
Random operation:	50 mm (2.0 in)	13 mm (0.5 in)
Sequential operation:	25 mm (1.0 in)	6 mm (0.25 in)

Resistance: 140 to 565 g (5 to 20 oz)

Design Notes:

- Use a roughened or concave surface to minimize finger slippage.
- Experience with electronic keyboards is tending to prejudice users toward lighter resistances and shorter displacements. Values twice those listed are usable but will probably cause unfavorable reactions by users.
- Provide a detent, or other immediate indication that the pushbutton has been depressed.
- For keyboard applications, see parameters listed in Figure 6.2-27.

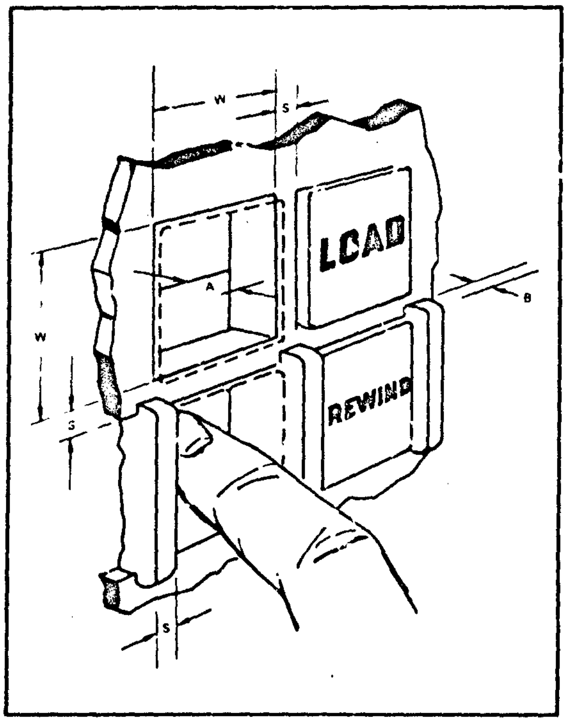

Figure 6.2-26. Legend Pushbuttons

Parameters:

Width and height (W): 20 to 38 mm (0.75 to 1.5 in)

Barrier width (S): 3 to 6 mm (0.12 to 0.25 in)

Barrier depth (B): 5 to 6 mm (0.20 to 0.25 in)

Displacement (A): 3 to 6 mm (0.12 to 0.25 in), with a minimum of 5 mm (0.20 in) for switches with two fixed positions.

Resistance: 140 to 565 g (5 to 20 oz)

Design Notes:

- Labeling must be legible when not illuminated (Label size and style is covered in Section 6.5).
- In most applications, use the illumination to indicate system status, not just control actuation.
- Internal projection of one of several labels can be used to make this a multifunction control (Ref. 18).

6.2.2 DISCRETE POSITION CONTROLS (CONTINUED)

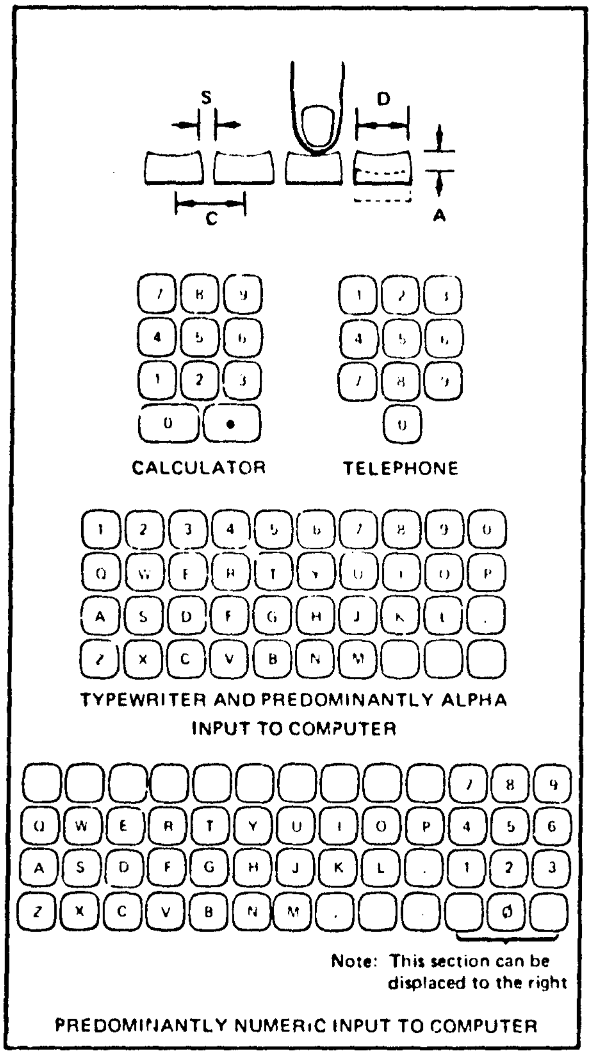

Figure 6.2-27. Keyboards

Parameters (Ref. 19,X)

Width (D): 10 to 19 mm (0.4 to 0.75 in). Special keys can be wider and miniature devices can utilize smaller keys.

Displacement (A): 1 to 5 mm (0.04 to 0.19 in)

Separation (S): No less than 6 mm (0.25 in) between edges of 13 mm (0.5 in) wide keys; less with wider keys

Center-to-center distance (C): 19 mm (0.75 in) preferred, but 16 mm (0.625 in) is acceptable

Resistance: 25 to 150 g (0.9 to 5.3 oz)

Slope: 10^{o} to 35^{o} preferred, with up to 60^{o} acceptable

Design Notes:

- Consistency in the key arrangement of the several keyboards used by a single operator is important. (See the discussion in Reference 12 of Section 6.3.)
- Arrangements illustrated here should be used where possible. Standards should be consulted for location of control and function keys (Ref. 20).
- Labels on interchangeable overlays can be used to obtain a multifunction keyboard.
- Feedback to inform the operator of control actuation is essential. This can be a detent, or a display action.
- Keyboard switches are used frequently. Therefore, if a detent is included to provide feedback, it must be very light. Also, operating force must be kept low (Ref. 15).
- The operator can more easily establish his finger location if the "home" keys, 4-5-6 on a calculator keyboard and A-S-D-F-J-K-L-; on a typewriter, have a distinctive surface. This can be provided by a different concavity or a small raised spot in the center of each key.

The arrangement of the alphabetic keys shown here is sometimes identified as the QWERTY format.

6.2.2 DISCRETE POSITION CONTROLS (CONTINUED)

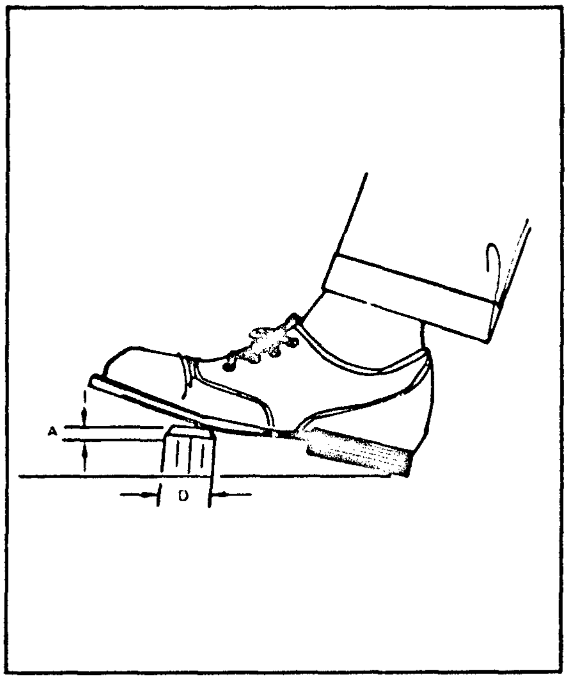

Figure 6.2-28. Foot Pushbuttons

Parameters:

Diameter (D): No less than 13 mm (0.5 in)

Displacement (A): 13 to 63 mm (0.5 to 2.5 in) for ankle flexion, 13 to 100 mm (0.5 to 4.0 in) for leg movement

Center-to-center separation: 225 mm (9 in) for random operation and 175 mm (7 in) for sequential operation

Edge-to-edge separation: 150 mm (6 in) for random operation and 100 mm (4 in) for sequential operation

Resistance: 1.8 to 9.0 kg (4 to 20 lb) if foot does not rest on control, 4.5 to 9.0 kg (10 to 20 lb) if foot does rest on control

Design Notes:

- Because operator will have difficulty locating this type of control, use it only if both hands are occupied.
- A foot guide is a useful aid in locating the control.
- Wide separation is necessary if there is more than one control.
- Use a nonslip surface on the control.
- The foot is relatively insensitive, so good indication of control activation is essential.

SECTION 6.2 REFERENCES

1. Chapanis, A. and Kinkade, R. G. Design of controls. Chapter 8 in Van Cott, H. P. and Kinkade, R. G., *Human Engineering Guide to Equipment Design* (Rev.), U. S. Govt. Printing Office, 1972.

   Woodson, W. E. and Conover, D. W. *Human Engineering Guide for Equipment Designers* (2nd Ed.). University of California Press, Berkeley, California, 1964.

   Morgan, C. T. *et al. Human Engineering Guide to Equipment Design. McGraw-Hill, New York, 1963.*

   Wohl, J. G. (Ed) *Human Factors Design Standards for the Fleet Ballistic Missile System: Volume II. Design of Equipment*. NAVWEPS-OD-18413A, U.S. Navy, 1962. Also available as AD 048895.

   U.S. Army Missile Command. *Human Engineering Design Criteria for Military Systems and Facilities*. MIL-STD-1472B (proposed), May 1974.

2. The relevant conversion factors are
   1 gram (g) = 0.0352 ounce (oz) = 0.0022 pound (lb)
   1 lb = 16 oz = 453.6 g
   1 gram-meter (g-m) = 1.39 ounce-inches (oz-in) = 0.087 pound-inch (lb-in)
   1 kilogram-meter (kg-m)= 7.23 pound-feet (lb-ft)
   1 dyne = 10^{-5} newtons = 0.00102 gram (or more correctly, gram weight)

3. Mehr, M. H., President, Measurement Systems Inc., Norwalk, Connecticut Personal Communication, December 1974. This company produces several types of isometric joysticks. At least some of these repeatedly incorporate sufficient joystick motion that the operator can easily sense when he is making a maximum input.

4. Mehr, M. H. and Mehr, E. Manual digital positioning in 2 axes: A comparison of joystick and track ball controls. 16th Annual Meeting, Human Factors Society, 1972, pp. 110-116. Setting accuracy in this study corresponded to one step in an 800 by 1000 digital TV display; it is possible, though not likely, that better display resolution would have allowed better positioning accuracy.

   Mehr, M. H. Two-axis manual positioning and tracking controls. *Applied Ergonomics*, Vol. 4.3, 1973, pp. 154-157. This is a good summary article.

5. See Ref. 4. Also, Mehr, M. H., Personal communication, December, 1974.

6. Foxboro Company. *Handwheel Speed and Accuracy of Tracking*. Report No. 3453, National Defense Research Committee, OSRD, Washington, D.C., 1943. Cited in Van Cott, H. P. and Kinkade, R. G. (Ed.), *Human Engineering Guide to Equipment Design*. U.S Govt. Printing Office, 1972, p. 367.

7. Katchmar, L. T. *Physical Force Problems: I. Hand Crank Performance for Various Crank Radii and Torque Load Combinations*. Technical Memorandum 3-57, U.S. Army Aberdeen Proving Ground, Md., 1957. Also available as AD 126991. Subjects were 75 Air Force personnel. The crank axis of rotation was perpendicular to the subject's chest and approximately at waist height.

8. Bilodeau, I. M. and Bilodeau, E. A. Some effects of work loading in a repetitive motor task. *J. Exper. Psychol.*, Vol. 48, 1954, pp. 455-467. The data illustrated are from Experiment I, which utilized a total of 250 Air Force trainees as subjects. Subjects turned a crank as many revolutions as possible against a fixed load for a fixed period of time.

9. Springer, W. and Streimer, I. *Work and Force Producing Capabilities of Man*. Document D2-90245, The Boeing Company, Seattle, Wa., 1962. Subjects were 15 young adult males. The crank axis of rotation was perpendicular to the subject's chest and at chest height.

10. Farrell, R. J. *Human Factors Analysis of 1540 Light Table Focus Mechanism*. Document D180-19053-1, The Boeing Company, Seattle, Wa., 1975. Most human engineering handbooks recommend a maximum resistance of 4.2 g-m (6 oz-in) for knobs. (See Ref. 1.) However, in this study all five subjects who turned the focus control on a mockup of a microscope indicated that a resistance of 11.3 g-m (16 oz-in) was acceptable.

    Also, the four subjects in the study illustrated in Figure 6.2-12 found a knob resistance of 14 g-m (19 oz-in) acceptable but objected to a resistance of 24 g-m (34 oz-in).

11. Jenkins, W. L. and Connor, M. B. Some design factors in making settings on a linear scale. *Appl. Psychol.*, Vol. 33, 1949, pp. 395-409. Four subjects were used in most parts of the study. Knob resistance was not constant, with more torque required during trials involving fewer turns. A subsequent study in which this factor was controlled (Ref. 13) indicated that the times in the figure may be slightly too small, particularly for the larger numbers of turns.

12. Spragg, S. D. S. and Devoe, D. B. The accuracy of control knob settings as a function of size of angle to be bisected and type of end-point cue. *Percept. and Motor Skills*, Vol. 6, 1956, pp. 25-28. Twelve subjects were tested. The three kinds of end-point cues used, a physical stop, a light, or a tone, had no consistent effect. The average error changed from 25 percent when bisecting 20 degrees to 11 percent when bisecting 160 degrees and was consistently in the clockwise direction from the true center.

13. Jenkins, W. L., Maas, L. O., and Rigler, D. Influence of friction in making settings on a linear scale. *J. Appl. Psychol.*, Vol. 34, 1950, pp. 434-439. Four young adult males served as subjects. Parameters of the task are illustrated in Figure 6.2-9.

14. Royal Naval Personnel Research Committee (London). Controls. Chapter 10 in *Human Factors for Designers of Naval Equipment*. 1970. Available as AD 890281.

15. Kinkead, R. D. and Gonzalez, B. K. *Human Factors Design Recommendations for Touch-Operated Keyboards. Final Report*. Document 12091-FR1, Honeywell Systems and Research Division, St. Paul, Minnesota, 1969.

16. Dean, R. D., Farrell, R. J., and Hitt, J. D. Effect of vibration on the operation of decimal input devices. *Human Factors*, Vol. 11, 1969, pp. 257-272.

17. Comments from operators and human engineers who have used this type of control.

18. For example, a legend pushbutton capable of displaying 12 different legends is made by Industrial Electronic Engineers of Van Nuys, California. It is activated by touching, rather than depressing, the front surface. Therefore it should not be used without some type of immediate feedback to the operator that he has successfully activated it.

19. Alden, D. G., Daniels, R. W., and Kanarick, A. F. Keyboard design and operation: A review of the major issues. *Human Factors*, Vol. 14, 1972, pp. 275-293.

Alden, D. G., Daniels, R. W., and Kanarick, A. F. *Human Factors Principles for Keyboard Design and Operation – A Summary Review*. Document 12180-FR1a, Honeywell Systems and Research Center, St. Paul, Minnesota, 1970.

20. American National Standards Institute (ANSI). *Alphanumeric Keyboard Arrangements Accommodating the Character Sets of ASCII and ASCSOCR*. ANSI X4.14-1971, 1971.

American National Standards Institute (ANSI). *USA Standard Code for Information Interchange*. USAF X3.4-1968, 1968.

6.3 CONTROL/DISPLAY LAYOUT

6.3.1 Location

6.3.2 Identification

6.3.3 Direction of Motion Stereotypes

6.3.4 Control Setting Indication

6.3.5 Special Requirements

SECTION 6.3 CONTROL/DISPLAY LAYOUT

NOTE: Because this entire section consists of recommendations, they are not listed separately here.

There are nearly as many ways to lay out most control/display systems as there are designers and critics available. Even if these ignore the numerous formalized design techniques available (Ref. 1), many will be easy to operate. The goal of this section is to outline some of the more basic approaches that will help make the system easy to use. If a formal systematic approach to the design is desired, the aforementioned reference should be consulted.

A more complete treatment of the many techniques and guidelines for layout of controls and secondary displays is also available (Ref. 2).

The starting point for laying out the controls for a new display device is recognition that the designer and the future user have different points of view. The operator's interest is limited to using the device as a tool to perform some task. Unlike the designer, he does not know and will seldom care about its internal workings. The control panel should, therefore, make operation of the device obvious and straightforward to the user. Minimal dependence should be placed on manuals or special training.

6.3.1 LOCATION

Operating controls and their associated displays should be located within the manual and visual work areas described in Section 6.1. The figures in Section 6.2 list the clearances needed between two controls of the same type, and these values are the best available for estimating the clearance required between dissimilar controls.

The position of each control relative to an associated display should be consistent within a piece of equipment. The controls should be placed where they do not interfere with the operator's view of the display. The normally accepted location for a control is immediately below its associated display.

Proper control placement within the work area depends on several principles:

- Frequency of Use–The most frequently used controls go in the most convenient locations. Large groups of important but infrequently used controls, such as those for setting up a computer, can be placed on panels that slide down into the control console when not in use. Controls used for maintenance should not be accessible during normal operation.
- Function–Controls related to a single function go in a group, not intermixed with controls for other functions. Panic controls, such as an emergency shutdown, should be isolated and easily accessible.
- Sequence of Use–Controls normally used in sequence should be arranged in a pattern, preferably ordered from left to right and top to bottom.
- Consistency–Sets of similar controls should have a consistent arrangement. If there are two sets, one to each side of the operator, and they contain only a few controls, mirror symmetry is as acceptable as identical arrangement.
- Logical Pattern–If there is a logical pattern that can be imposed on the controls to make their locations more meaningful to the operator, it should be followed. Possibilities include the geometrical arrangement of the controlled elements and the positioning of computer setup controls according to mathematical value.
- Visual Access–If the display user must visually check the control setting, it should be conveniently visible from the user's normal head position.

6.3.1 LOCATION (CONTINUED)

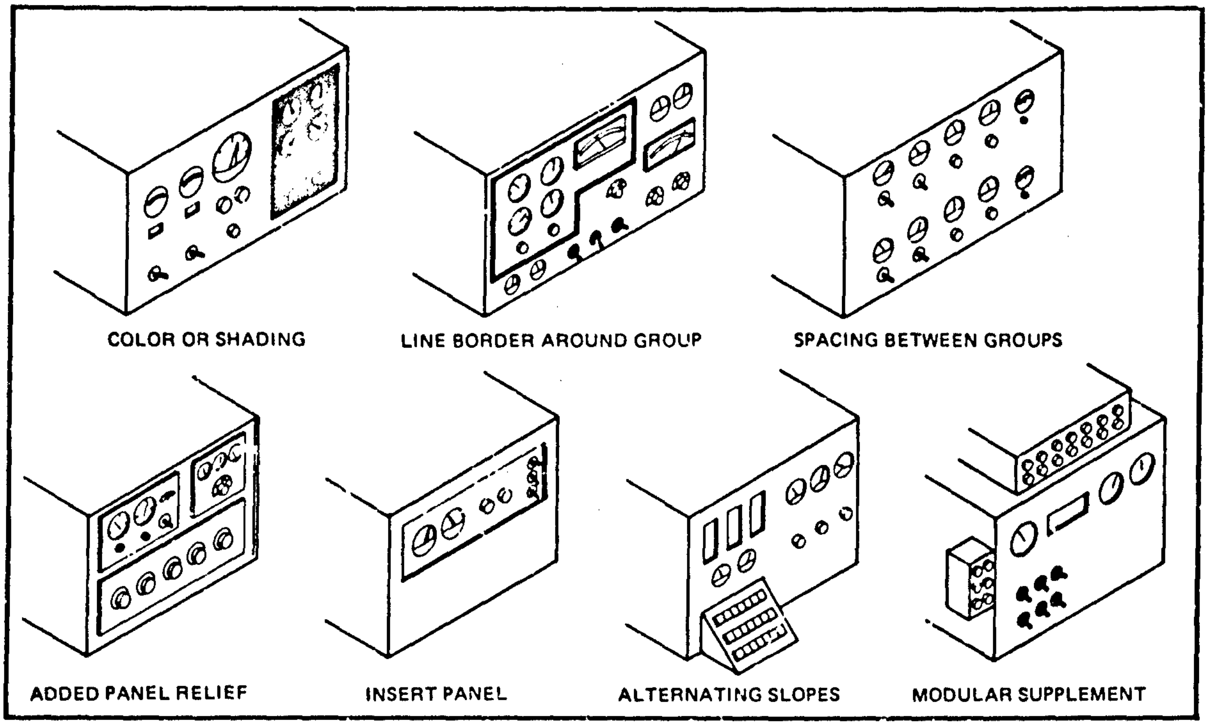

Figure 6.3-1. Examples of Ways to Accentuate Control Groupings (Ref. 3)

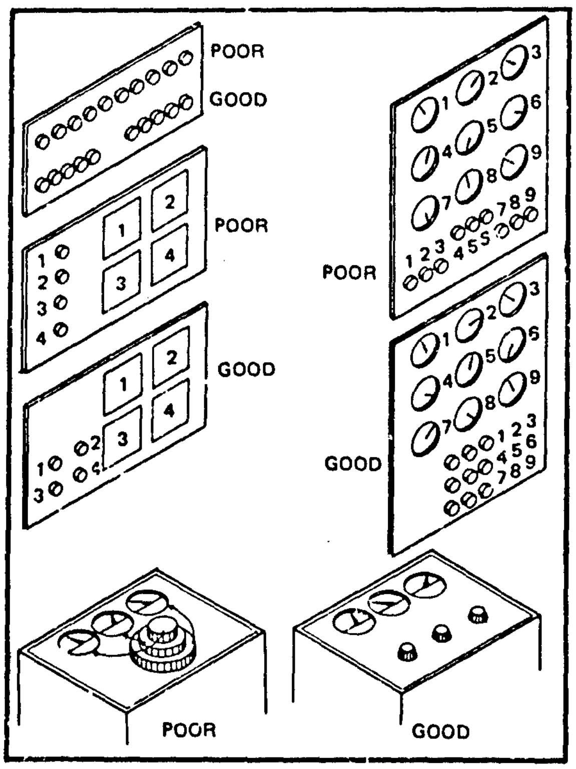

Figure 6.3-2. Examples of Poor and Good Control/Display Arrangements (Ref. 3)

6.3.2 IDENTIFICATION

Ideally, controls will be identified adequately so that the user will know the purpose of each control before he activates it. While learning to operate the device, he will depend primarily on the labeling to establish the function of each control. After becoming familiar with the device, however, he will reach for each control more or less automatically, relying on his memory of its location and shape.

Because individuals differ in how they associate controls with the elements they control, redundant identification of controls is desirable. In one prototype instrument, the association was indicated three different ways, by relative location, by color, and by a number code. Among the several operators of the equipment, all three methods were used (Ref. 4).

Labels as a means of identifying a control are covered in Section 6.4. The use of control location for this purpose is treated in Section 6.3.1. Other methods include shape and color.

Color is much less effective than location or shape as a means of identifying controls. This is particularly true at the low ambient illumination levels typical in areas where imagery displays are used. As the operator becomes familiar with the display, he depends less on vision to determine which control he is about to operate. Single-color coding should be limited to red, orange, yellow, green, and blue (Ref. 5). Red is classically associated with danger and in most applications should be reserved for this use.

Any control that may be used while the operator is looking at the image in the display, rather than at the control, should be selected and positioned for blind use. The most important consideration is to place the control where it is not likely to be confused with any other control. A separation of 125 mm (5 in) is generally considered adequate (Ref. 5), but if use of the wrong control might have serious consequences, a larger separation is desirable. Shape coding, as is described in Figure 6.3-3 below, is a very desirable technique for reducing confusion between controls. Unfortunately, it is often rejected on aesthetic grounds just when it is most needed. Probably the most common example is the automobile dashboard, where headlight and windshield wiper controls are usually identical in shape and very close together.

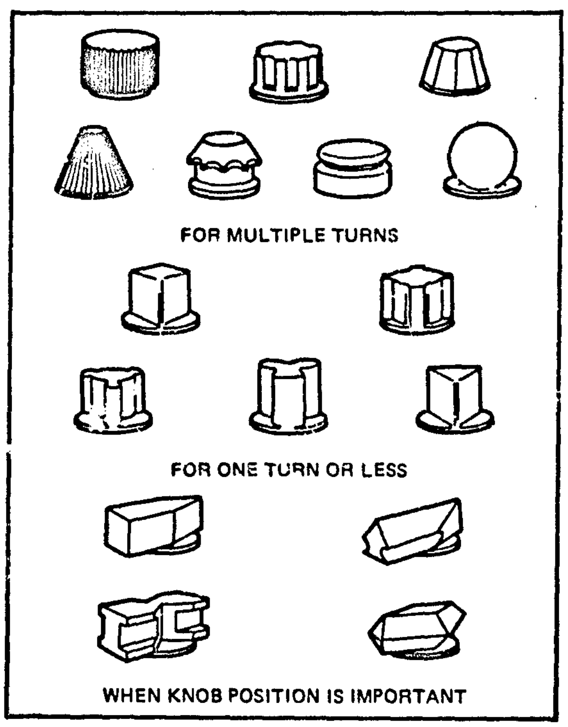

Figure 6.3-3. Shape-Coded Knobs. Optimum shapes to facilitate identification of knobs by touch have been determined experimentally (Ref. 6). Although most are not made commercially, these shapes can be used as a guide when selecting from among available designs. If operation without visual reference to the controls is necessary, separate adjacent controls by 125 mm (5 in).

6.3.3 DIRECTION OF MOTION STEREOTYPES

An operator will generally expect a particular control action to produce a particular kind of change in the controlled element. For example, clockwise rotation of the steering wheel normally causes a turn to the right. Equipment designed in accordance with these expectations will be operated faster and with fewer errors, particularly as operators are learning. However, these expectations are based on experience and are therefore subject to change as a result of new experiences.

Probably the most important element that moves in an imagery display is the imagery itself. With a lever-type control, the designer must choose between "with" and "against" motion of the image. Actually this distinction is arbitrary, since users seem to be able to think in terms of moving either the imagery or the viewing device. In the absence of test data demonstrating the superiority of one control/imagery motion relationship over the other, either is acceptable. Where more than one display is used by an operator, however, consistency is important.

In many other control/display situations, but not in all, population stereotypes have been established. These are considered below. Where no stereotype exists, or when a stereotype cannot be followed, and an incorrect control movement could have an undesirable effect, the control must be labeled to indicate the type of response that will occur. This would apply, for example, to a machine screw with a left-hand thread.

Direction of motion stereotypes vary among countries. In England, for example, a toggle switch would be turned on by moving it downward, rather than upward as illustrated in Figure 6.3-4.

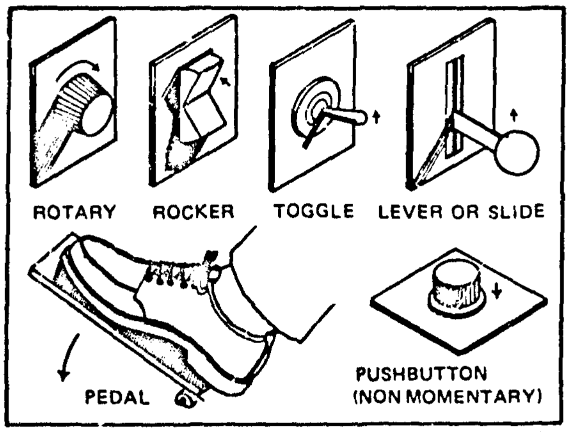

Figure 6.3-4. Typical Control Response Stereotypes. The response generally expected from the illustrated control actions is for the equipment to turn on, the output to increase, or motion forward, clockwise, up or to the right (Ref. 7).

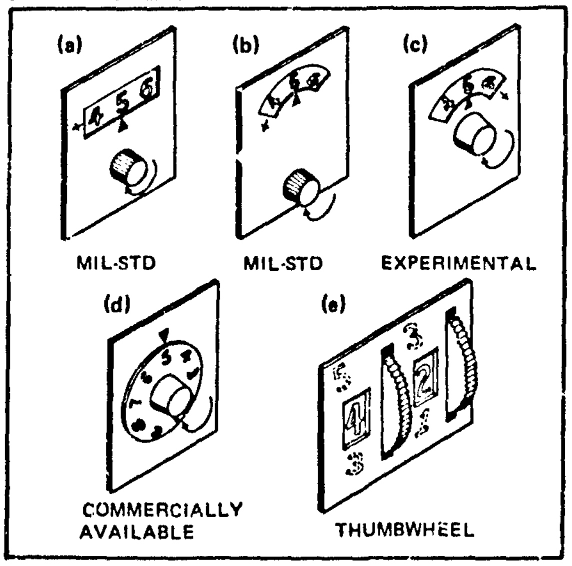

Figure 6.3-5. Moving Scale/Fixed Pointer Displays. There is no consistent stereotype for this style of device. The military standard for human engineering requires clockwise rotation to increase the scale value, but this is achieved by scale motion in the direction opposite to knob rotation in (a) and (b) (Ref. 8). Test subjects preferred and made fewer errors with design (c), in which the scale setting decreased with clockwise rotation (Ref. 9). Design (d) is the only moving scale knob available from one major electronic equipment supplier (Ref. 10). Most thumbwheels are arranged as in (e). With the exception of thumbwheels, which may be required because of their special features, and design (d), in which the relationship between the control and the display is obvious, moving scale-fixed pointer designs should be avoided.

6.3.3 DIRECTION OF MOTION STEREOTYPES (CONTINUED)

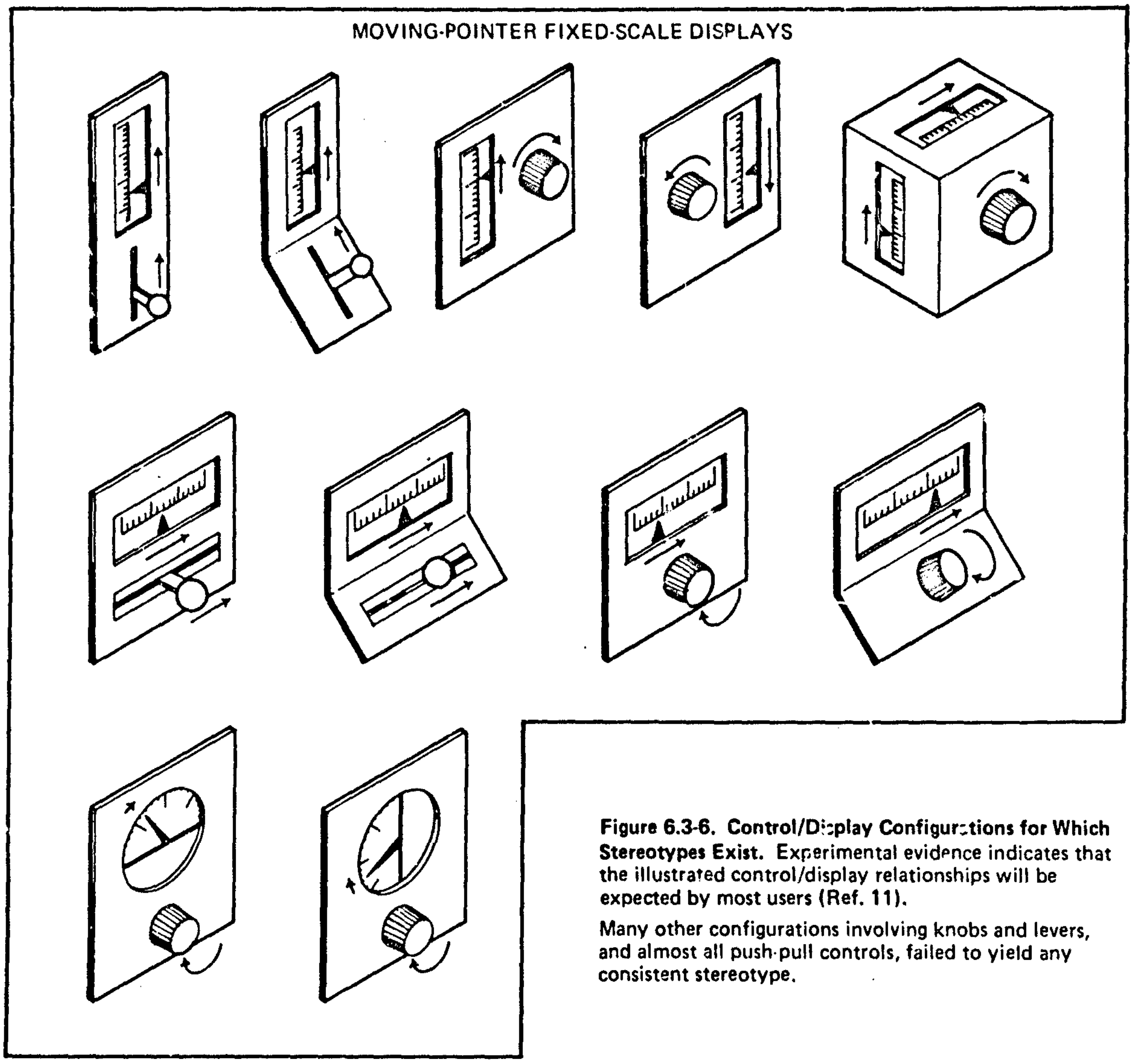

Figure 6.3-6. Control/Display Configurations for Which Stereotypes Exist. Experimental evidence indicates that the illustrated control/display relationships will be expected by most users (Ref. 11).

Many other configurations involving knobs and levers, and almost all push-pull controls, failed to yield any consistent stereotype.

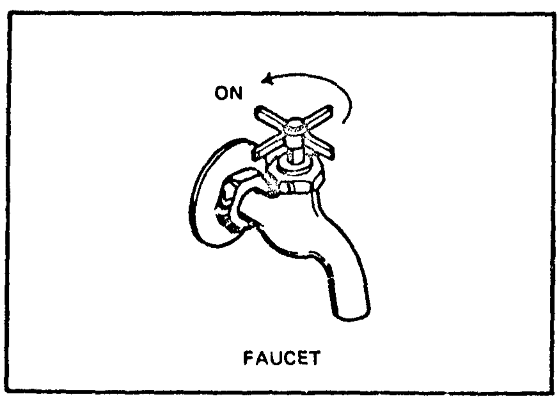

Figure 6.3-7. Common Controls That Do Not Match the Population Stereotype. Through usage, devices with a control/display relationship contrary to the stereotype observed in the laboratory can become accepted. In a sense, the pushbutton telephone-calculator keyboard conflict (Figure 6.2-27) is a similar situation (Ref. 12).

6.3.4 CONTROL SETTING INDICATION

The setting of a control should be obvious either from the status of the display or from the appearance of the control. Avoid *parallax* between a rotary control pointer and scale by using a knob shape that places the pointer in nearly the same plane as the scale marks.

6.3.5 SPECIAL REQUIREMENTS

Several special features of controls sometimes require consideration.

Damage--Controls in certain locations are particularly susceptible to damage and should be protected by recessing or guards. Examples are controls located where they would be struck by the armrest on an operator's chair or devices moved frequently from room to room which might be struck against the edge of a door.

Accidental Activation–A control may be actuated by mistake because it is close to a frequently used control of similar shape, or simply because it is where the operator rested his elbow. Numerous methods can be used to prevent this:

- Recess the control or provide a guard.
- Provide a cover.
- Use an interlock, such as a lift-to-throw toggle.
- Use a different control type, such as a rotary knob instead of a pushbutton.

Operator Comfort--Use controls with rounded edges to prevent operator discomfort. The most frequent offenders are small, sharp tabs on thumbwheels and sharp-edged teardrop-shaped rotary knobs.

Display Response–The response to a control input, such as a change in focus or zoom magnification, should occur as rapidly as possible after the control input occurs. This is primarily a problem in servomechanisms.

SECTION 6.3 REFERENCES

1. Kidd, J. S. and Van Cott, H. P. System and human engineering analyses. Chapter 1 in Van Cott, H. P. and Kinkade, R. G. (Ed.), *Human Engineering Guide to Equipment Designs,* U.S. Government Printing Office, 1972. This chapter provides a good summary of the several techniques in use.

2. For a sample of the material available, see Ref. 3 and 5.

3. Design of individual workplaces. Chapter 9 in Van Cott, H.P. and Kinkade, R. G (Ed.), *Human Engineering Guide to Equipment Design*, U.S. Government Printing Office, 1972.

4. Unpublished evaluation of a prototype imagery display by the senior author and Anthony A. Garra in 1972.

5. Chapanis, A. and Kinkade, R. G. Design of controls. Chapter 8 in Van Cott, H. P. and Kinkade, R. G. (Ed.), *Human Engineering Guide to Equipment Design*, U.S. Government Printing Office, 1972.

6. Hunt, D. P. and Craig, D. R. *The Relative Discriminability of Thirty-One Differently Shaped Knobs.* Report WADC-TR-54-108, Wright Air Development Center, WPAFB, Ohio, 1954. Summarized on page 366 of Ref. 5.

7. See Ref. 5.

8. U S. Army Missile Command, *Human Engineering Design Crtieria for Military Systems and Facilities*, MIL-STD-1472B (proposed), May 1974. See paragraphs 5.1.3.5 and 5.1.3.6.

9. Bradley, J. V. *Desirable Control-Display Relationships for Moving-Scale Instruments.* USAF-WADC Tech. Report. No. 54-423. Cited in Ref. 11.

10. Allied Electronics, *Engineering Manual and Purchasing Guide*, No. 740, Tandy Corp., Chicago, 1974 (also known as the *1974 Allied Radio Catalog*).

11. Loveless, N. E. Direction-of-motion stereotypes: A review. *Ergonomics*, Vol. 11, 1968, pp. 357-383. A total of 58 references are reviewed.

12. As Figure 6.2-27 illustrates, calculator and telephone keyboards provide a classic example of a conflict in control layout. Based on the limited information available on selection of the telephone keyboard (Deininger, R. L. Human factors engineering studies of the design and use of pushbutton telephone sets, *Bell System Tech. J.*, July 1960, pp. 995-1012), it appears that the calculator arrangement was rejected because it was 3 percent slower than the arrangement finally adopted. (In a study using housewives as test subjects, Conrad, R. and Hull, A. J. The preferred layout for numerical data-entry keysets, *Ergonomics*, Vol. 11, 1968, pp. 165-173, the telephone arrangement was also superior.) Apparently, however, no consideration was given to the desirability of making the telephone arrangement compatible with the calculator arrangement then in use. The resulting conflict between the two arrangements would have affected only a small portion of the population, except for the pocket calculator revolution that now threatens to make calculator keyboards more numerous than pushbutton telephones.

6.4 SECONDARY DISPLAYS

6.4.1 Cathode Ray Tube (CRT's)

6.4.2 Discrete Alphanumeric Displays

[redacted]

6.4.3 Indicator Lights

6.4.4 Auditory Displays

SECTION 6.4 SECONDARY DISPLAYS

As used here, the term "secondary display" applies to any display not used for viewing imagery. Secondary visual displays are used primarily to present information in alphanumeric or graphic form, as on a CRT, a microfiche projector, or a discrete alphanumeric device, or to present information about discrete events, as in the case of an indicator lamp.

In a sense, the collateral or reference materials used by the image interpreter, such as maps, target keys, and printed reports, also constitute secondary displays. In most cases, however, the display designer is concerned with these materials only to the extent of integrating a location for viewing them into the display workstation.

The emphasis in this section is on the kinds of secondary displays most commonly found on, or in association with, imagery displays. Information on the design of the displays such as the following can be found in the indicated references:

- Mechanical counters (Ref. 1).
- Scales, as used on meters and dials (Ref. 2).

In some cases, it will be more reasonable for the designer of an imagery display to select from among the many commercially available secondary displays, rather than design one himself. Therefore Section 6.4.1 includes a discussion of techniques for evaluating secondary displays used to present symbolic information. Although these appear in the section discussing CRT's, they apply equally to discrete alphanumeric displays (Section 6.4.2).

SECTION 6.4 SECONDARY DISPLAYS

6.4.1 CATHODE RAY TUBES (CRT's)

RECOMMENDATIONS:

Use the Lincoln/Mitre font, or one proven equally legible in tests. Keep in mind that even a good font can be poorly implemented within a particular device, making a legibility evaluation of the final design very important.

For short messages or when characters must be identified out of context, use only uppercase alphanumeric characters. For extended passages of text, add lowercase characters.

For alphanumeric and a small number of special symbols, a 5 by 7 dot matrix is adequate. If more than a half dozen special symbols are required, if symbols are printed over each other, if extreme accuracy is required under a heavy workload, or if both uppercase and lowercase letters are required, increase the dot matrix size to at least 7 by 9 or go to a random-position stroke technique.

For closed-circuit television viewing of hard-copy alphanumeric characters, provide at least 10 raster lines across each character and position the display so that each character subtends at least 12 and preferably 15 arc minutes. If special symbols are involved or if extremely high reading accuracy is necessary, each parameter should be increased by 20 to 40 percent. Requirements for low-contrast symbols, as will occur on some maps, should be determined experimentally.

Symbols displayed on CRT's fall into two categories, alphanumeric and special. The latter range from simple punctuation marks to complex symbols used only in particular applications (Ref. 3). As symbols become more complex, the number of display resolution elements necessary to make them legible increases.

The emphasis in this section is on the impact of alphanumeric character style, or font, on legibility. Although a few sets of special-purpose symbols have been published (Ref. 3), symbol reading errors depend so heavily on what other potentially confusing symbols are in the set of symbols in use that legibility testing of the selected set is usually necessary.

Uppercase alphanumeric characters can be read more accurately under marginal conditions than lowercase characters (Ref. 4,C), probably because they are larger. As a result, they should be used whenever characters must be recognized with extreme accuracy or when they must be read out of context. The combination of uppercase and lowercase characters provides information about the structure of text material. This combination should be retained in displays when large quantities of text material must be read and when the display resolution is adequate for lowercase characters.

Within and between characters, the dimensions generally found acceptable are as follows:

- A stroke width of 7 to 20 percent of character height; values less than 13 percent may be less tolerant to very difficult viewing conditions (Ref. 5). These values are based on hard-copy displays.

- A character width of 50 to 100 percent of character height has generally been found acceptable (Ref. 6). Again, these values are based on tests with hard-copy displays.

- Horizontal space between characters equal to 20 to 35 percent of character height and vertical spacing between lines equal to 50 to 100 percent of character height, with a minimum value of 30 percent, is suggested (Ref. 7). These values are typical and pleasing in appearance. Fairly large deviations are unlikely to have much effect on performance.

A line length of 60 to 80 characters for text and 20 to 40 characters for data entry has been suggested (Ref. 8). These values are based on experience in developing computer-controlled alphanumeric displays. No relevant experimentation is known.

The symbol characteristics necessary to ensure legibility on a CRT display depend in part on which of two basic methods is used to generate the symbols. One method is to use closed-circuit television with a hard-copy image such as printed text or a map. This is the technique

6.4.1 CATHODE RAY TUBES (CRT's) (CONTINUED)

represented in Figure 6.4-1. When the information to be displayed exists in digital form, the symbols can be generated electronically within the display. Because it eliminates misregistration between raster lines and symbol elements, the latter approach makes more efficient use of the display.

For well-shaped uppercase alphanumeric characters viewed on closed-circuit television, 10 raster lines across each character have generally resulted in acceptable legibility (Ref. 9). Adequate visual size is also necessary, as is illustrated in Figure 6.4-1. A reasonable minimum size would appear to be at least 12 arc minutes, with a preferred value of at least 15 arc minutes. (Uppercase characters on this page subtend an angle of 15 arc minutes at a distance of about 45 cm, or 18 in.) For special symbols, more raster lines have been found necessary. In one study 16 raster lines and 16 arc minutes across each symbol yielded maximum performance (Ref. 10). A less adequate alphanumeric character font may also require more raster lines. Maximum legibility of typewritten characters of unspecified font, for example, required 14 to 18 raster lines and 18 to 21 arc minutes (Ref. 11,D).

Electronic character generation techniques fall into three categories, dot matrix, stroke matrix, and random position stroke. Each category can be further subdivided according to the size of the matrix or the number of random position strokes. Common dot-matrix sizes, for example, are 5 by 7, 7 by 9, and 7 by 11. Odd numbers are usually used to allow character symmetry and to allow character elements to be centered.

The different character generation techniques and matrix sizes have been compared in several studies of alphanumeric character legibility. The results are:

- A 3 by 5 dot matrix produced only marginally legible characters (Ref. 12,X)

- Using the Lincoln/Mitre font, a 5 by 7 dot matrix was read as accurately and was almost as fast as a 7 by 11 dot matrix (Ref. 12,X). This result held for the two displayed character sizes tested, 6 and 22 arc minutes. Comparing the two sizes, 6-arc-minute characters yielded a drop in accuracy from about 98 to 94 percent, and a drop in speed from about 170 to 70 characters per minute.

- Using the Lincoln/Mitre font, random-position strokes drawn within a 5 by 7 or 9 by 9 matrix were read more accurately and faster than a 7 by 11 dot matrix when the alphanumeric symbols were printed over one another (Ref. 13,X). There was no performance difference when they were not overprinted.

- Using a different font and different viewing conditions, a 7 by 9 dot matrix was read more accurately and faster than a 5 by 7 dot matrix (Ref. 14,C). It was also faster and more accurate than a 7 by 9 dot matrix in which the dots were stretched horizontally.

Reference 14 also included a comparison between dot matrix and stroke written characters. Unfortunately, a different font was used with each construction technique, making it impossible to draw any conclusions from the results.

The most thoroughly studied CRT alphanumeric font is the Lincoln/Mitre (Figure 6.4-2). Several others have also been developed (Ref. 15) but there is no known direct experimental comparison between any of them and the Lincoln/Mitre design. In the absence of such data, the Lincoln/Mitre is recommended because:

- Even when it is displayed in a simple 5 by 7 dot matrix, it is essentially 100 percent recognizable under good viewing conditions (Ref. 16,X).

- Two competing fonts are those developed by the Royal Aircraft Establishment (RAE) and Vartabedian. An experimental comparison of the RAE and Vartabedian fonts indicated the RAE was superior (Ref. 17,C), and visual inspection of the RAE font suggests that several possible confusions, such as C/O and 2/Z, are more likely with it than with the Lincoln/Mitre (Ref. 18).

- Fonts utilizing grossly distorted letters and numerals, such as the Lansdell and Foley fonts (Ref. 19), can reduce confusion between characters. However, these are more difficult to learn, they are difficult to reproduce electronically, and they are unlikely to retain any advantage when combined with a large number of special symbols.

Although the Lincoln/Mitre font is recommended here, any other font is also acceptable if it is demonstrated to

6.4.1 CATHODE RAY TUBES (CRT's) (CONTINUED)

be either adequately legible for the intended task, or as legible as the Lincoln/Mitre font. It is also important to remember that the Lincoln/Mitre font illustrated in Figure 6.4-2 must be modified to fit within the symbol generation capability of the display, and this can have considerable impact on legibility. It would not be difficult, for example, to fit the Lincoln/Mitre font into a 5 by 7 dot matrix in a manner that would increase the chance of reading mistakes.

Most alphanumeric character reading errors involve confusions between only a few of the characters in the set. Some of the more common confusions are listed below.

O(letter)/0(numeral)
I(letter)/1(numeral)
B/8
S/5
A/4
C/D/G/Q/O
U/V/W

High symbol contrast is important for good legibility. The largest problem is usually not with the contrast of the display, but with the amount of contrast reduction because of reflected ambient light. The principal ways of controlling this loss are as follows:

- Install an antireflection screen over the CRT face (Ref. 20 and Section 4.4.3).
- Use a transparent phosphor in the CRT.
- Shield the CRT face from ambient light.
- Reduce the level of ambient light in the work area.
- Increase the display luminance so that the contrast loss is less.

Most CRT legibility test data have been collected on symbols displayed near the center of the display. Resolution decreases near the periphery of most CRT's and an allowance should be made for this reduction when setting requirement criteria. One study suggests a size increase of [illegible]0 percent is required (Ref. 21). This value is highly dependent on the particular display used.

In many instances it may be more appropriate to purchase a commercially available CRT display instead of designing one. In this situation, it may be necessary to perform tests to establish that the displayed characters are adequately legible. The remainder of section 6.4.1 is devoted to this topic.

First, the intended display function must be studied to determine what level of legibility is required. The least legibility is required for reading text because potential uncertainty about a particular symbol is usually eliminated by viewing it in context. The most stringent legibility requirement is imposed when individual symbols must be identified with near total certainty. Most military command and control display tasks, and many nonmilitary tasks, fall into the latter category.

Repetitive tasks, such as reading characters from a display during a test or routine work situation, almost always result in a few errors. Therefore, a legibility test criterion of zero errors is unlikely to be obtained in any test situation, no matter how good the display. A reasonable success criterion must therefore allow a few errors. One organization active in designing and evaluating military displays has proposed the following legibility criteria for experienced subjects reading characters on displays intended for military applications (Ref. 22):

- At least 97 percent of responses must be correct.
- No more than 0.3 percent of total responses can be in error because of confusion between any particular pair of symbols, nor more than 0.45 percent because of confusions with any single symbol.
- The reading speed must be at least 150 alphanumeric characters or 50 special-purpose symbols per minute.

A completely realistic evaluation of display legibility is not possible because there is no way to recreate worst case conditions of room illumination, distraction from other tasks and, perhaps, boredom. One approach, instead of attempting to predict performance in a work situation, is to select the display that is most resistant to a reduction in legibility when viewing conditions are degraded. For example, the test subject can be placed farther than normal from the display, or each symbol can be exposed for only a small fraction of a second. In theory at least, whichever display is best under these

6.4.1 CATHODE RAY TUBES (CRT's) (CONTINUED)

degraded conditions will also be least likely to be read incorrectly during regular use.

A crude evaluation of this type can be conducted by displaying selected symbols and having a subject attempt to identify them as he moves closer to the display. His errors, and the maximum viewing distance at which each character can be read correctly, will provide a good basis for comparing different symbol sets and different displays. Using these data to decide whether a particular display is sufficiently legible is difficult because it requires a largely arbitrary selection of a specific criterion. In the absence of any accepted standard, it is suggested that on a good display, subjects who are not pressured by time requirements should be able to read symbols with near perfect accuracy at a viewing distance at least twice that used during normal operation.

The following guidelines should be used when testing the legibility of a group of displays:

- Use test subjects with normal vision.
- Allow the subjects time to become familiar with the font. Otherwise they won't know whether a circle with a slash through it indicates a zero or the letter O (Ref. 23).
- Provide training if special symbols are involved and test to establish that the training was successful.
- Test near the periphery of the display, as well as near the center.
- Test under worst case lighting conditions.
- Unless it is not relevant to the expected display application, test with individual characters so that context cues are eliminated.

When evaluating the legibility of a set of characters, it is important to remember that judgments of relative legibility may not match the results of performance tests.

6.4.1 CATHODE RAY TUBES (CRT's) (CONTINUED)

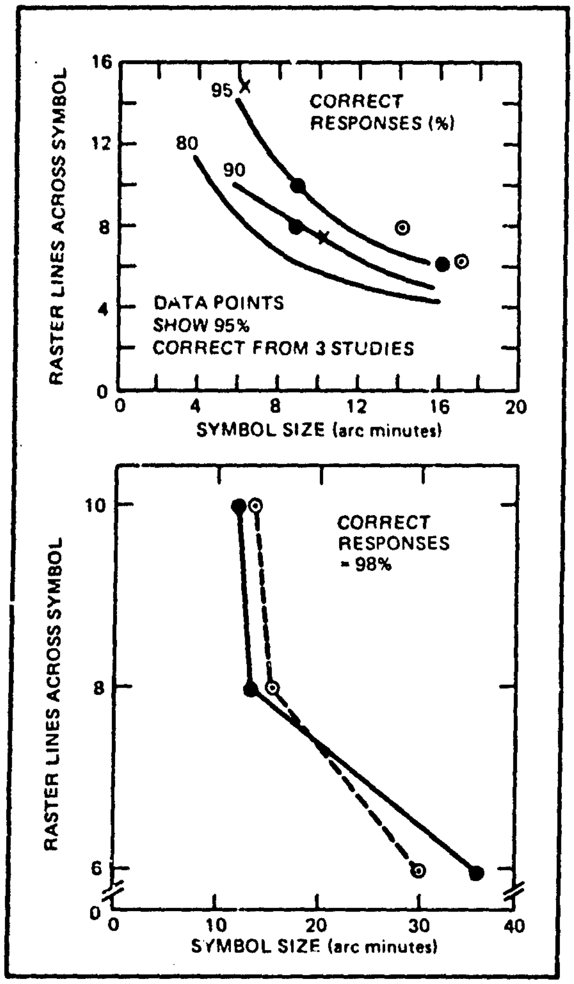

Figure 6.4-1. Interaction Between Raster Lines Across a Symbol and Symbol Size. When symbols are displayed on closed-circuit television, there is a limited interaction between the number of raster lines across the symbol and the visual size of the symbol. The upper part of this figure illustrates results combined from three different studies. The plotted points indicate the number of raster lines and the symbol height necessary to obtain 95-percent correct responses in each of the three studies. These were obtained by interpolation between curves fit to the original observed data points (Ref. 24,X). The upper (95 percent) curve shown here was then fit to these plotted points (Ref. 24,X). The 90 and 80 percent curves were developed in the same fashion.

The lower part of the figure is from a single study and is presumably based on a similar manipulation of the test data (Ref. 25,X). The solid and dashed curves refer to two different character fonts.

Depending on the accuracy required and on the relative availability of raster lines and display visual size, these two figures suggest the need for providing at least 8 to 10 raster lines across each symbol and of displaying each symbol at angular sizes of at least 12 to 15 arc minutes. To provide a safety margin, these figures should be increased somewhat.

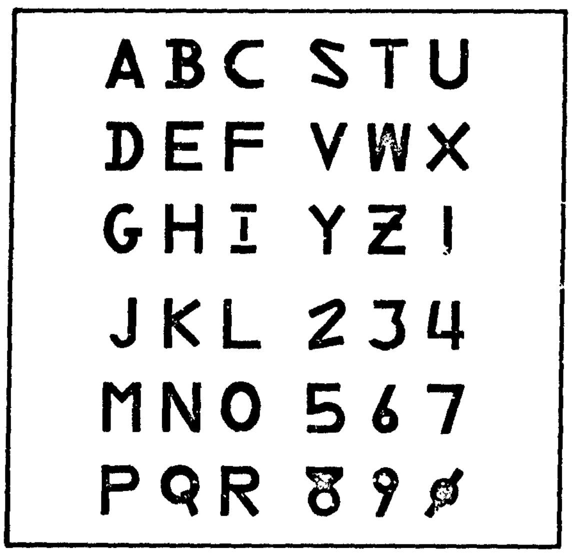

Figure 6.4-2. The Lincoln/Mitre Font. This figure illustrates the Lincoln/Mitre font developed for use on electronic displays (Ref. 26). Although it has not been demonstrated to be the best font in existence for this purpose, no other font has been demonstrated to be superior; furthermore, it has the advantage of having been extensively tested on electronic displays.

Note that this font will change shape considerably, depending on the characteristics of the display and on how it is adapted to the display. As a result one version on a 7 by 9 dot matrix, for example, may be more legible than a different version on the same matrix.

6.4.2 DISCRETE ALPHANUMERIC DISPLAYS

RECOMMENDATIONS:

Provide a visual angle of at least 15 and preferably 45 arc minutes across the vertical dimension of discrete alphanumeric displays.

Use a display device that has a high contrast under all expected lighting conditions.

Use displays in which the numerals are made up from a matrix of seven straight segments only where these offer an advantage over more traditionally shaped numerals. This advantage need not be large.

Considering the popularity of discrete alphanumeric displays, particularly the light emitting diode (LED) and the liquid crystal display (LCD), there is a surprising lack of test data on the conditions under which these displays are legible and on the relative legibility of different designs. The few studies known are summarized below They are limited, unfortunately, to numeric rather than alphanumeric displays. If letters must also be displayed and the complexity of a CRT is not warranted, then selection of a character style should depend on the same factors as are discussed in Section 6.4.1.

A well-shaped, high-contrast discrete alphanumeric symbol should be legible at about the same height at which a CRT character is legible, about 15 arc minutes (Section 6.4.1). However, the very small amount of data available on such devices, which unfortunately are based on an obsolete design, indicates that under time pressure, symbols subtending 30 arc minutes are considerably more legible than those subtending 15 arc minutes (Ref. 27,X).

There are application differences which suggest that a discrete alphanumeric character probably should be larger than one displayed on a CRT. CRT displays are generally used for large quantities of information, and in order to display as much as possible at one time, there is a need to use the smallest characters that are adequately legible. Discrete alphanumeric displays, however, are usually used for much smaller messages, eliminating much of the advantage of extremely small characters. Therefore, such characters should generally be made easier to read by making them at least 30 and preferably 45 arc minutes high. An ideal display size, for a panel viewed from 70 cm (28 in), is 9.5 mm (0.375 in), which results in a visual size of 46 arc minutes.

Many modern numeric displays consist of seven segments that can be illuminated in appropriate combinations to obtain the numerals 0 through 9. In one study, numerals made up of from two to seven of the seven straight segments in a matrix were compared with traditionally shaped numerals drawn with both straight and curved lines (Ref. 28,B). The segmented numerals were more difficult to read under time pressure, but when the time pressure was relaxed, there were no differences. Whether the differences observed would persist with practice was not evaluated. In any case, they were not sufficiently large to preclude use of seven-segment numerals whenever they offer some significant benefit, such as cost reduction or increased reliability. In addition, it is likely that their extensive use in calculators and digital watches will soon make them as familiar to most users as the more traditional numeral shapes.

Two other studies in which numeric displays were compared serve to demonstrate the importance of maintaining contrast in self-luminous displays. Of the three displays tested in one study, the one that proved most difficult to read was that in which each of the 10 numerals was engraved on a separate plastic plate, in a stack of 10, and the plate containing the numeral to be displayed was illuminated from the side (Ref. 29,B). This display was more difficult to read apparently because of light reflected from intervening plates. Because there are so many good alternatives, this type of display should be avoided.

The second study was considerably more ambitious in that it compared nine different numeric displays, many of which are currently popular (Ref. 30). Both reading time and accuracy were measured. The results, unfortunately, are somewhat difficult to interpret. The two best displays both consisted of a pattern of dots arranged much like a seven-segment display, but with the individual dots controllable so that slightly better shaped characters could be obtained. The better of these two

6.4.2 DISCRETE ALPHANUMERIC DISPLAYS (CONTINUED)

was a red LED with a reported luminance that was lower, by a factor of 15, than any of the other eight displays. It is not clear why this did not cause any reduction in legibility. There was some indication the authors intended to discuss this problem further after making more luminance measurements.

The worst of the nine displays was another seven-segment LED, the popular MAN-1 made by Monsanto. The seven segments were straight lines, which may have made the numerals more difficult to read. Much more important was the fact that this display did not include the red filter normally included to prevent ambient light from being reflected from unlit segments to the viewer's eye. As a result, all seven segments were always slightly visible.

The visibility of segmented alphanumeric displays that radiate in certain narrow spectral regions can be enhanced by the addition of a filter that transmits only in the same spectral region. When successful, this reduces the amount of light reflected from unlit segments of the display, and from the area surrounding each segment. This technique works well with red LED's and is standard on them. It is not very successful with green and orange LED's. An analysis of the probable reasons is available (Ref. 32).

Certain types of color-defective individuals, specifically *protanomalous* and *protanopic* individuals (Figure 5.2-19), may have difficulty with red LED displays. Because of their reduced sensitivity in the red region, the effective luminance and hence the contrast of a red LED display is much reduced for these individuals (Ref. 33). This problem can be expected in perhaps 2 percent of the male population and 0.04 percent of the female population. It will not occur with green LED's, and probably not with yellow ones.

There is some indication, thus far without empirical substantiation, that some individuals with apparently normal color vision have difficulty viewing red LED displays (Ref. 34). It is not obvious why this should occur, nor is it possible to predict whether it will eventually result in any limitations on the use of red LED's. Increasing the size of the display slightly is apparently an adequate solution (Ref. 35).

The display evaluation techniques described in Section 6.4.1 for CRT's can also be used with discrete numeric displays.

SECTION 6.4 SECONDARY DISPLAYS

6.4.3 INDICATOR LIGHTS

Indicator lights are useful for displaying display status information. They are effectively limited to two or perhaps three states. If associated with an operator-controlled function, they should show equipment status not control position. Legend lights are generally preferable to ordinary indicator lights because the label and the light can share the same panel area.

To ensure that they can be easily seen, indicator light luminance should be at least 50 percent above the highest expected surround luminance.

Some means of checking to see whether an indicator will not light because it is burned out should be provided.

The following color code for indicator lights should be followed (Ref. 36):

- Flashing red is used to indicate that a potential hazard to personnel, equipment, or imagery exists and immediate corrective action by the operator is required.
- Red is used to indicate that a portion of the display is inoperable or that a condition exists that is undesirable. It generally means that some action or special caution on the part of the operator will be required.
- Yellow is used to indicate that a marginal condition exists. In a sense, it is like a red signal but less severe or critical.
- Green is used to indicate that satisfactory conditions exist and it is appropriate to proceed.
- White is used to indicate conditions that have no right or wrong connotation.
- Blue is used like white, as an advisory light. Use of blue should be kept to a minimum.

Flashing lights of any color should be used only when it is necessary to attract the operator's immediate attention. A rate of 3 to 5 Hz is satisfactory.

6.4.4 AUDITORY DISPLAYS

Auditory signals provide a convenient means of displaying status information to a display user without increasing his visual load. They are particularly useful for warning of hazardous conditions or of situations that require some response from the operator. A particularly successful nondisplay application has been the use of a set of prerecorded messages to provide a pilot with specific information about a potentially hazardous condition on his airplane.

Extremely important auditory signals should be at least 10 dB above ~~the~~ ambient noise level. They should last only ~~5~~ or 10 seconds, but should then repeat until the required operator response occurs. Operator shutoff should not disable the signal so that it will not sound in response to a new hazard. The volume control should generally be accessible to maintenance personnel and not to the operator.

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3. Barmack, J. E. and Sinaiko, H. W. *Human Factors Problems in Computer-Generated Graphic Displays.* Study S-234, IDA/HQ-66-4820, Institute for Defense Analysis, 1966. (Also available as AD 636170.) See pp. 32-33.

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4. Kinney, G. C. and Showman, D. J. *Studies in Display Symbol Legibility: XVIII. The Relative Legibility of Uppercase and Lowercase Typewritten Words.* Report MTR-394, The MITRE Corp., 1967. Also, Report ESD-TR-67-106, USAF Electronics Systems Division, 1967. Also, *Information Display,* Sept./Oct. 1967, pp. 34-39. This report includes a brief summary of previous research in this area.

5. See p. 174 of Ref. 2.

6. See p. 170 of Ref. 2.

7. See Ref. 8 and p. 176 of Ref. 2.

8. Groner, G. F. *A Guide to Display Terminals That Enhance Man/Computer Communications.* Document R-1183, Rand Corp., Santa Monica, California, 1973.

9. See p. 364 of Ref. 2.

10. See p. 374 of Ref. 2.

11. Giddings, B. J. Alpha-numerics for raster displays. *Ergonomics,* Vol. 15, 1972, pp. 65-72.

12. See p. 47 of Ref. 16.

13. See p. 50 of Ref. 16.

14. Vartabedian, A. G. Developing a graphic set for cathode ray tube display using a 7x9 dot pattern. *Appl. Ergonomics,* Vol. 4, 1973, pp. 11-16.

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16. Shurtleff, O. A. Legibility research. *Proc. Soc. Info. Display,* Vol. 15, No. 2, 1974, pp. 41-51.

17. Huddleston, H. F. A comparison of two 7x9 matrix alphanumeric designs for TV displays. *Appl. Ergonomics,* Vol. 5, No. 2, 1974, pp. 81-83.

18. Based on visual inspection by the senior author. The Vartabedian font appears in Ref. 14.

19. See p. 156 of Ref. 2.

20. Sach, G. M. The effect of filters on contrast and readability of CRT display. *Proc. Soc. Info. Display,* Vol. 11, No. 4, 1970, pp. 177-186.

21. See p. 177 of Ref. 2.

22. See Figure 30 of Ref. 16.

23. The tradition apparently is for each group to put the slash through whichever character, the zero or the letter O, that they use least.

24. Hemingway, J. C. and Erickson, R. A. Relative effects of raster scan lines and image subtense on symbol legibility on television. *Human Factors*, Vol. 11, 1969, pp. 331-338.

25. See Figure 6 of Ref. 16.

26. See Figure 32 of Ref. 16.

27. See p. 190+ of Ref. 2.

28. Gibney, T. K. *Legibility of Segmented Versus Standard Numerals: The Influence of the Observer's Task.* AMRL-TR-68-124, Aerospace Medical Research Labs, 1968.

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31. Radl-Koethe, H., Saupe, I. and Schubert, E. *Vergleichende Untersuchung der Lesbarkeit Selbstleuchtender Numerischer Anzeigen.* Forschungsbericht Nr. 6, Forschungsinstitut für Anthropotechnik, Meckenheim, 1971.

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34. Andreien, H. Displays for digital systems. *Control Engr.*, Vol. 21, July 1974, pp. 67-70. See p. 70.

Also see Ref. 35.

35. Based on comments by designers of military aircraft control panels.

36. U.S. Army Missile Command. *Human Engineering Design Criteria for Military Systems and Facilities.* MIL-STD-1472B (proposed), May 1974.

6.5 LABELS

6.5.1 Purpose

6.5.2 Location

6.5.3 Content

[redacted]

6.5.4 Dependence on Lighting

6.5.5 Character Design

6.5.6 Spacing

SECTION 6.5 LABELS

NOTE: Because this entire section consists of recommendations, they are not listed separately here.

Labels on equipment may range from the few letters or numbers required to identify a control or display to the several paragraphs required to describe critical operator or maintenance procedures. The recommendations for labels summarized here are from a compilation of suggestions in several sources (Ref. 1), with modifications where appropriate based on experience with imagery displays. Also, see the discussion of character style in Section 6.4.1.

6.5.1 PURPOSE

Labels serve a number of different functions:

- Identify the function of a control, a display, or an item of equipment.
- Indicate the setting of a control or the value of a display indication.
- Instruct personnel in correct procedures.
- Warn personnel of potential hazards to themselves or to the equipment.

Ideally, labels should allow an operator with minimal instruction to operate a new piece of equipment successfully and without danger to himself or the equipment. Two factors make this goal difficult to achieve. First, the designer already knows the function of every control and therefore has difficulty appreciating the problems of the new user.

Second, the assumption is often made that all users will have access to and will study the instruction manual before operating the equipment. Few work environments are structured with enough rigidity to ensure that this will occur. Therefore, the labels should be at least marginally adequate by themselves, and in particular, should alert the user of any potential dangers.

6.5.2 LOCATION

Each label should be placed in unambiguous association with the control or display element to which it refers. The preferred location is immediately above the control or display. However, the most important requirement is that the label be easy to read and visible to the user at all times. Also, label location should be consistent throughout the equipment. Labels containing information irrelevant to equipment operation, such as manufacturer's part numbers, trade names, maintenance instructions, etc., should be placed outside of the operator's central field of view.

6.5.3 CONTENT

Labels should consist of common words that are readily understood and ordinarily used by the expected operators of the equipment. Brevity is important, but use of abbreviations and symbols should be minimized. When used, abbreviations and symbols should be well known and conform to accepted standards.

Controls and displays should be labeled according to function. The operator needs to know the action or operating mode that will result from control use, not the mechanism involved.

Labels should be consistent and unambiguous. More than one term should not be applied to the same thing. For example, if two rolls of film are to be placed on a light table, the one closest could be referred to as the Forward, Front, or even the Primary roll, but no more than one term should be used. In this example, Front is best because Forward could be confused with the film obtained from the forward camera of a two-camera collection system, and this might actually be the film that the user would choose to place at the back of the light table.

6.5.4 DEPENDENCE ON LIGHTING

Labels must be readable under all anticipated illumination conditions. If the illumination is at least 11 lux (1.0 foot candle), black characters on a light panel are appropriate. If operator adaptation to low light levels is necessary, use of white or self-luminous characters of adjustable brightness on a dark panel will reduce the amount of light reaching the user's eyes. If the "on" state of a pushbutton is indicated by illuminating it, the pushbutton legend should be visible even though it is off.

6.5.5 CHARACTER DESIGN

The legibility of a label depends on several factors:

- Character size Recommendations are in Figure 6.5-1 below.
- Stroke width and gap width–These two dimensions are usually made nearly equal and are expressed as a proportion of character height in Figure 6.5-2 below.
- Character width–Most characters should be 65 to 80 percent as wide as they are high. The letters M, W, and I and numerals 1 and 4 are exceptions. Some situations, such as a curved surface, may require an increase in width up to 100 percent of height.

Uppercase letters are easier to read than lowercase (Ref. 2) and should be used exclusively except in extended labels such as detailed instructions.

LABEL SIZE CATEGORY	APPLICATION	CHARACTER HEIGHT	NOMINAL POINT SIZE
MAJOR	CONTROL GROUP OR PANEL	5.6 mm (0.22 in)	24
INTERMEDIATE	CONTROL OR DISPLAY	4.0 mm (0.16 in)	18
MINOR	CONTROL POSITION	3.2 mm (0.12 in)	14
MINIMUM	INSTRUCTIONS	2.4 mm (0.09 in)	-

Figure 6.5-1. Preferred Character Dimensions. The character dimensions listed here are based on a nominal viewing distance of 71 cm (28 in). Sizes for other viewing distances should be scaled to yield the same *visual angle*.

TYPE OF LABEL	TYPICAL TYPE STYLE	PREFERRED RATIO OF HEIGHT-TO-STROKE WIDTH
HIGH CONTRAST DARK LETTERING ON A LIGHT PANEL	ALTERNATE GOTHIC, FUTURA MEDIUM, OR COPPERPLATE	6:1 TO 8:1
BACK LIGHTED LETTERING ON DARK PANEL	FUTURA LIGHT	10:1 TO 12:1 (see text)

Figure 6.5-2. Type Style and Stroke Width. Appropriate type styles for and relative stroke widths for dark and light characters are listed here. Research with dark lettering indicates that if the illumination level and reading time are adequate, height to stroke width ratios between 3:1 and 15:1 are equally readable (Ref. 3,X).

For the special case of highly luminous characters viewed in near or total darkness, light lines will appear wider than they are and stroke width should be reduced so that the height to stroke width ratio falls between 12:1 and 20:1.

6.5.6 SPACING

The following guidelines should be followed in label spacing:

- One stroke width between characters
- One character width between words
- One-half the character height between lines

All of these clearances should be doubled if adequate space is available.

SECTION 6.5 REFERENCES

1. *Human Engineering Design Criteria for Military Systems, Equipment and Facilities.* MIL-STD-1472 B, Proposed, U.S. Army Missile Command, May 1974.

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   Also see Ref. 3.

2. Kinney, G. C. and Showman, D. J. *Studies in Display Symbol Legibility: XVIII. The Relative Legibility of Uppercase and Lowercase Typewritter Words.* Report MTR-394, The MITRE Corp., 1967. Also, Report ESD-TR-67-106, USAF Electronics Systems Division, 1967. Also, *Information Display*, Sept./Oct. 1967, p. 34-39. This report includes a brief summary of previous research in this area.

3. Semple, C. A., Jr., Heapy, R. J., and Conway, E. J., Jr. *Analysis of Human Factors Data for Electronic Flight Display Systems.* AFFDL-TR-70-174, Air Force Flight Dynamics Lab, 1971. Pages 165-180 provide a review of symbol dimensions on legibility.

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SECTION 6.6 ACOUSTIC NOISE

Three kinds of limits must be imposed on the amount of acoustic noise produced by a display. Each of these is considered in detail in the following sections.

- Noise exposure–The display must not expose the user to a noise level that might cause a loss of hearing; very few displays even approach this noise level.
- Communication–The display user must be able to communicate adequately with nearby individuals and over the telephone.
- Comfort–In order to function effectively, the noise must not be disruptive nor should it cause the display user to become dissatisfied with his work situation.

When establishing a noise design limit for a display, the ambient noise environment in which it will be used must be considered. On the one hand, if the environment is already too noisy care must be taken to ensure that the new display does not aggravate the problem. On the other hand, there is no point in paying a high price to reduce the display noise level much below the point where it has no impact on the total room noise. The graph in Figure 6.6-3 provides a convenient means of making the necessary decibel computations.

The noise level at the operator's work location depends not only on the amount of noise the display produces but also on the amount that is reflected back from surfaces in the room. This topic is treated in Section 6.6.7 and must be considered when specifying the measurement conditions that will be used to establish whether the noise design limit has been met.

There are many resources available to the designer faced with a requirement to measure or reduce noise. An extensive reference literature exists (Ref. 1), and there are several periodicals that provide information on recent developments, particularly in the area of noise exposure limits. These same periodicals provide access to noise measurement and reduction equipment and information on consultants (Ref. 2).

SECTION 6.6 ACOUSTIC NOISE

6.6.1 TERMINOLOGY AND ACRONYMS

Acoustic technology utilizes numerous terms and acronyms. The ones that appear in this document are summarized here. More complete definitions appear in the rest of Section 6.6 and in the Glossary.

Many authors have attempted to limit certain terms, particularly level, sound level, and sound pressure level, to very specific meanings (Ref. 3). Judging by the recent acoustic literature, these attempts have not been very successful.

dB	–	DECIBEL; 10 TIMES THE LOG TO THE BASE 10 OF THE RATIO OF TWO POWERS
dBA	–	A-WEIGHTED SOUND LEVEL
LEVEL	–	THE RATIO OF TWO QUANTITIES; EXPRESSED IN dB
N/m^2	–	PRESSURE IN NEWTONS PER SQUARE METER
PW	–	SOUND POWER
PWL	–	SOUND POWER LEVEL
re	–	RELATIVE TO THE GIVEN REFERENCE VALUE
SP	–	SOUND PRESSURE
SPL	–	SOUND PRESSURE LEVEL
SL	–	SOUND LEVEL; USUALLY MEASURED OVER THE ENTIRE AUDIO SPECTRUM
SIL	–	SPEECH INTERFERENCE LEVEL
PSIL	–	PREFERRED-FREQUENCY SPEECH INTERFERENCE LEVEL
NC	–	NOISE CRITERION CURVE
NCA	–	ALTERNATE NOISE CRITERION CURVE
PNL	–	PERCEIVED NOISE LEVEL
PNdB	–	A PNL VALUE IN dB
OCTAVE	–	A BAND OF FREQUENCIES WITH LIMITS IN THE RATIO OF 2:1

Figure 6.6-1 Acoustic Terms and Acronyms

6.6.2 UNITS AND CALCULATIONS

Sound power measurements are usually expressed in *decibels* (dB). The decibel is defined as 10 times the logarithm of the ratio of two powers (Ref. 4):

$$PWL \text{ (in dB)} = 10 \log \frac{PW}{PW_{ref}}, \text{ where}$$

PWL = the sound power level of a particular sound in dB.

PW = the sound power of the sound, and

PW_{ref} = a reference sound power, usually 10^{-12} watts (Ref. 5).

Four features of this definition deserve special comment:

- The term *level* means a ratio relative to a reference quantity is involved; levels are properly expressed in dB.
- The ratio is between two powers.
- The reference power must be specified.

Both the ear and the microphone respond to sound pressure, not sound power. The sound power of a source cannot even be measured directly, but must be calculated from one or more sound pressure measurements (Ref. 6). Therefore, sound is usually treated in terms of pressure, rather than power.

Sound power is equal to the square of sound pressure, multiplied by a constant (Ref. 7). Because "decibel" refers to the ratio of two powers, it also refers to the square of the ratio of two sound pressures:

$$SPL = 10 \log \frac{SP^2}{SP_{ref}^2} = 20 \log \frac{SP}{SP_{ref}}, \text{ where}$$

SPL = the *sound pressure level* of a particular sound, in dB,

SP = the sound pressure of the sound, and

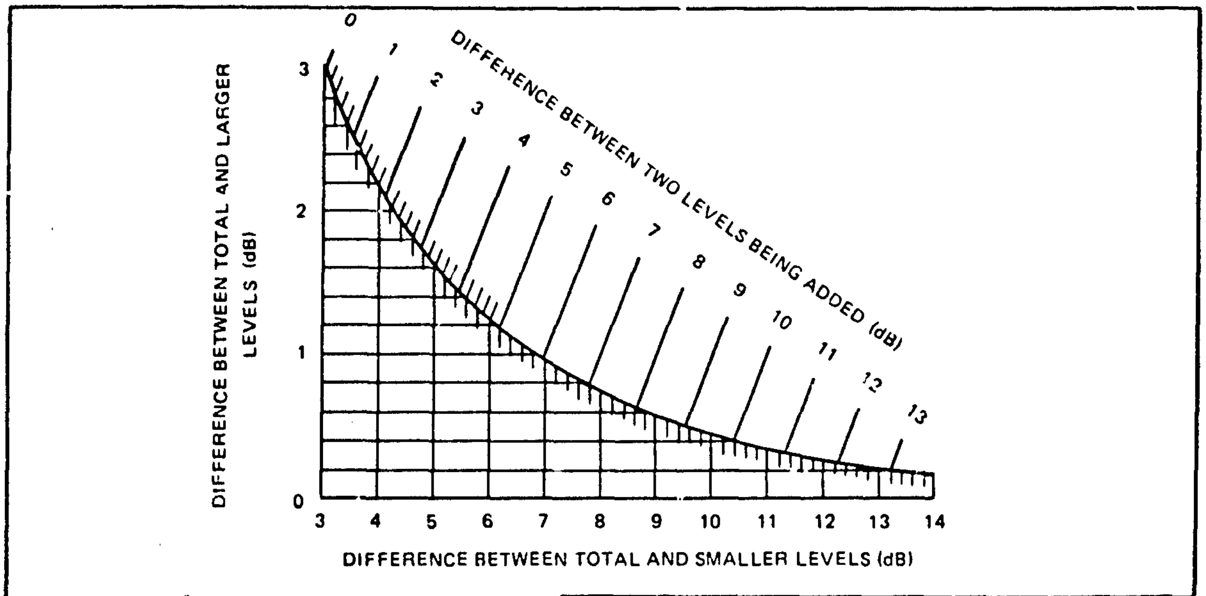
SP_{ref} = the reference sound pressure, which is 2×10^{-5} N/m^2 throughout this document and in most others (Ref. 8).

The reference pressure for a sound pressure level (SPL) should always be stated, particularly on test data forms or in a design specification. However, the use of 2×10^{-5} newton/square meter (N/m^2) as a reference has become so universal that some authors no longer bother to cite it in research reports.

DECIBELS (dB)	POWER RATIO ($10 \log \frac{PW}{PW_r}$)	PRESSURE RATIO ($20 \log \frac{SP}{SP_r}$)
-20	0.010	0.100
-10	0.100	0.316
-6	0.251	0.501
-3	0.501	0.708
-2	0.631	0.794
-1	0.794	0.891
0	1.000	1.000
1	1.259	1.122
2	1.585	1.259
3	1.995	1.413
6	3.981	1.995
10	10.000	3.162
20	100.00	10.000

Figure 6.6-2: Typical Decibel Values. This list of sound power and sound pressure ratios corresponding to selected decibel values illustrates several characteristics of these units. For example, because sound power, but not sound pressure, is additive, two equally powerful sound sources will yield twice as much sound power as one, an increase of approximately 3.01 dB, but the sound pressure only increases by a factor of $\sqrt{2}$, or 1.414. Similarly, to cut sound pressure by a factor of 2 requires a reduction in sound power of 2^2, or 4, which corresponds to -6.02 dB.

6.6.2 UNITS AND CALCULATIONS (CONTINUED)



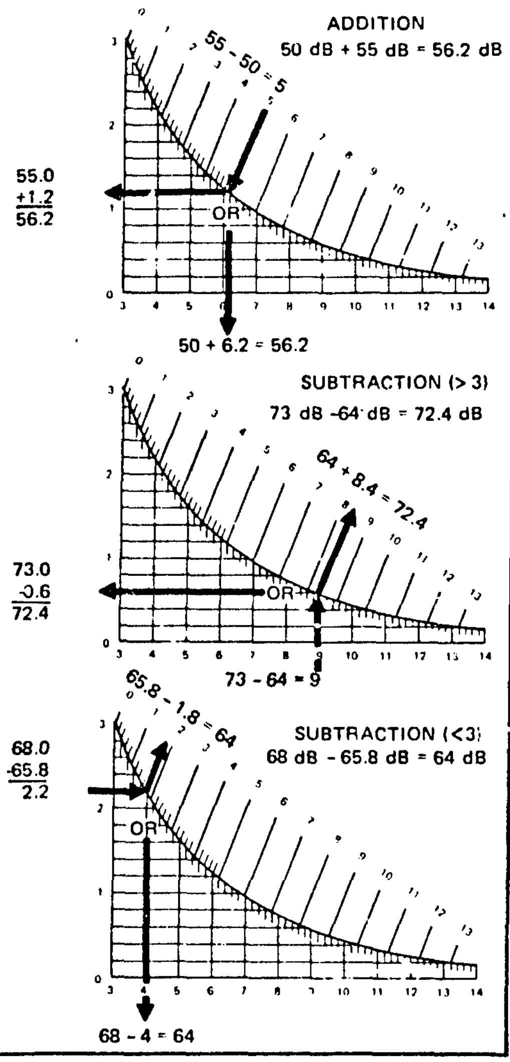


Figure 6.6-3: Computations with Decibels. Decibel values can be combined by working back through the equations shown above, or by the use of this graph (Reference 9).

To add two decibel values, enter the upper scale with the difference between them and read down to find the amount to add to the smaller, or read to the left to find the amount to add to the larger. The first example shows these two methods of adding 50 dB and 55 dB to obtain 56.2 dB.

The technique for subtraction depends on whether the difference between the total and the number being subtracted is larger or smaller than 3. If larger, enter from below and go up to find the amount to add to the smaller number, or go up and then continue left to find the value to subtract from the larger number. The middle example illustrates these two methods of obtaining 73 dB-64 dB = 72.4 dB.

For subtraction when the difference is less than 3, enter from the left and go right to find the amount to subtract from the smaller number, or go right and then continue down to find the amount to subtract from the larger number. The bottom example illustrates these two methods of obtaining 68 dB-65.8 dB = 64 dB.

The most common situation requiring subtraction of decibel values occurs when the noise level of a display must be measured in the presence of background noise. Referring again to the middle example, the noise level with the display running would be 73 dB and the background with it off would be 64 dB. Subtracting the background from the total measurement shows that the noise level of the display alone is 72.4 dB.

6.6.3 FREQUENCY SPECTRUM

The frequency range over which noise measurements are usually made covers the range of hearing for most adults, nominally 20 to 12,000 Hz. Sound pressure level may be measured over this entire spectrum or only over a portion of it. For full spectrum measurements the statement of the resulting sound level must indicate the relative weighting given the different parts of the spectrum. The commonly used weightings are summarized in Figure 6.6-4.

A better understanding of a noise problem can be obtained from separate measurements along small portions of the spectrum. This is most commonly done by measuring in octave or third-octave bands as described in Figure 6.6-5 below.

To compare sound pressure level values between bands of different widths, a correction for bandwidth is necessary. So long as the sound is more or less distributed over the range of frequencies involved, the following relationship holds:

$SPL_B = SPL_A - 10 \log A/B$, where A and B are the relative widths of the two bands. For example, the conversion from third octave to full octave bands is:

$$SPL_1 = SPL_{1/3} - 10 \log \frac{1/3}{1} = SPL_{1/3} + 5 \text{ dB}.$$

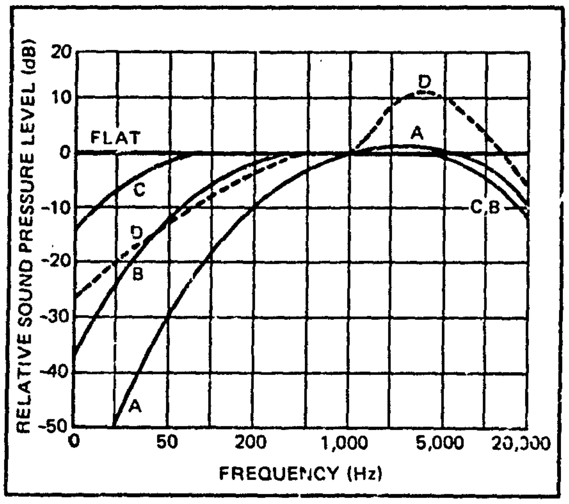


Figure 6.6-4: Frequency Weighting Curves. The three standard frequency weighting curves, A, B, and C, are illustrated (Ref. 10). An overall, or flat frequency response, is also included on most sound-level meters. A fourth weighting curve, D, is coming into use for measuring aircraft noise.

Originally the A curve was intended to match the response of the meter to the ear at relatively low sound levels, while the B and C curves were intended for successively higher sound levels. At present, almost all sound-level (full spectrum) measurements are made with the A curve, and the B and C curves are used primarily to obtain information on the spectral distribution of the sound energy when an octave band analyzer is not available.

Sound-level measurements must include a statement of the weighting curve used. Measurements made with the A curve are generally given as dBA or dB(A).

6.6.3 FREQUENCY SPECTRUM (CONTINUED)

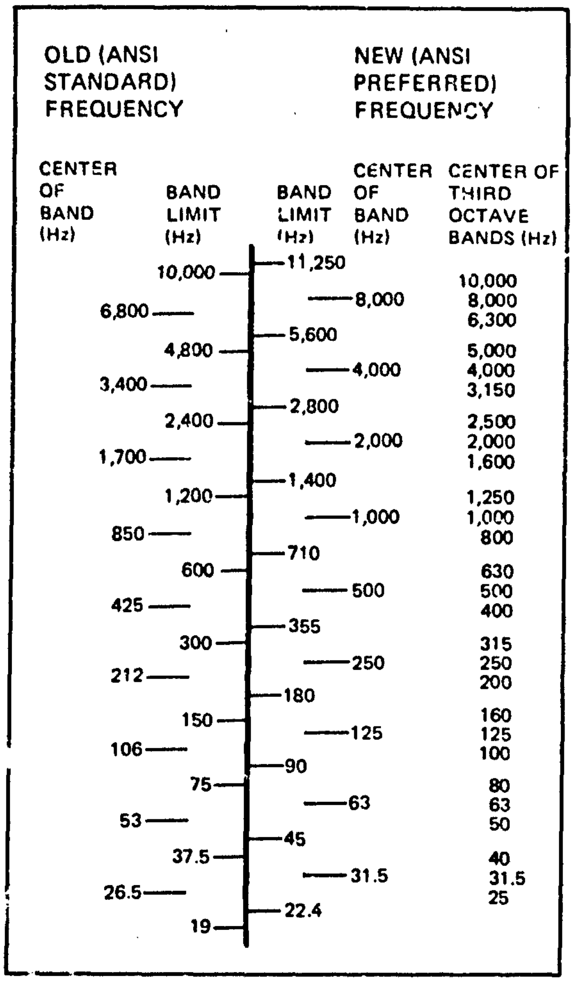


Figure 6.6-5: Octave and Third-Octave Band Frequencies. An octave band covers a frequency range of 2 to 1, while a third octave band covers a range of $2^{1/3}$ to 1.

Two sets of octave bands are in use, the American National Standards Institute (ANSI) Preferred Frequencies and the older ANSI Standard Frequencies (Ref. 11). Whenever possible, the new frequencies should be used. The center and limiting frequencies for both sets of octave bands are illustrated, along with center frequencies for the preferred third octave bands. Octave bands in the new set are designated by their center frequency, 250, 500, 1,000, etc., and those in the old set by their limiting frequencies, 300-600, 600-1200, etc.

6.6.4 NOISE EXPOSURE (INJURY) LIMITS

RECOMMENDATION:

Limit the daily noise dose, as defined in Figure 6.6-6, to 1.0. This will permit 8-hour exposure to a noise level of 90 dBA. Higher noise levels or a longer work day require use of the figure.

Do not expose personnel to a noise level in excess of 115 dBA.

If the daily noise dose, as defined in Figure 6.6-6, exceeds 0.5, provide audiometric testing of personnel in order to determine if hearing loss is occurring.

NOTE: These recommendations are required by law in many situations.

Excessive exposure to noise is harmful to hearing. Establishment of exposure limits is complicated by their economic impact and by the fact that the exact occupational noise exposure at which hearing loss begins is still controversial (Ref. 12). In the limited data that are available, hearing loss due to occupational noise is often hard to distinguish from loss due to other noises (Ref. 13) and from the loss normally associated with aging.

In most occupational situations, noise exposure is limited by Federal regulations issued by the U.S. Department of Labor's Occupational Safety and Health Administration (OSHA) (Ref. 14). Although the legal status of these regulations for Federal and military personnel is not exactly certain (to this writer), they provide the best available guidance for the display designer.

The new OSHA noise exposure standards limit 8-hour exposure to 90 dBA, with exposure to higher levels, up to a maximum of 115 dBA, permitted for shorter durations. Noise level and duration in combination determine the *daily noise dose*, as outlined in Figure 6.6-6 below. The daily noise dose must not exceed a value of 1.0 which is equivalent to an 8-hour exposure to 90 dBA. If the daily noise dose exceeds 0.5, which is equivalent to an 8-hour exposure to 85 dBA, *audiometric monitoring* of the employee is required in order to determine if any hearing loss is occurring. There are some hints that limitation of the daily noise dose to 0.5 will eventually be required (Ref. 15).

Test equipment used to establish that a noise level does not exceed the exposure limit must conform to applicable standards (Ref. 16). As the A in dBA indicates, the A-weighted frequency response (Figure 6.6-4) must be used. The "slow" setting should be used in order to average the noise level over small fluctuations.

6.6.4 NOISE EXPOSURE (INJURY) LIMITS (CONTINUED)

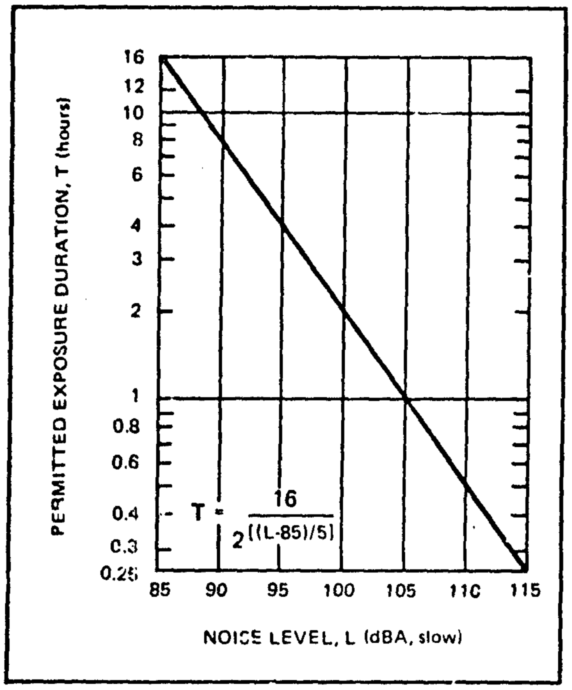


Figure 6.6-6: Determination of Daily Noise Dose. Under new OSHA regulations, occupational noise exposure is limited in terms of a daily noise dose, N_D, where N_D is the sum of the ratios, $R_1 \ldots R_n$, one of which is calculated for each of the noise levels to which the individual is exposed during a single day. The R for each noise level, L, is the actual duration of exposure to that noise level, divided by the permitted daily exposure duration, T. The value of T for any L can be obtained from either the curve or the equation shown here.

For example, suppose that an individual is exposed during a workday to 95 dBA for 1 hour, to 90 dBA for 2 hours, and to 85 dBA for 6 hours. This yields a daily noise dose, $N_D = 0.25 + 0.25 + 0.375 = 0.875$, calculated as follows:

L(dBA)	T(hours)	R
95	4	0.25
90	8	0.25
85	16	0.375

As is described on the previous page, a value of N_D in excess of 0.5 requires monitoring of employees for hearing loss. Values in excess of 1.0 are not permitted

6.6.5 COMMUNICATION

RECOMMENDATION:

In order to ensure convenient voice communication over a distance of 2 meters, limit the preferred frequency speech interference level (PSIL) to 52 dB. Limits for other distances can be estimated from Figure 6.6-7.

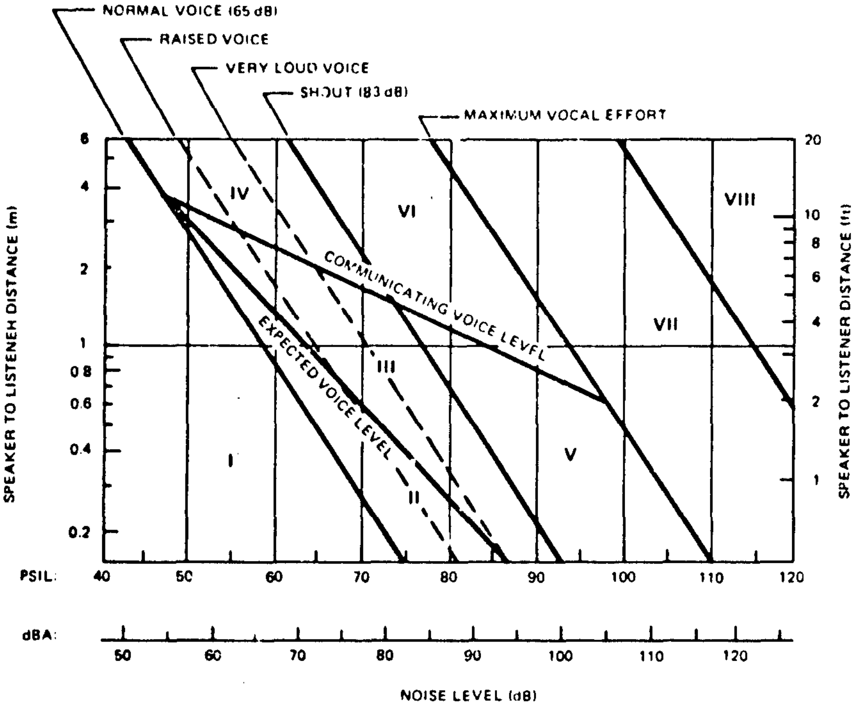
Excessive noise interferes with voice communication. The amount of noise that can be tolerated depends on the type of information being interchanged and on the level of communication success required. This document is limited to normal, face-to-face conversation as would occur between display users within a single room or via a telephone. Special techniques, not treated here, are available to evaluate communication success with specialized electronic communication systems or when a limited message set is utilized, as between pilots and air traffic controllers (Ref. 17).

One of the earliest methods of evaluating the impact of noise on voice communication was the speech interference level (SIL) developed by Beranek in the late 1940's (Ref. 18) and later refined by him (Ref. 19). The SIL of a noise is the arithmetic average of the sound pressure level (SPL) in the three standard octave bands centered at 850, 1,700 and 3,400 Hz; if the 425-Hz octave has a SPL more than 10 dB above the 850-Hz octave, it is also included in the average. With the establishment of new octave band frequencies (Figure 6.6-4), the SIL became the PSIL, or preferred [frequency] speech interference level. The PSIL is the arithmetic average of the three octave bands centered at 500, 1,000 and 2,000 Hz. For typical noises, SIL is 3 dB less than PSIL (Ref. 20).

Many other methods of describing the speech interfering properties of a noise have been tried, ranging from the simple A-weighted sound level, dBA, to units that are relatively complicated to measure and calculate, such as perceived noise level (PNL) (Ref. 20). Most of these methods are about equally effective in describing the effects of most noises on communication, probably because most noises in a particular environment, for example an office, have very similar spectral distributions. Sound level, measured as dBA, is therefore effective because, unless there is a preponderance of noise in the octaves above 2,000 Hz, a situation not found in most office or industrial noises, it provides a very good estimate of PSIL. For typical noises, dBA has a value 7 dB greater than PSIL (Ref. 20).

In tests with a wide range of noise types, PSIL predicted the amount of speech interference as well as any other measure for noises with normal spectra and better than any of the others tested for noises with diverse spectra (Ref. 21). Therefore, PSIL appears to be the best currently available, simple measure of the effect of noise on speech communication.

6.6.5 COMMUNICATION (CONTINUED)



I PREFERRED ENVIRONMENT; COMMUNICATION POSSIBLE WITH NORMAL VOICE

II ACCEPTABLE; THE NORMAL INCREASE IN VOICE LEVEL EXPECTED IN NOISE IS ADEQUATE TO MAINTAIN COMMUNICATION

III ACCEPTABLE BUT UNDESIRABLE; COMMUNICATION POSSIBLE BUT CONSCIOUS EFFORT TO INCREASE VOICE LEVEL IS NECESSARY

IV NOT ACCEPTABLE FOR MOST APPLICATIONS; EVEN WITH CONSCIOUS EFFORT, COMMUNICATION WILL PROBABLY BE POOR (THIS REGION WAS NOT TESTED IN THE ORIGINAL SIL-PSIL EXPERIMENTATION).

V,VI NOT ACCEPTABLE; LIMITED COMMUNICATION POSSIBLE BUT ONLY BY SHOUTING; VOICE IS DIFFICULT TO UNDERSTAND AT THIS LEVEL.

VII UNAIDED COMMUNICATION IMPOSSIBLE

VIII COMMUNICATION WITH AMPLIFIED SPEECH IMPOSSIBLE

Figure 6.6-7. Relationship of PSIL to Effective Communication Distance. The preferred frequency speech interference level (PSIL) is the recommended method for specifying the limiting noise level that will allow adequate communication. The impact of noise, as measured by PSIL, on the distance over which individuals can communicate by voice is illustrated here. This figure is based largely on the original Beranek data (Ref. 18), but has been replotted by one of the researchers responsible for the comparison of different methods of measuring noise (Ref. 20).

The dBA scale is included because it provides a quick estimate of PSIL so long as the noise energy is both regularly distributed across the frequency range and is not concentrated at frequencies above 2000 Hz. However, dBA should not be used for specifying communication noise limits.

The straight line plots of voice levels show what will occur if the speaker is not aware of the noise level. This might occur because the listener but not the speaker is in the sound field of the noise source. An extreme but common example is attempting to hear someone speaking in a normal voice in an adjacent room while you are shaving with an electric razor.

If the speaker is aware of the noise, his voice level will increase by approximately 3 dB for each 10 dB increase in noise level above 50 dB PSIL; this is his "expected voice level." If, in addition, the speaker is aware that the listener is having difficulty understanding him, he will increase his voice level by 5 dB rather than 3 dB, resulting in his "communicating voice level."

As the speaker's voice increases from a shout at 83 dB to his maximum vocal effort, there is little if any improvement in the listener's ability to distinguish what is being said.

As an illustration of how to use this figure, consider a conference room where individuals separated by up to 5m (16 ft) expect to communicate with a normal voice level. The maximum noise level is 45 dB PSIL. For an imagery interpretation work station where brief conferences of two to four persons are common, communication over 2m (6 ft) should probably be possible, without the need to exceed a normal voice level. This leads to an upper limit on the noise level of 52 dB PSIL.

6.6.6 COMFORT

RECOMMENDATION:

To ensure a comfortable work environment at an imagery display, do not allow the noise level to exceed the NC-45 curve in Figure 6.6-9.

If economy dictates a compromise and the restrictions listed in Figure 6.6-10 are met, an NCA-45 curve as defined in that figure can be substituted.

Eliminate low frequency variations in noise level.

Simply limiting noise to a level that allows voice communication between individuals does not ensure that the noise will not be disruptive to their work nor that it will not cause dissatisfaction with work conditions. For example, in the series of studies that led to the development of speech interference level (SIL), a considerable amount of opinion data was collected (Ref. 19). In an engineering and drafting office that had a SIL of 55 dB and an estimated PSIL of 58 dB, a noise level just at the limit for reasonable communication according to Figure 6.6-7, the user comments as summarized by the author were: "Noise situation terrible. Complaints of fatigue and irritation." (Ref. 22). A reduction in noise level of 8 dB, to an SIL of 47 dB (an estimated PSIL of 50 dB) was considered to be acceptable. Because this kind of data is so sensitive to numerous uncontrolled variables, such as general job satisfaction and prior experience with noise, drawing conclusions from it is difficult. However, in the absence of anything better, the available Beranek data, collected from the occupants of many different offices, are summarized in the next figure.

In the course of these studies, Beranek observed that SIL predicted communication success, but that other aspects of the noise, particularly the low frequency energy level, had a strong effect on the noise ratings he obtained. After an involved analysis he developed a set of curves intended to establish whether a satisfactory noise environment exists. These are known as noise criterion (NC) curves.

When the noise level of a piece of equipment is limited by an NC curve, none of the octave bands may exceed that curve. This works well with most noises, which have relatively continuous spectra. However, because noises with peaked spectra are generally not as loud as their corresponding NC curves (Ref. 23), these curves sometimes yield a conservative design limit. This problem has also limited their usefulness as a research tool in favor of more comprehensive measures of loudness such as perceived noise level (PNL). In fact, given the current sophistication of such methods of calculating loudness there is some question whether NC curves would ever have been developed (Ref. 23).

Because the NC curves represent approximately equal loudness contours, they provide the designer with a useful indication of how much the energy in each octave band is contributing to the loudness of his device.

Some noises that contain pure tones, or high concentrations of energy in a narrow band, sound louder than an overall measure of their sound level would indicate. This phenomenon has been amply demonstrated (Ref. 24) and is included as a correction term in the standard method for computing aircraft loudness used by the Federal Aviation Agency (Ref. 25). However, recent research indicates that measures of loudness that include a correction for pure tones were no better than those without a correction, so the matter has not yet been resolved (Ref. 26). If a correction does prove to be necessary, it will apply only to unitary measures of loudness like dBA or perceived noise level (PNL). There is no evidence of the need for such a correction with NC curves nor for PSIL or dBA as they are used in the previous two sections.

The voice level data in Figure 6.6-7 illustrate how, if the noise distribution in a room is uneven, a noisy piece of equipment can cause annoyance for workers who are not annoyed directly. Consider, for example, a speaker attempting to communicate with nearby listeners in a sound field of 80 dB PSIL. He would raise his voice level so that he would be heard by a possibly unwilling listener 6m (20 ft) away in a sound field of 55 dB PSIL.

Although such large irregularities in noise distribution are not frequent, this phenomenon has been observed with one prototype imagery display (Ref. 27). This

6.6.6 COMFORT (CONTINUED)

device had a high flow of air at the film gate, resulting in considerable high frequency noise. Possibly because high frequency sound tends to travel in straight lines while low frequencies pass around obstacles, or perhaps simply because the two frequency ranges were absorbed differently throughout the room, the region close to the new display was very noisy while the far end of the room was very quiet, and speakers at the display sometimes were disturbing to individuals attempting to concentrate on their work at the far end of the room.

Slow variations in noise level are a special problem. These occur because of beats between strong noise frequencies that differ by less than a few cycles or as a result of cyclic variation in the behavior of the noise source.

Although these kinds of sounds are universally acknowledged to be very disturbing for the listener, there is at present no objective method for specifying design limits.

Noise at very high frequencies, well above the hearing range for most individuals, is another potential problem not covered specifically by ordinary noise specifications. Under certain conditions, such noise can apparently cause serious physical discomfort in susceptible individuals (Ref. 28).

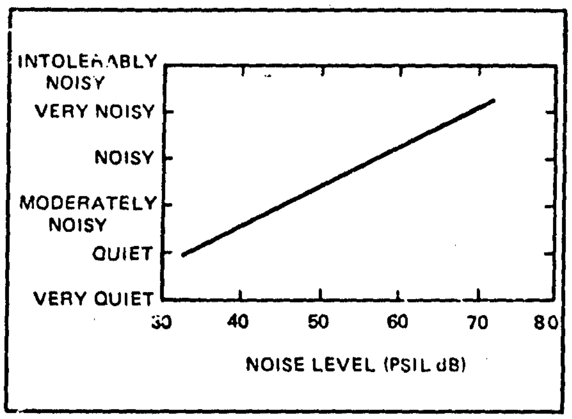


Figure 6.6-8: Effect of Noise Level on Noise Ratings. This curve summarizes average noise ratings made by about 200 office workers surveyed in the series of studies that led to the development of NC curves (Ref. 29). About 24 different rooms, at an Air Force base and in commercial buildings, are represented. The workers, approximately in order of their frequency in the sample, were stenographers and clerks, engineers, foremen, executive secretaries, and executives.

6.6.6 COMFORT (CONTINUED)

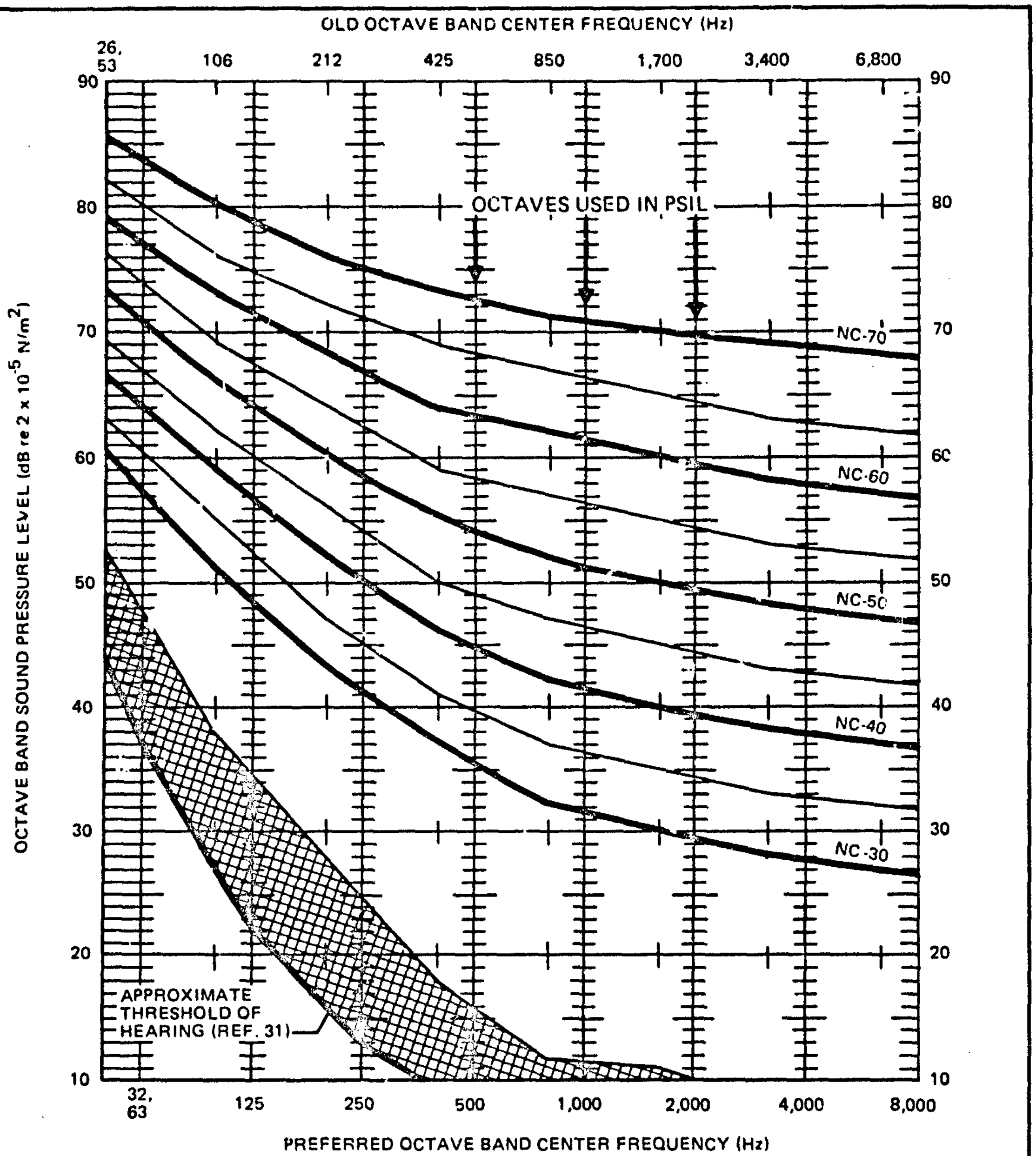


Figure 6.6-9: Noise Criterion (NC) Curves (Ref. 30). Noise criterion (NC) curves were developed by Beranek as a basis for specifying office noise limits (Ref. 22). When used in this way, none of the eight octave bands can exceed its level on the specified NC curve. Note that the lowest of these bands is not a true octave, but is actually the average of two octaves.

The number assigned to each curve is determined by its sound level in the (old) octave band centered at 1700 Hz.

The SIL for each curve is the same as its NC number and the PSIL is 1 dB higher. This contrasts with the 3 dB difference between SIL and PSIL found for typical noises. The overall sound level of an NC curve, in dBA, is 10 dB higher than the curve number. Because most noise spectra are irregular, a difference between dBA and NC number of 5 dB is more typical. Measuring dBA is not an adequate method of estimating an NC number.

6.6.6 COMFORT (CONTINUED)

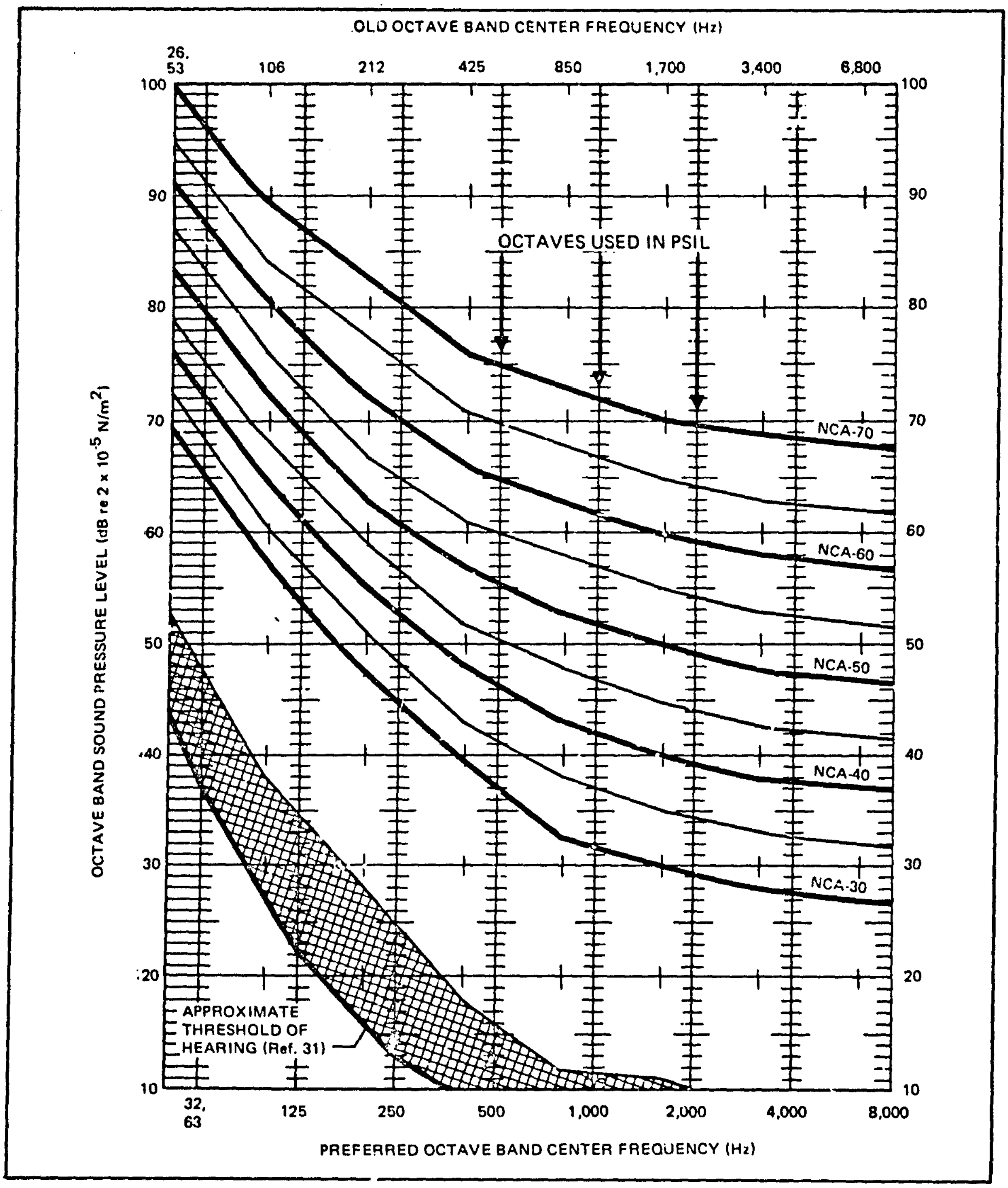


Figure 6.6-10: Alternate Noise Criterion (NCA) Curves (Ref. 30). Alternate noise criterion (NCA) curves allow an increase in the noise level of the lower frequency octave bands and therefore an increase in loudness with no change in speech interference level. They are intended to be used in place of NC curves only in instances where the need for extreme economy makes it impossible to achieve the desired NC curve. In addition, the noise must be steady and free of beats.

6.6.6 COMFORT (CONTINUED)

NOISE CRITERION (NC)	CONVERSATION DISTANCE		MAXIMUM CONFERENCE SIZE	TELEPHONE USE	SUGGESTED APPLICATION	COMMENTS
	NORMAL	RAISED VOICE				
20-30	—	—	50 PEOPLE	—	EXECUTIVE OFFICES	VERY QUIET
30-35	3.0-9.1m (10-30 ft)	—	20 PEOPLE	—	SEMIPRIVATE OFFICES, RECEPTION ROOMS	—
35-40	1.8-3.7m (6-12 ft)	—	1.8-2.4 m (6-8 ft) TABLE	—	MEDIUM SIZED OFFICES	—
40-50	0.9-1.8m (3-6 ft)	1.8-3.7 m (6-12 ft)	0.9-1.8 m (3-6 ft) TABLE	OCCASIONALLY SLIGHTLY DIFFICULT	ENGINEERING AND DRAFTING ROOMS	—
50-55	0.3-0.7m (1-2 ft)	0.9-1.8 m (3-6 ft)	2-3 PEOPLE	SLIGHTLY DIFFICULT	TYPING AND BUSINESS MACHINE USE	—
55 +	—	—	—	DIFFICULT	NOT SUITABLE FOR OFFICE	VERY NOISY

Figure 6.6-11. Noise Criterion (NC) Curve Applications. The best available recommendations for application of NC curves to work situations are those developed by Beranek and summarized here (Ref. 19). Making the assumption that imagery displays would fit most appropriately into an engineering and drafting room type of noise environment, these data imply that the noise should not exceed NC curves 40 to 50.

The maximum conference size was unfortunately defined in this study in terms of the number of people in some cases, and in terms of the size of conference table in use in other cases.

6.6.7 ROOM REVERBERATION AND ABSORPTION

RECOMMENDATIONS:

In areas where display users must communicate by voice, provide a room reverberation time of approximately 0.5 second.

Measure display noise level in an area with reverberation time and sound reflections typical of those found in the area where it will be used.

The sound reflected from room surfaces is known as *reverberation*. If the delay relative to the original sound is small, the reflections and the original will fuse and be heard singly by the listener. If the delay is long he will hear a separate sound, called an echo.

As a sound makes successive reflections it will die out because of absorption at the reflecting surfaces and in the medium through which it is passing. A room can be characterized by its *reverberation time*, T_{60}, which is the time required for the sound pressure level (SPL) to decay 60 dB (Ref. 32).

If the reverberation time is long, the room is termed "live" and a spoken word is heard first directly and then as a series of reflections. A certain amount of reverberation is desirable because it makes speech sound alive and natural. Too much reverberation is undesirable because reflections arrive at the same time as a subsequent word and interfere with its perception.

If the reverberation time is short, the room is termed "dead." There is less interference between words, but because the sound of the word decays before it can propagate through the room, communication may be reduced. The limited data available on reverberation time requirements are summarized in Figure 6.6-12.

Limited data (Ref. 33) suggest workers can tolerate more noise, perhaps 5 to 10 dB more on the set of noise criterion (NC) curves in Figure 6.6-9 if the noise is produced by several equally noisy machines and if the room is made very dead by the use of sound absorbing materials. The effect on communication was not evaluated in this study, but there is no reason to believe that the acoustical treatment would help.

Because of its impact on noise level, the reverberation time of the test room must be considered when measuring noise, particularly if a contract specification is involved. A test area with a very short reverberation time results in the best measurement of the display noise, but may underestimate the noise at the display operator's workstation when it is used in a normally reverberant work room. Extensive data on the magnitude of this effect are not available, but in one study the effect of room reverberation time for 250-Hz noise 2m (6 ft) from the acoustic center of a machine was as follows (Ref. 34):

REVERBERATION TIME	RELATIVE NOISE LEVEL
0.05 second	0
0.11 second	+2.0 dB
0.22 second	+3.2 dB

The contribution of reflected sound to a noise measurement can be estimated by measuring the noise at more distant points (Ref. 35). If the level at these points is at least 6 to 8 dB lower, the contribution of reflections is less than 1 dB (see Figure 6.6-3) and can safely be ignored.

6.6.7 ROOM REVERBERATION AND ABSORPTION (CONTINUED)

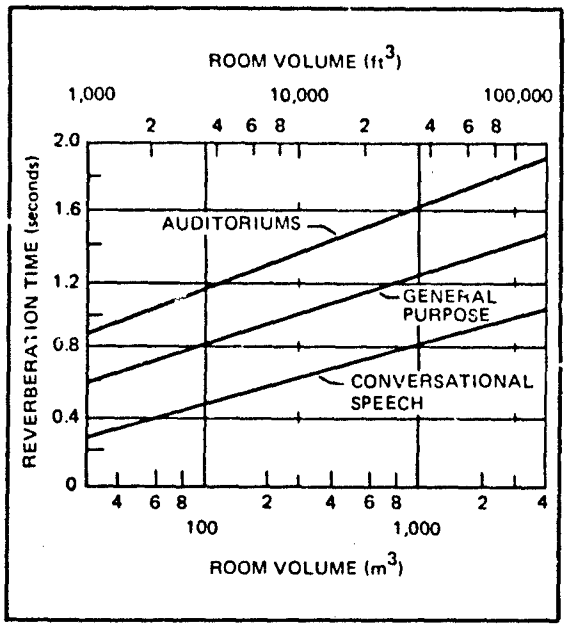


Figure 6.6-12: Preferred Reverberation Time. The origins of reverberation time design recommendations are not well documented, but they appear to be due primarily to architectural experience. One set of recommendations (Ref. 36) is illustrated here and indicates that larger rooms require longer reverberation times. Other sources give generally similar numbers:

- Reference 37
  - Speech studio – 0 to 0.7 second
  - Classroom, conference room – 0.3 to 1.2 seconds
  - Auditorium – 0.7 to 1.5 seconds
- Reference 32
  - Office – 0.5 second
  - Large conference room, small auditorium – 0.8 second

SOUND ABSORPTION COEFFICIENTS			
MATERIAL	FREQUENCY (Hz)		
	125	500	2,000
BRICK WALL, PAINTED	0.01	0.02	0.02
PLASTER, GYPSUM	0.02	0.02	0.02
MARBLE	0.01	0.01	0.02
WOOD PANELING	0.10	0.10	0.08
DRAPERIES, LIGHT	0.04	0.11	0.30
DRAPERIES, HEAVY	0.10	0.50	0.82
CARPET, WOOL	0.09	0.21	0.27
CARPET AND PAD	0.20	0.35	0.50
CHAIR, UPHOLSTERED	3.50	3.50	3.50
PEOPLE, STANDING	2.00	4.70	5.00
PEOPLE, SITTING	0.70	0.50	1.60

Figure 6.6-13. Absorption Coefficients and Reverberation Time. If a particular work environment is too live, it is possible to reduce the reverberation time by the addition of materials that will absorb more of the sound, either on the walls or as freestanding or ceiling-hung panels. The absorption coefficients of several standard materials at different frequencies are listed here (Ref. 32). In general, if the average absorption coefficient of a room is greater than 0.2 the reverberation time is sufficiently small that the room can be considered dead, while if it is less than 0.2 the room is considered live (Ref. 32).

For simple room shapes, the sound absorption coefficients for the wall surfaces can be used to calculate reverberation time (Ref. 32). In most situations, the geometry is so irregular that such computations are nearly impossible. If the proper instrumentation is available, the reverberation time of a room can be measured (Ref. 34).

6.6.8 NOISE MEASUREMENT

This section is intended as a review of the factors that must be considered in order to obtain correct noise measurements. Extensive information on this topic is available in standard sources (Ref. 38) and is usually also found in the instruction manuals provided by the equipment manufacturer.

6.6.8.1 INSTRUMENTATION

The basic equipment required for sound level measurements includes a microphone, an analyzer to allow measuring a small portion of the frequency spectrum, a meter to indicate the sound level, and a field calibrator. To determine if noise level criteria based on frequency has been met (Sections 6.6.5 and 6.6.6), an analyzer which allows measurement of octave bands is essential; if the cause or correction of the noise is a concern or if some deviation from the criteria is to be considered, one-third octave band analysis is preferred.

A set of good quality headphones is a very useful item of auxiliary equipment. When inserted in the output jack of the sound level meter or analyzer they enable the operator to listen to the portion of the sound spectrum being measured. In addition to aiding in checkout of the measuring system, they provide a means of judging directionality and identifying components of the sound.

Instrumentation used to make acoustic measurements must meet the appropriate standards (Ref. 16).

6.6.8.2 CALIBRATION

Calibration of the entire measurement system by feeding a known acoustic energy into the microphone is essential before making measurements. This process should be carried out according to the manufacturer's directions. The electrical-response calibration included in most instruments is not adequate since it does not include a test of the microphone.

Most field calibration sources are limited to a single frequency. Calibration over a range of frequencies should be performed at regular intervals and whenever there is any indication the measuring system is not performing properly.

6.6.8.3 TEST PROCEDURE

Only a few of the many requirements for obtaining good noise measurements are considered here. A thorough understanding of the instructional material provided by the manufacturer of the test instrumentation is obviously essential. Considerable material on measurement techniques is also available in the various handbooks on acoustics (Ref. 38).

Measurements should be made with the microphone in the approximate head location of each operator of the equipment under test, and of each operator who would normally be stationed nearby. The noise produced in each operating mode of the equipment should be measured separately.

Measurement on equipment should indicate the sound generated by the device under test without contamination by sound reflected from walls, other equipment or personnel. Reflected sound can be ignored if the noise level at the measurement point is 6-8 dB above the level at more distant points, indicating a contribution of less than 1 DB to the measurement (Ref. 35). Otherwise the reflectivity should be reduced. (See Section 6.6.7.) Test personnel should avoid standing near the microphone, since reflection and absorption by the body can change the measured sound pressure level at certain frequencies by more than 5 dB (Ref. 39).

If strong narrow frequency components are present, standing waves may occur. If they are present the sound pressure level will vary cyclically as the microphone is moved away from the noise source. The correct noise level may be taken as the arithmetic average of the maximum and minimum levels observed; if the difference is greater than 6 dB, the correct value may be considered as 3 dB below the maximum level.

6.6.8.3 TEST PROCEDURE (CONTINUED)

When measurements are being taken in the operational setting to determine the noise level to which an operator is being exposed, no corrective procedures for reflected and background noise should be used.

If octave band data are recorded manually, two quick checks are recommended to preclude gross errors, such as the common mistake of misreading the dB attenuator. The first is to add the band sound pressure levels and verify the total is within 3 dB of the overall sound level. The second is to plot the data on graph paper as it is collected.

The background noise in the test room should be measured and its contribution to the other measurements assessed. If the difference between background noise level and the value measured when the equipment under test is operating is less than 10 dB, the correction procedure described in Figure 6.6-3 should be used. If the difference is less than 3 dB, the measurements will not accurately reflect the noise from the equipment and, unless the noise criterion has obviously been met, a different test environment will be required.

6.6.8.4 SUPPORTING DATA

Adequate records are essential to interpretation of the data. A standard form should be prepared and used regularly (Ref. 40). The following types of information should be included:

- Date and location of the test
- Test personnel
- Test instrumentation, including model and serial numbers
- Calibration procedure and data
- Equipment under test, including model and serial numbers and operating modes for which noise was measured
- Test room configuration, size, and location of equipment, with special emphasis on microphone locations (photographs and sketches should be provided)
- Background noise data
- Observations of noise characteristics by test personnel
- Test data
- Corrected test data

SECTION 6.6 REFERENCES

1. Beranek, L. L. (Ed.) *Noise Reduction.* McGraw-Hill, New York, 1960.

   Beranek, L. L. *Acoustic Measurements.* Wiley, New York, 1949.

   Kinsler, L. E. and Frey, A. R. *Fundamentals of Acoustics.* Wiley, New York, 1962.

   Kryter, K. D. *The Effects of Noise on Man.* Academic Press, New York, 1970. This book provides the most extensive coverage available of pre-1970 research on annoyance and hearing damage due to noise. A total of 914 references and 376 very detailed illustrations are included. Coverage of the impact of noise on voice communication is very limited. Many acoustics experts disagree with some of Dr. Kryter's conclusions concerning the impact of occupational noise on hearing loss. See Ref. 12.

   Wood, A. B. *A Textbook of Sound.* Bell & Sons, London, 1960.

   Also, see Ref. 6 and 39.

2. *Sound and Vibration; Noise Control; Journal of the Acoustical Society of America; Noise News.*

3. See, for example, Ref. 23.

4. Huntly, R. A bel is ten decibels. *Sound and Vibration.* Vol. 4, January 1970, p. 22. According to this article, decibel was the name given to a unit (known as "transmission unit" or "mile of standard cable") that was used in America to describe transmission loss in cables. The comparable European unit was approximately 10 times as large, so a unit equal to 10 decibels, the bel, was also introduced.

5. At one time a reference power (PW_{ref}) of 10^{-13} watts was used in the USA.

6. Peterson, A. P. G. and Gross, E. E. *Handbook of Noise Measurement.* General Radio Co., West Concord, Mass., 1967. See Section 2.3 of this reference.

7. The complete relationship between sound power (PW), sound pressure (SP), and an intermediate parameter, sound intensity (I), is $PW = IA = SP^2\ A/\theta c$, where A is area, θ is the density of the medium and c is the velocity of the sound. The usual reference level for I is 10^{-12} watts/m^2. See, for example, Mitchell, W. S. Vibration and acoustic fundamentals. Chapter 1 in Blake, M. P., and Mitchell, W. S. (Ed.) *Vibration and Acoustic Measurement Handbook.* Spartan, New York, 1972.

   The term "intensity" is avoided in this document because, in addition to its precise meaning here, it is often used in an imprecise sense to refer to the strength of a sensation or signal.

8. Equivalent ways of expressing the most commonly used reference sound pressure, SP_{ref}, are 2×10^{-5} newton/square meter (N/m^2), 20 micronewton/square meter (μN/m^2), 0.0002 dyne/square centimeter (dyne/cm^2), and 0.0002 microbar (μbar).

   A reference sound pressure of 10^{-16} watt/cm^2 (10^{-12} watt/m^2) has also been used and is, for most practical purposes, equivalent to 2×10^{-5} N/m^2. See Section 6.10 of Ref. 6.

9. This chart is the same as one appearing in Appendix II of Ref. 6; it was originally developed by R. Musa.

10. These curves are defined in Ref. 16.

11. American National Standards Institute (ANSI). *Preferred Frequencies for Acoustical Measurements.* ANSI S1.6, 1967. (See also the definition of octave in the glossary.)

    ANSI has in the past been known as the American Standards Association (ASA), among other names.

12. Guignard, J. C. and Johnson, D. L. The relation of noise exposure to noise induced hearing damage. *Sound and Vibration.* January 1975, Vol. 9, pp. 18-23. This paper reviews the data utilized in arriving at the new OSHA noise exposure standard. It also touches briefly on the disagreement with the new standard by one acoustic expert, Dr. K. D. Kryter (see below).

    Moran, R. D. Practical problems in enforcing OSHA noise exposure regulations. *Sound and Vibration.* June 1974, Vol. 8, pp. 4, 6, 8, 10, 12, 14. This review article suggests that, in addition to being difficult to apply, the new OSHA noise exposure standard may be unnecessarily restrictive.

Kryter, K. D. Impairment to hearing from exposure to noise. *J. Acoust. Soc. Am.* Vol. 53, No. 5, 1973, pp. 1211-1234. This paper is followed by comments by several other individuals (pp. 1235-1243), and by a reply to these comments by Kryter (pp. 1244-1252).

Also, see Ref. 15 and the letters in *Sound and Vibration*. Vol. 8, March 1974, pp. 16, 18, 20.

Because the energy in a pure tone is concentrated at one point in the cochlea, or organ of hearing, the possibility exists that it is more damaging than indicated by a dBA reading. There is no known research on this specific topic.

13. Rupp, R. R., Banachowski, S. B., and Kiselewich, A. S. Hard-rock music and hearing damage risk. *Sound and Vibration.* Vol. 8, January 1974, pp. 24-26.

14. Occupational Safety and Health Administration (OSHA), U.S. Department of Labor. Occupational noise exposure--Proposed requirements and procedures. *Federal Register.* Vol. 39, No. 207, October 24, 1974, pp. 37,773 - 37,778. This regulation results from the Occupational Safety and Health Act of 1970.

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30. These curves were originally given in Ref. 22, using the old ANSI Standard Frequencies. They were redrawn by Kryter, Ref. 23, page 335, to include the new Preferred Frequencies.

31. Auditory thresholds have been measured by many different experimenters. The band shown here includes summary data from Figure 186 of Ref. 23, and from Figure 5 of Licklider, J. C. R., Basic correlates of the auditory stimulus. Chapter 25 in Stevens, S. S. S. *Handbook of Experimental Psychology.* Wiley, New York, 1951.

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6.7 COMPUTER INTERFACE

6.7.1 Organization

6.7.2 Keyboards

6.7.3 Light Pens

6.7.4 Voice Input

6.7.5 System Response Time

SECTION 6.7 COMPUTER INTERFACE

The interface between humans and computers has many different aspects. This section treats one, the input of information or commands by the human to the computer. A second, the display of information by the computer to the human, is treated in Section 6.4. Both of these topics, plus more general ones such as the philosophy of human/computer system design, are treated extensively in other sources (Ref. 1).

When a real-time display such as a cathode ray tube (CRT) is in use, it is often necessary for the operator to designate a particular location on the display screen. This is usually done with a cursor, which consists of some symbol such as a bar under the location on the display where a change will occur if commanded by the operator. Many devices have been used to control the position of the cursor, including an array of four pushbuttons, a track ball, a finger-operated joystick, a knee-operated joystick, a small movable device with two rollers underneath–one for the X-axis and one for the Y-axis signal–called a mouse, and even one that partially eliminates the need for the cursor–the light pen. Esoteric devices such as the eyeball tracker (Ref. 2) can also be used for this purpose, but their complexity and cost make them appropriate only for very special situations.

- The set of four pushbuttons, one for each direction of cursor movement, is simple, and it blends in well with the other pushbuttons when it is used on a keyboard. Because it can command only one cursor velocity, it is necessarily slower than many other controls.

- The finger-operated joystick is fast and accurate if well designed (Ref. 3,B), it takes little space, and it is commercially available. If poorly designed, however, it will not perform well (Ref. 4). (Also see Sections 6.2.1 and 3.10.4.)

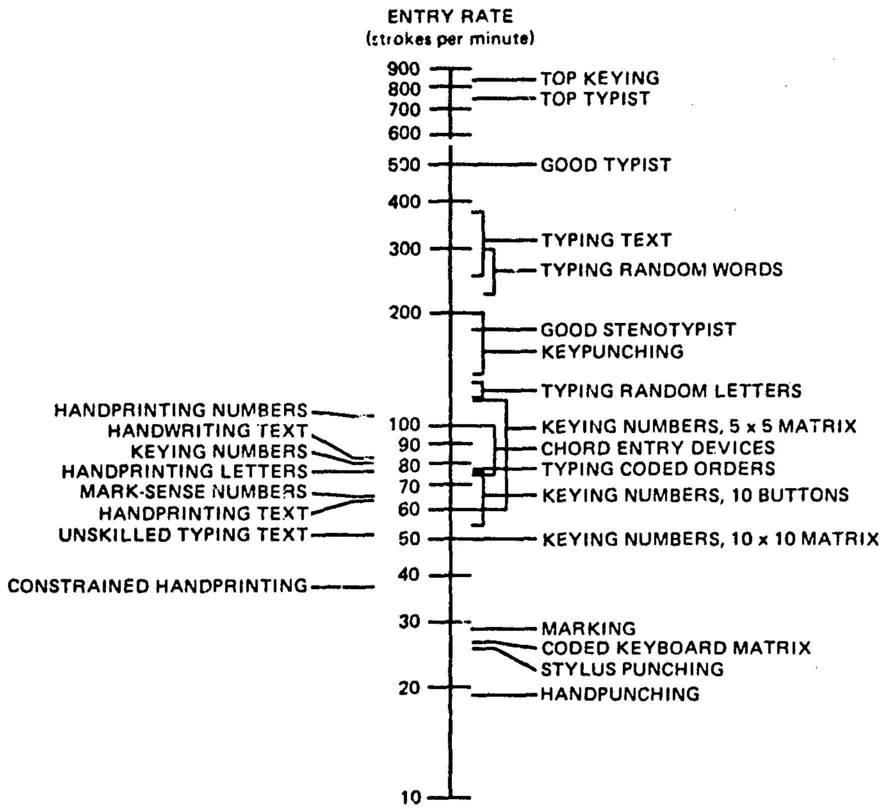
- The mouse is very fast, accurate, and easy to learn to use (Ref. 4,B). On the negative side, it requires a relatively large unobstructed space for operation.

- The knee control is fast and reasonably accurate (Ref. 4,B). It frees both hands for use on the keyboard, but it places a restriction on leg position that may be fatiguing over time.

- The light pen is fast and accurate (Ref. 4,B). It also presents certain problems, which are covered in some detail in Section 6.7.3.

- The graphics tablet produces a signal on the CRT wherever it is touched with a stylus. It offers many of the advantages of the light pen. In addition, because it can be placed in any convenient location, it does not require the user to hold his arm in an uncomfortable position nor does the stylus obscure the display.

The most popular means of inputting information or commands to a computer is the keyboard. It is discussed in Section 6.7.2 below. Devices that recognize hand-printed alphanumeric characters directly have been developed (Ref. 5) also, but these are technically complex and usually place restrictions on the operator. As Figure 6.7-1 below illustrates, constrained handprinting is slower than even unskilled typewriting, so for most applications this input technique offers no advantage over an ordinary keyboard.



NOTES: Keying generally refers to the operation of card punch devices.

Chord entry involves the simultaneous depression of several keys (as on a musical instrument).

Mark-sense is a hand-marked version of the computer punch card.

Figure 6.7-1. Representative Manual Entry Rates (Ref. 6,X). This figure summarizes data entry rates for different devices, work situations, and operator skill levels obtained in approximately 11 different studies. Although the minimum average stroke interval for a skilled typist illustrated here is about 60/830, or 0.07 second, between stroke times of 0.05 or even 0.02 second will occur, particularly when typing common words like "the" (Ref. 7).

SECTION 6.7 COMPUTER INTERFACE

6.7.1 ORGANIZATION

For most computer interface tasks, such as information retrieval or the entering of the description of a target into a data bank, there are many different kinds of hardware that can be used satisfactorily. Much more important will be the extent to which the operator's task is integrated into the hardware and computer software.

When the task sequence is structured, there are several ways of reducing the demand on the operator. If there are only a few options, the input controls can be designed to reflect this sequence. That is, the operator might work from left to right across a matrix of pushbuttons, selecting one from each column. With slightly more sophisticated hardware, the pushbutton options available to the operator at a particular step in the sequence can be illuminated. If there are more input options than there is space for pushbuttons, legend pushbuttons capable of displaying 10 to 12 different labels are available so that each pushbutton can be used to control several different functions. If the task is structured but there are many different options, or if the structure is likely to change, the computer software can be used to indicate to the operator on a CRT the control options available or the input information required at each step.

6.7.2 KEYBOARDS

This section considers keyboard features of particular importance in the preparation of reports and in the control of computers and computer-driven displays. The term "keyboard" is generally limited to an array of pushbutton-type controls, or keys, but many of the comments made here also apply to comparable arrays of other controls such as toggle switches. Specific details of keyboard design, such as key resistance and key spacing, are covered in Section 6.2.2.

The keys on a keyboard can be divided into two categories. Keys representing each category are often included on a single keyboard.

- Function keys control a single action or function. Typical function keys are those controlling erase and cursor movement. A special-purpose function key might record the information that a specific class of target was present in the imagery.

- Free response keys control individual symbols, primarily alphanumeric characters, that represent information or which can be combined to command a particular function.

Function keys provide more rapid control of particular functions, but they limit the number of controlled functions to the number of keys available. Free response keys impose no such limit on the number of functions, but they provide much slower access to each function.

If functions are used only in certain sets, the number of functions can be increased by providing a master control that assigns one of the possible sets to a single set of keys. Some method of changing the key labels so that the operator will remain aware of the functions in use must be provided. For tasks that follow a fixed or programmable sequence of sets of functions, automatic reassignment of functions to keys, with appropriate automatic changes in labeling, can result in a considerable simplification of a complex task.

The most common keyboard layout is the so-called QWERTY arrangement used on typewriters and illustrated in Figure 6.2-27. Although it is generally recognized that other key arrangements such as that developed by Dvorak are more efficient, the differences in performance that have been measured are not considered sufficient to compensate for the disruption that would result from a change to a new configuration (Ref. 8).

6.7.3 LIGHT PENS

A light pen is a device, often pencil shaped, that is held against the face of a CRT to indicate the location of a desired display change. For many applications, the light pen is much more convenient and faster than an alternative such as a joystick-controlled cursor (Ref. 9). The potential difficulties to be considered when evaluating a light pen are listed below. Other summaries of this topic are available (Ref. 10).

- Most CRT's are located so that the light pen user must keep his arm extended and nearly horizontal. Without some type of support, which would probably interfere with pen positioning, this arm position is quickly fatiguing.
- The cable connecting the light pen to the display can interfere with positioning the pen; it tends to obscure parts of the display, and if heavy, it can increase arm fatigue.
- The positioning accuracy of the pen may be inadequate, particularly with the large parallax introduced by a thick CRT faceplate. This problem can be reduced by providing an indication of the display change about to be made, with the change becoming permanent only after a confirming control input by the user.

6.7.4 VOICE INPUT

There are two ways the display operator can use his voice as a means of inputting information or commands. The first, which is largely limited to information such as the report of a target seen in the display, is to record the report on tape for later transcription into typed or keypunched form. The transcription can be made either by the display user or by a clerk. The transcription time is about the same with either approach (Ref. 11), but the use of a clerk frees the display operator to spend more time looking at imagery. Whether a significant amount of time could be saved depends on the individual work situation. One problem, no matter who does the transcription, is that some operators will probably find it difficult to compose a report orally, rather than in written form.

A second way to use voice input is with an electronic device that recognizes words directly. The technology in this area is improving, with claims in trade journals (Ref. 12) of devices with vocabularies of 150 or even 1,000 words, and a requirement for each operator to repeat each word only about ten times before the device can recognize it consistently. This kind of device can make a large contribution in a situation where an operator must keep both hands free, or where he is already overburdened with too many controls. Because such situations do not usually occur with imagery displays, and because of the very high cost of such devices, there are no obvious imagery display applications at present. Increased operator fatigue, at least with older voice recognition devices, is also a potential problem (Ref. 13).

Computer queries to the operator to indicate what information is required next, much as is described in Section 6.7.1, would probably make oral reporting easier, more efficient and more error free. The hardware and software required are not insignificant.

Voice displays are discussed very briefly in Section 6.4.4. It is intriguing to consider applications of voice displays that allow the display user to listen to the report generated from previous coverage of a target while he views it on new coverages. Although this might have some applications in tasks such as the detection of changes in target status, implementation of a workable system is a formidable task. One of the disadvantages associated with a voice display—the fact that speech is much slower than reading—can be partially overcome by the recent development of electronic devices that allow tape-recorded speech to be played at up to three times normal speed (Ref. 14). Other disadvantages remain, such as the greater difficulty in accessing a specific portion of a report and in scanning an entire report at very high speed to find a particular part of interest.

6.7.5 SYSTEM RESPONSE TIME

RECOMMENDATIONS:

Keep display user waiting times as short as possible. The suggested limit for a new page to appear is 5 seconds, and for a page to scroll, or move vertically by a single line, the suggested limit is 1 second.

If longer delays are necessary, inform the user of the anticipated duration of the delay, and why it is occurring.

Inform the user of a control input error immediately.

User tolerance to the time lag between an input command and the display response depends on many factors. Delays of more than a few seconds, if they occur frequently, may seriously reduce work time and disrupt the operator's thought process. The acceptability of such waiting periods is likely to depend heavily on the user's intellectual and emotional commitment to the display system. That is, the user will be more tolerant of system delays that he regards as essential or helpful than of those he considers a waste of money or as interfering with getting a job completed.

The acceptability of waiting periods of more than a few seconds can be increased by providing the user with an indication of how much waiting time remains, and of why the delay is occurring. Also, it is very important to inform the operator of errors rapidly. Waiting many seconds for a machine response, only to learn that the command was in error, will only add to the frustration due to the error.

Based on experience in developing alphanumeric CRT displays, but not on any test data, the following general guidelines have been suggested. No relevant controlled experimentation on any of these topics is known.

- Small changes, such as the insertion or deletion of a character or the movement of a cursor, should occur almost instantly after the input command (Ref. 15).
- Waiting times for a new page of a display should not exceed a few seconds, and the time required for a display page to scroll, or move up or down by a single line, should not exceed 1 second (Ref. 15).

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6.8 SAFETY

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SECTION 6.8 SAFETY

It is essential that exposure of personnel to dangerous situations be kept to an absolute minimum. Design recommendations for the principal hazards that might be faced by display operating and maintenance personnel are discussed in this section.

6.8.1 NONIONIZING RADIATION

CAUTION:

Because of new test data and experiments still in progress, safety limits for nonionizing radiation are in a state of flux. Lower limits are likely, particularly in the 300 nm to 500-nm region.

RECOMMENDATION:

In spectral regions where the effect of radiant energy is to heat the surface of the body, which generally means wavelengths from 315 nm to about 10^6 nm, limit exposure of more than a few tens of square centimeters of body surface to a radiant energy level of less than 0.025 W/cm^2 (Ref. 1). (This limit is in addition to those in Sections 6.8.1.1 through 6.8.1.4.)

The display user can see the displayed image best if it has a high luminance (Section 3.2.6). However, this high luminance must not result in sufficient radiant energy reaching the user's eye or skin that there is any chance of injury. Because the effect of nonionizing radiant energy is so dependent on wavelength, different safety limits are necessary in different parts of the electromagnetic spectrum. These are presented in Sections 6.8.1.1 through 6.8.1.5 below.

Radiant energy that reaches body tissue is either reflected, transmitted, or absorbed. Energy that is absorbed can affect body tissue in two ways:

- If the radiant energy has the proper wavelength, it can have a direct biological, or biochemical, effect. The best known examples are certain wavelengths in the ultraviolet region, which cause tanning, or, if the exposure is excessive, sunburn, and wavelengths in the 400- to 700-nm region which, if they reach the retina in sufficient quantity, yield the sensation of *light*. (Radiant energy that has a direct biochemical effect is known as *actinic*. This term is generally used for ultraviolet but not for visible radiant energy.)

- All absorbed radiant energy not stored in chemical form as a result of a direct biological reaction remains as heat, which, unless it is radiated or conducted away from the body tissue, causes a temperature rise. If the temperature rise is excessive, injury to the tissue results. Smaller temperature rises, in body areas such as the skin, will cause discomfort and sweating or, in some cases, a drying of the skin. The Illuminating Engineering Society (IES) handbook (Ref. 1) suggests a radiant energy limit of 0.025 W/cm^2.

Figure 6.8-1 shows the generally accepted mode, and location, of the action of radiant energy at different wavelengths. Very recent data suggest that there is also direct biological damage to the retina in the blue, or short-wavelength region of the visible spectrum (Ref. 2). This is discussed further in Section 6.8.1.3).

The radiant energy exposure limits given in this section are the most realistic possible given the present state of knowledge. It is likely that within a few years more realistic limits will be possible in some spectral regions and in many cases these will be lower and more restrictive. Among the reasons for these changes are the following:

- Techniques for assessing biological damage are becoming more sensitive.

- Additional data on corneal injury due to radiant energy with wavelengths of 300 nm and longer are being collected, in order to derive a more correct *action spectrum* in this region (Figure 6.8-3) (Ref. 3). It is anticipated that these tests will include more trials involving lengthy exposure to low energy levels, reducing the current need to derive criteria for such situations from data on brief, intense exposures.

6.8.1 NONIONIZING RADIATION (CONTINUED)

- The recent reporting of a direct biological, rather than thermal, effect of radiant energy in the short wavelength, or blue, region of the visible spectrum is likely to result in lower limits in this spectral region (Ref. 2).

- There is a suspicion that for wavelength regions in which the damage mechanism is biochemical rather than thermal, exposure to radiant energy at one wavelength may lower the damage threshold at other wavelengths.

Many different sets of units are in use. When a direct biological damage mechanism is involved, or when the duration of exposure is so brief that the rate at which heat is conducted away from the tissue where the radiation is being absorbed is irrelevant, then it is most appropriate to speak in terms of the total energy in units such as joules (J) or watt seconds (W sec). When the damage mechanism is primarily thermal, and the exposure is long enough that conduction of heat away from the tissue is important, it is more appropriate to use units that indicate power, or the rate at which radiant energy is being absorbed. These are watts (W) or joules per second (J/sec). These are discussed further in Figure 6.8-2 and in Section 6.8.1-3. Energy is generally expressed as energy per unit area, or energy density.

Accurate measurement of radiant energy levels in some of the spectral regions discussed in this section is very difficult. This is particularly true in the spectral region below 400 nm, where the permissible amount of radiant energy is many times lower than the amount of radiant energy in the 400- to 700-nm region required to provide adequate image luminance (Ref. 4). The American National Standards Institute (ANSI) standard for laser safety suggests that measurements should be accurate within ±20 percent, at least whenever the available technology permits this level of accuracy (Ref. 5).

Several extensive summaries of the effects of nonionizing radiation are available (Ref. 6).

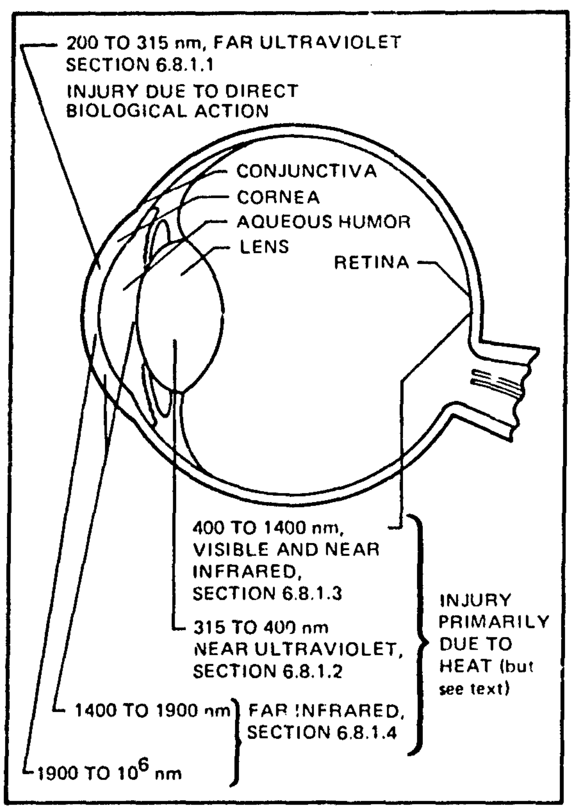


Figure 6.8-1. Impact of Radiant Energy on the Eye. The portions of the eye most affected by radiant energy in the various parts of the electromagnetic spectrum are illustrated here, along with the section numbers where each is treated in detail (Ref. 6). Not included in this illustration is microwave radiation (Section 6.8.1.5), which is generally absorbed by all body tissue.

6.8.1 NONIONIZING RADIATION (CONTINUED)

ENERGY

DEFINITION: ENERGY IS THE CAPACITY TO DO WORK

UNITS: 1 JOULE (J) = 1 NEWTON METER = 10^7 ERGS
= 10^7 DYNE CENTIMETERS
= 0.24 (GRAM) CALORIES

POWER

DEFINITION: POWER IS THE RATE AT WHICH WORK IS DONE; IT IS ALSO THE TIME RATE OF FLOW OF ENERGY

UNITS: WATTS (W)

LUMINOUS POWER

DEFINITION: RADIANT POWER, WEIGHTED ACCORDING TO LUMINOSITY CURVE OF EYE (*Figure 3.2-2 and 5.2-7*)

UNITS: LUMENS (lm)

CONVERSIONS

1 JOULE = 1 WATT SECOND
1 JOULE/SECOND = 1 WATT
1 WATT (at 555 nm) = 680 LUMENS

NOTE: THE PREFIX m MEANS 10^{-3}; HENCE 1mW = 0.001W.

Figure 6.8-2. Units Used in Specifying Radiant Energy Limits. Depending on the duration of the exposure, it may be most useful to give limits on radiant energy in terms of energy units, such as joules (J), or in terms of the rate of flow of radiant energy (power) units, such as watts (W). The relationship between these units is summarized here.

When radiant energy in the visible region of the spectrum, nominally 400 to 700 nm, is involved, it is helpful also to use units that indicate the visual effectiveness of the radiant energy. The standard unit, the lumen, is related to radiant power as is shown here. Wavelengths other than 555 nm receive a smaller weight, as is defined by the *luminosity curve* for the eye in Figures 3.2-2 and 5.2-7. For example, 1 watt at 650 nm yields only 73 lumens. For some purposes, it is also useful to know that 1 lumen per square meter steradian (1 lm/m^2 sr) equals 1 cd/m^2 (0.3 fL).

The relationship between lumens and watts varies as a function of lamp type, and of course as a result of any filters in use. For example, a typical 500-watt incandescent lamp yields approximately 50 lumens for each watt of radiant energy, with the latter measured over the wavelength range of 400 to 1400 nm (Ref. 7). The comparable value for a cool white fluorescent lamp is 300 lumens.

6.8.1.1 ULTRAVIOLET RADIANT ENERGY (200 to 315 nm)

RECOMMENDATION:

Limit daily radiant energy exposure to an effective value of 0.003 J/cm^2, measured as described in Figure 6.8.4. (For exposure of large skin areas, also see the recommendation at the beginning of Section 6.8.1.)

Most radiant energy absorbed by the body is converted to heat. Radiant energy in the *actinic*, or active, ultraviolet region of the spectrum, with a wavelength of approximately 200 to 315 nm, has an additional direct biological effect on the skin and eyes. The skin responds by an increase in pigmentation (tanning), or if the exposure is excessive, with *erythema* or reddening, as in sunburn.

In the eye, energy in this spectral region is absorbed by the *cornea* and *conjunctiva* (Figure 3.1-1). If the exposure is excessive, a very painful condition known as *photokeratitis*, or *keratoconjunctivitis* results. The symptoms, which typically appear about a half day after exposure, include the sensation that a foreign body, like sand, is in the eye, an aversion to bright lights, tears, and spasms of the eyelid (Ref. 8). The symptoms usually last 6 to 24 hours (Ref. 8) and except in extreme cases, are not permanent (Ref. 9). The most frequent causes of photokeratitis are excessive exposure to a welding arc or sun lamp.

The ultraviolet radiant energy from the sun is also sufficient to cause photokeratitis, at least around noon in certain areas such as the tropics (Ref. 10). For several reasons, including the shielding of the eyes from most direct rays of the sun by the face and because most rays that do strike the eye arrive at an oblique angle and glance off, photokeratitis from the sun is very rare. The principal exception is when the ultraviolet rays are reflected into the eyes by snow, which is the only commonly occurring natural material that reflects in this spectral region (Ref. 10).

Although most of the radiant energy from the light sources used in imagery displays is at wavelengths longer than 315 nm, even a typical low wattage incandescent lamp filament can produce a biologically significant amount of radiant energy below 315 nm (Ref. 11). Typical optical materials, such as most kinds of glass (Ref. 12) and plastic, have very low transmission in the region below 315 nm and this usually serves to eliminate any hazard. However, because the amount of ultraviolet energy required for injury is so low and because an injury is potentially so serious, all new displays should be checked.

Because the radiant energy in the visible region of the spectrum is so much greater in an imagery display than is the permissible ultraviolet radiant energy, measurements to establish whether ultraviolet limits are being exceeded are difficult to obtain. Unless the spectral cutoff of the spectroradiometer is extremely sharp, a major portion of the reading obtained may be due to radiant energy with a wavelength longer than 315 nm. If an adequate instrument is not available, it may still be possible to demonstrate that a particular display does not exceed permissible ultraviolet limits. This can be done by using a filter with known, extremely low, transmission in the hazardous ultraviolet region and high transmission in the longer wavelength region to obtain an estimate of the minimum contribution of the longer wavelengths to the reading (Ref. 10). Many types of readily available glass should be suitable.

NOTE:
In most imagery displays, the presence between the illumination source and the eye of a sheet of glass with near zero transmittance in the spectral region close to and below 315 nm should eliminate the risk of corneal injury. The data in this section, plus a spectral output curve for the illumination source in use, should allow calculation of how close to zero the transmittance must be.

6.8.1.1 ULTRAVIOLET RADIANT ENERGY (200 to 315 nm) (Continued)

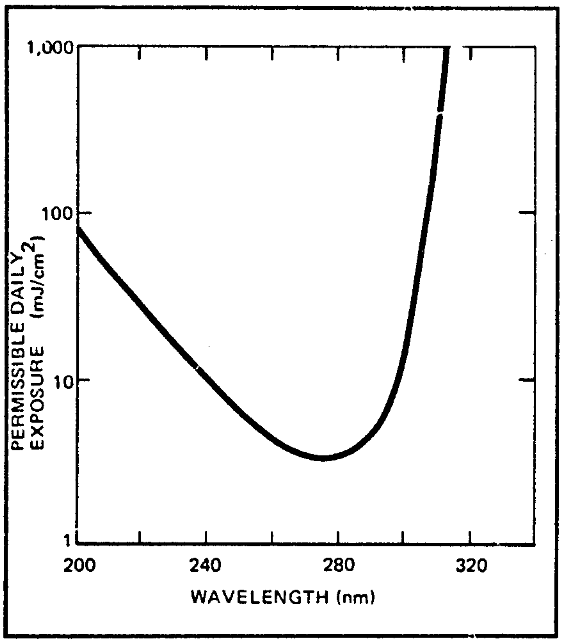


Figure 6.8-3. Ultraviolet Action Spectrum. The best available *action spectrum*, or relative spectral effectiveness of radiant energy in causing undesirable effects in the cornea, is illustrated here (Ref. 13). This curve was fit by Sliney to several sets of test data (Ref. 10) and is used in the recommendations of two major safety organizations (Ref. 14). The current laser exposure limit uses a similar maximum energy value, 3 mJ/cm^2, but differs in that it gives equal weight to the entire spectral region from 200 to 302 nm (Ref. 15).

Data collected by Pitts *et al.* (Ref. 8), and which were used by Sliney in developing this curve, suggest that radiant energy with a wavelength longer than 290 nm has more effect than is indicated here (Ref. 16). Although the differences between this curve and Pitt's curve are small, the impact on the effective irradiance value will be large if the amount of radiant energy is decreasing rapidly in the 290- to 315-nm region. This is the situation for sunlight and for certain combinations of artificial illumination and glass (Ref. 17).

It is understood that experiments are in progress to refine this curve, particularly in the region above 300 nm (Ref. 3).

6.8.1.1 ULTRAVIOLET RADIANT ENERGY (200 to 315 nm) (Continued)

$E_{eff} = \Sigma\ E_\lambda\ S_\lambda\ \Delta_\lambda$, WHERE:

E_{eff} = EFFECTIVE IRRADIANCE IN THE 200-nm TO 315-nm SPECTRAL REGION, IN mW/cm^2

E_λ = MEASURED SPECTRAL IRRADIANCE IN mW/cm^2 nm

S_λ = RELATIVE SPECTRAL EFFECTIVENESS (dimensionless) (see below)

Δ_λ = BANDWIDTH IN NANOMETERS (nm)

WAVELENGTH (nm)	RELATIVE SPECTRAL EFFECTIVENESS (S_λ)	DAILY EXPOSURE LIMIT (mJ/cm^2)
200	0.03	100
210	0.075	40
220	0.12	25
230	0.19	16
240	0.30	10
250	0.43	7.0
254	0.5	6.0
260	0.65	4.6
270	1.0	3.0
280	0.88	3.4
290	0.64	4.7
300	0.30	10
305	0.06	50
310	0.015	200
315	0.003	1000

EFFECTIVE IRRADIANCE, E_{eff} (mW/cm^2)	MAXIMUM EXPOSURE PER DAY*
0.0001	8 HR
0.0002	4 HR
0.0004	2 HR
0.0008	1 HR
0.0017	30 MIN
0.0033	15 MIN
0.005	10 MIN
0.01	5 MIN
0.05	1 MIN
0.1	30 SEC
0.3	10 SEC
3.0	1 SEC
6.0	0.5 SEC
30.0	0.1 SEC

*THESE VALUES ASSUME THAT NO OTHER OCCUPATIONAL EXPOSURE OCCURS

Figure 6.8-4. Exposure Limit for Actinic (200- to 315-nm) Ultraviolet Radiant Energy. The best available limit for occupational exposure of the eye or skin to radiant energy in the spectral region of 200 to 315 nm is illustrated here. This limit is based on the action spectra in Figure 6.8-3 and has been recommended by the American Conference of Government and Industrial Hygienists (ACGIH) (Ref. 18) and by the National Institute for Occupational Safety and Health (NIOSH) (Ref. 19).

The maximum daily exposure permitted is an effective irradiance of 3 millijoules (3 milliwatt seconds) per square centimeter (mJ/cm^2). The equations and tables shown can be used to convert irradiance measured in each part of the spectrum to total effective irradiance. Alternatively, if sensors with a spectral sensitivity like Figure 6.8-3 become available, only a single measurement will be required.

For corneal exposure, the irradiance must be measured over an area no larger than about 1 mm (Ref. 15).

There is some uncertainty whether the 3-mJ/cm^2 effective irradiance limit should be reduced in situations where exposure is repeated on many consecutive days. The implication drawn from documents containing this limit is that it need not be reduced. Recent reviews are contradictory in that they indicate either that no reduction is required (Ref. 20) or that the available data are inadequate to draw any conclusion (Ref. 10). In neither review was any test data cited. In the only known study in which the effect of repeated exposures was tested (Ref. 21), it was concluded that—

- Exposures of one-third threshold, given daily, resulted in perceptible injury after six exposures.
- Exposures of one-sixth threshold, given daily over a long period, produced no effect except perhaps a slight immunity against greater exposures.

The threshold data from this particular study are not directly comparable to the 3-mJ/cm^2 figure because a broadband source was used. The best available modern data suggest that the single-exposure threshold is an effective irradiance of 4 mJ/cm^2. If the repeated-exposure data are correct, this value would imply that a 3-mJ/cm^2 limit is too high for some work situations.

6.8.1.2 NEAR ULTRAVIOLET RADIANT ENERGY (315 to 400 nm)

RECOMMENDATION:

Limit eye and skin radiant energy exposure in the 315- to 400-nm region to 0.001 W/cm^2 for exposure durations longer than 1,000 seconds and for shorter durations, to no more than 1 J/cm^2 within a 1,000-second period, measured with a maximum aperture of 1 mm. (For exposure of large skin areas, also see the recommendation at the beginning of Section 6.8.1.)

Radiant energy in the 315- to 400-nm region is absorbed primarily in the lens of the eye, and to a lesser extent in the cornea and aqueous humor (Figure 3.1-1) (Ref. 22). There is some suggestion that excessive exposure in this spectral region can cause cataracts to form in the lens. For example, in one test 16-minute exposure to a 1.5-mm-diameter, 325-nm laser beam with a corneal irradiance of 0.85 W/cm^2 (a total power of 0.01 W) resulted in a cataract in the eye of a rabbit (Ref. 23). However, considerably more data is necessary in order to set reliable design limits.

The best available limits, for the eye or the skin, are 0.001 W/cm^2 for exposures longer than 1,000 seconds. For shorter exposures, the limit is 1 J/cm^2 (1 W sec/cm^2) in any 1,000-second period (Ref. 24). The appropriate measurement area is 1 mm or less in diameter.

As is discussed in Section 3.2.7.2, radiant energy in the 315- to 400-nm region should also be minimized because it causes the eye to fluoresce and the resulting veiling luminance reduces image contrast.

6.8.1.3 VISIBLE AND NEAR-INFRARED RADIANT ENERGY (400 to 1400 nm)

RECOMMENDATIONS:

Limit eye exposure to surfaces larger than about 1 degree to the effective radiance values in Figure 6.8-6.

For any source that might come within a factor of about 1,000 of reaching the limits of Figure 6.8-6, reduce the proportion of radiant energy at wavelengths shorter than 560 nm. (For achromatic displays, this will be easy, but when color must be displayed, the requirements of Sections 3.2.7 and 5.2 must also be considered.)

Preferably, prevent eye exposure to intense point sources. If this is not possible, consult Reference 25 for the appropriate limits.

Limit long duration skin exposure to 0.2 W/cm^2, measured with a maximum aperture of 1 mm (Ref. 26). (For exposure of large skin areas, also see the recommendation at the beginning of Section 6.8.1).

This section covers the prevention of eye damage as a result of radiant energy with a wavelength of 400 to 1400 nm from a source that subtends a visual angle greater than about 1 degree. It does not treat the potential hazard from the following two kinds of point sources in this same spectral region because it is assumed that display operation and maintenance personnel will not be exposed to such sources. If a potential for such exposure exists, the referenced documents should be consulted.

- Viewing of a laser beam. This is potentially very dangerous. A standard is available (Ref. 5).
- Viewing of point sources such as high-wattage lamp arcs and filaments. These are also potentially dangerous, and shields and electrical *interlocks* should be used to prevent their being viewed. The laser safety standard (Ref. 5) is a useful guide to appropriate limits, but application of these limits may require use of computational techniques described in other sources (Ref. 25).

Visible and near-infrared radiant energy, with a wavelength of 400 to approximately 1400 nm, is largely transmitted by the ocular media of the eye and absorbed at the retina (Figure 6.8-5). Unlike corneal injury from ultraviolet, injury to the retina is generally permanent (Ref. 27). As a result, special care must be taken to avoid retinal damage.

Retinal damage due to an excessive amount of radiant energy has generally been assumed to be due to a thermal mechanism. However, recent evidence indicates that damage also occurs through direct biochemical action, at least in the short-wavelength (blue) end of the visual spectrum (Ref. 2). For a 1,000-second exposure on a monkey retina, if the absorbed energy required to cause damage at 550 nm is assigned a value of 1, the relative amount of absorbed energy required at 400 nm was only 0.005, while at 700 nm it had increased to a value of 7 (these values, in addition to being relative, are only approximate).

Two factors that have an impact on whether a particular retinal energy density will cause damage are retinal image size and exposure time. Heat is more easily conducted away from a small area, which reduces the temperature rise and hence the damage. This effect is relatively unimportant for image sizes greater than a few degrees (Ref. 28).

Brief exposures cause less retinal temperature rise and hence less damage than long exposures. Exposure to extremely intense sources, such as the sun or an incandescent lamp filament, are usually brief and are usually limited to the duration of the blink reflex, or about 0.2 second (Ref. 28). However, individuals can overcome this reflex and stare at such sources. In the case of an eclipse of the sun, the result can be serious.

6.8.1.3 VISIBLE AND NEAR-INFRARED RADIANT ENERGY (400 to 1400 nm) (Continued)

The best available exposure limits for imagery displays are described in Figure 6.8-6. These limits were developed for laser sources. Because localized retinal heating can result from the speckle pattern produced by the coherent radiant energy from a laser, limits based on laser energy such as these may be conservative for display applications, where the radiant energy is not coherent. Conversely, since these limits do not yet reflect the data collected in the last couple years, they may be too generous.

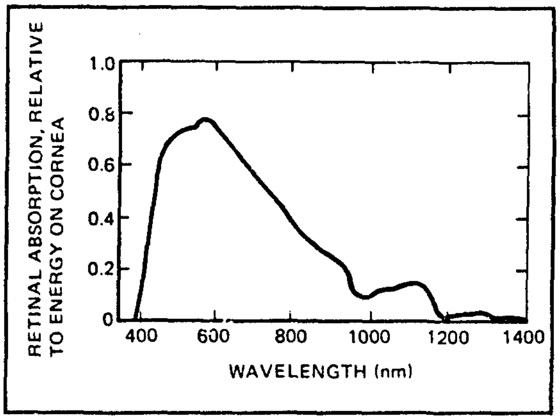


Figure 6.8-5. Retinal Absorption of Energy Incident on the Cornea. This figure illustrates the relative amount of radiant energy incident on the cornea that actually reaches the retina and is absorbed there (Ref. 29). For purposes of computing exposure limits, this curve is estimated by the more uniform curve shown in Figure 6.8-6.

The results of most experiments on retinal damage are reported in terms of radiant energy per unit area absorbed by the retina. Since the energy used in the experiment is actually measured at the cornea, the reported retinal value must be calculated by use of a curve such as the one shown here, plus of course, a measurement of pupil diameter.

EXPOSURE TIME, t (seconds)	MAXIMUM PERMISSIBLE RADIANCE	
	ENERGY (J/cm^2sr)	POWER (W/cm^2sr)
<10	$10\,t^{1/3}$ K	$10\,t^{-2/3}$ K
10 TO 10^4	20 K	20 K t^{-1}
>10^4	–	0.002 K

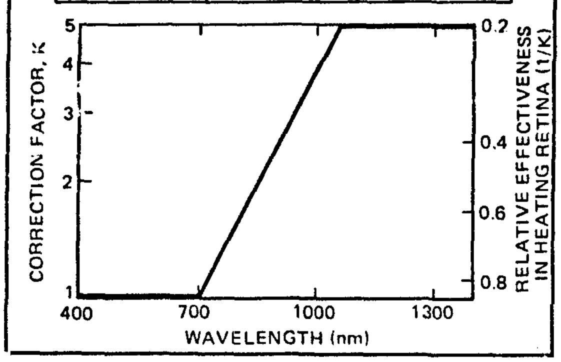
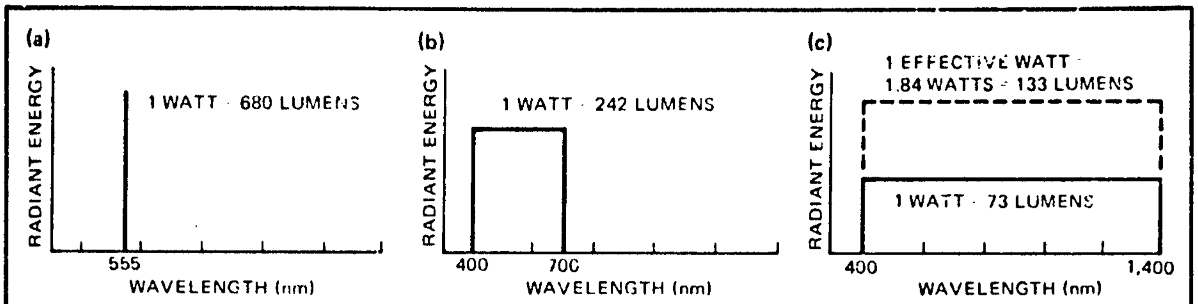


Figure 6.8-6. Maximum Safe Exposure to 400- to 1400-nm Radiant Energy. The best available limits for exposure of the eye to radiant energy with a wavelength of 400 to 1400 nm are the values from ANSI Standard Z136.1 illustrated here (Ref. 15). These apply to any source larger than about 1 degree; smaller sources are more properly described by different units (Ref. 30). No correction for pupil size, such as that described in Section 3.2.4, is used here.

Note that for wavelengths longer than 700 nm, a correction factor, K, is required to compensate for the increase in absorption in the ocular media and the decrease in absorption by the retina in this spectral region (Figure 6.8-5) (Ref. 15).

6.8.1.3 VISIBLE AND NEAR-INFRARED RADIANT ENERGY (400 to 1400 nm) (Continued)



WAVELENGTH RANGE (nm)	LUMENS PER WATT OF RADIANT ENERGY	LUMENS PER EFFECTIVE WATT OF RADIANT ENERGY	IMAGE LUMINANCE AT MAXIMUM PERMISSIBLE IMAGE RADIANCE cd/m^2 (fL)		
			1 SEC	100 SEC	10^4 SEC
(a) 555	680	680	68,000,000 (20,000,000)	1,400,000 (410,000)	14,000 (4,100)
(b) 400 TO 700	242	242	24,200,000 (7,000,000)	480,000 (140,000)	4,800 (1,400)
(c) 400 TO 1,400	73	133	13,300,000 (3,900,000)	270,000 (78,000)	2,700 (780)

Figure 6.8-7. Estimation of Permissible Image Luminance. The permissible exposure limits in Figure 6.8-6 are increased in inverse proportion to the effectiveness, or relative spectral retinal absorption, of the image radiance. When appropriate image spectral radiance data are not immediately available, it may be helpful to be able to estimate whether a particular image luminance exceeds permissible exposure limits. the relationship between luminance and radiance has been published for typical lamps (Ref. 7) but these values cannot be used directly because radiant energy with a wavelength greater than 700 nm is less effective in heating the retina.

If the spectral distribution of radiant energy in the displayed image is known, the luminosity function for the eye (Figure 3.2-2) can be used to calculate the ratio between luminance and effective radiance and hence, the permissible luminance. This process is illustrated here for three hypothetical equal-energy-per wavelength sources that differ in wavelength range. Since the monochromatic source (a) falls at the peak of the luminosity curve, 555 nm, it has by far the largest ratio of the three and, by the definition of luminance, the largest possible for any source. The next largest ratio is for the 400- to 700-nm source (b), followed by the source that includes the full 400 to 1400 range (c). Note that because radiant energy with a wavelength longer than 700 nm is less efficient in heating the retina, the total permissible energy for this latter source is increased by a factor of about 1.8 over that permitted for the other two sources. Source (c) also happens to be the equal energy source identified as E in Figure 5.2-13.

In the absence of test data it is not possible to say how close any specific display comes to either of the broad-band sources used here. However, filters to remove infrared are readily available, and these would likely be used with any very strong source in order to protect the film as well as the eye from unnecessary heat. Hence, any well designed high-luminance display should at least approach the 242 lumens per watt figure of the 400- to 700-nm source used here.

The two most important exposure durations are the brief glance when the operator accidentally looks into the display while the luminance is turned up and no film is in place, and his exposure for several hours during a normal workday. A typical blink response to an intense and unexpected light is about 0.2 second (Ref. 28), but even assuming that the operator briefly overcomes this response and looks for a full second, the calculations shown here suggest that he will still be safe with an image luminance of 24,200,000 cd/m^2 (7,000,000 fL) for a 400- to 700-nm equal-energy source. These calculations also show that an exposure for several hours to a source with the same spectral characteristics and a luminance of 4,800 cd/m^2 (1,400 fL), is safe.

Although the spectral distributions are not the same, it is instructive to compare these values with luminances for typical surfaces (Ref. 7):

- 40W fluorescent lamp: 7,000 cd/m^2 (2,000 fL)
- Bright clear sky: 3,000 cd/m^2 (1,000 fL)
- Candle flame: 10,000 cd/m^2 (3,000 fL)

Note that the lumen per watt values shown here involve radiant energy over a limited bandwidth, not input energy. Output lumens per watt of energy used by a typical electric lamp range from 10 to 100 (Ref. 31).

6.8.1.4 FAR-INFRARED RADIANT ENERGY (1400 to 10^6 nm)

RECOMMENDATION:

Limit chronic eye and skin radiant energy exposure in the 1400- to 10^6-nm region to 0.01 W/cm^2. For brief exposure, on the order of a few minutes, the limit is 0.1 W/cm^2. Use a measurement aperture of 1 mm for wavelengths shorter than 10^5 nm, and an aperture of 11 mm for longer wavelengths. (For exposure of large skin areas, also see the recommendation at the beginning of Section 6.8.1.)

Radiant energy with a wavelength of 1400 to 1900 nm is absorbed by the cornea and aqueous, and beyond 1900 nm it is largely absorbed by the cornea. The ANSI Z136 limit for eye or skin exposures of 10 seconds or more, in the wavelength region from 1400 to 10^6 nm, is 0.1 W/cm^2, with the measurement being made with a 1-mm aperture for wavelengths up to 10^5 nm, and an aperture of 11 mm for longer wavelengths (Ref. 15).

It has been suggested that although an exposure of 0.1 W/cm^2 for a few hours or even days will not cause any injury, the limited evidence of eye damage in a few glass and steel workers exposed for 10 to 15 years to infrared irradiances of 0.08 to 0.4 W/cm^2 makes a limit of 0.01 W/cm^2 a more appropriate choice for situations involving long-term exposure (Ref. 32).

6.8.1.5 MICROWAVE RADIANT ENERGY

RECOMMENDATION:

Limit microwave radiation, over the frequency range of 10^7 to 10^{11} Hz, to 0.01 W/cm^2, averaged over a 0.1-hour period.

Microwave energy is largely absorbed by the body. Although there is limited evidence of direct biological action at certain frequencies, the only well established hazard from microwave radiation is direct heating of body tissue to an excessive temperature (Ref. 33).

Microwave radiation is usually defined as covering the region of the electromagnetic spectrum from $3x10^8$ to $3x10^{11}$ Hz, which corresponds to wavelengths of 1m to 1mm (Ref. 34). The Occupational Safety and Health Administration (OSHA) exposure limit, which covers a slightly different frequency range, 10^7 to 10^{11} Hz, is 0.01 W/cm^2, averaged over a 0.1-hour period (Ref. 35).

6.8.2 IONIZING RADIATION

Ionizing radiation is very dangerous and personnel exposure must be kept to a minimum. Ionizing radiation from imagery displays is generally limited to low-intensity X-rays from an occasional television monitor.

There are two personnel categories for exposure to ionizing radiation, "occupational" and "nonoccupational." "Occupational" exposure limits apply only to personnel working in a special restricted area. Such individuals must wear a radiation monitoring device and must receive periodic medical examinations to check for radiation injury. It is unlikely that these restrictions would be necessary for the manufacture, repair, or use of imagery displays. All other radiation exposure falls into the "nonoccupational" category.

Limits on exposure to ionizing radiation are subject to change. The current (1975) limits for "nonoccupational" exposure are (Ref. 36):

- 500 mrem over 1 calendar year
- 100 mrem over 7 consecutive days
- 2 mrem over 1 hour

On the same date, maximum allowable X-ray output from a television monitor, (Ref. 37), was 0.5 milliroentgen per hour, measured 5 cm from the monitor housing under worst case conditions of both control settings and component failure.

Regulation of exposure to ionizing radiation is shared among several government agencies. The display designer is most likely to be involved with two, or possibly three:

- The Bureau of Radiological Health (BRH), part of the Food and Drug Administration, which in turn is part of the Department of Health, Education, and Welfare. The BRH sets limits on radiation from electronic products (See Ref. 37.)
- The Occupational Safety and Health Administration (OSHA), which is part of the Department of Labor. OSHA sets limits on worker exposure to potential hazards.
- The Nuclear Regulatory Commission (NRC), formerly the Atomic Energy Commission (AEC).

6.8.3 ELECTRICAL

NOTE: Because electrical safety standards are subject to change, the values given here are suitable primarily for general guidance. For current standards, consult the latest version of MIL-STD-454, Standard General Requirements for Electronic Equipment (Ref. 38).

With an electrical potential of 30 volts, or even somewhat less, conditions leading to low body resistance such as relatively large skin area (arm or hand) contact with a wet metal surface can result in sufficient current, more than 10 ma at 60 Hz, to be fatal (Ref. 39). Hence, display equipment should be designed to protect operators and maintenance personnel from accidental contact with voltages in excess of 30 volts root mean square (rms) or direct current (d.c.).

6.8.3.1 PHYSICAL BARRIERS

To reduce the risk of accidental contact when connectors are separated, electrical potentials should be present only on female pins.

All contacts, terminals, and like devices having voltages between 70 and 500 volts rms or d.c. with respect to ground should have barriers or guards to minimize accidental contact by operating or maintenance personnel. Holes in the barrier may be provided for maintenance testing. Assemblies operating at potentials in excess of 500 volts rms or d.c. should be completely enclosed from the remainder of the assembly. The barrier, guard, or enclosure should be marked to indicate the approximate highest normal voltage (nearest round number) that may be encountered upon its removal.

6.8.3.2 TEST POINT VOLTAGE REDUCTION

When the operation or maintenance of equipment employing potentials in excess of 300 volts peak could require that these voltages be measured, the equipment should be provided with test points so that all high voltages can be measured at relatively low potential level, but in no case should the potential exceed 300 volts peak relative to ground. This may be accomplished through the application of voltage dividers or other techniques, such as the use of safety-type panel meters and multipliers. If a voltage divider is used, the voltage divider resistance between the test point and ground must consist of at least two equal value resistors in parallel. Full details shall be given in the maintenance manual as to the method used in the equipment to obtain the voltages at the test points.

6.8.3.3 DISCHARGING DEVICES

Discharging devices should be provided to discharge high-voltage circuits and capacitors unless they discharge to 30 volts within 2 seconds or less. These protective devices should be positive acting, highly reliable, and be actuated automatically when the case or rack is opened. When resistive bleeder networks are used to discharge capacitors, the bleeder network should consist of at least two equal valued resistors in parallel.

6.8.3.4 LEAKAGE CURRENT

All equipment, with the exception of that specifically intended for use in a hazardous electrical environment by personnel who are trained and skilled in electrical maintenance, should comply with the provisions of "American National Standard for Leakage Current for Appliances" (Ref. 40). This standard prescribes a maximum leakage current for 120V, 60-Hz appliances of 0.5 ma for 2-wire and 3-wire cord-connected portable appliances, and 0.75 ma for 3-wire cord-connected appliances that are not portable.

6.8.3.5 WARNING LABELS

Personnel should not be dependent on operating or maintenance manuals to become aware of potential hazards. All contacts, terminals, and like devices having potentials in excess of 500 volt rms or d.c. should be clearly marked with a label like the following that indicates the voltage:

DANGER HIGH VOLTAGE
_____ VOLTS

The lettering should be clearly legible, white or aluminum on a red background. The label should be as permanent as the life expectancy of the equipment. It should be permanently placed as close as possible to the point of danger. This can be on a unit or terminal block basis and is not intended to apply to individual tie points.

6.8.3.6 GROUNDING

Equipment should be designed so that all external parts are at ground potential. Antenna and transmission line terminals should also be at ground potential, except for radio frequency energy on their external surfaces.

A point on the electrically conductive chassis or equipment frame should serve as the common tie point for the static ground and power ground. The path from the equipment tie point to ground should

- Be continuous and permanent.
- Have ample current-carrying capacity to conduct safely any operating or fault currents that may be imposed upon it.
- Have sufficiently low impedance to limit the potential above ground and to facilitate the operation of the over-current devices in the circuit. Inactive wires in long conduits or cables should be grounded to allow for stray or static electricity discharge.
- Have sufficient mechanical strength to minimize possibility of ground disconnection.

6.8.3.7 GROUNDING TO CHASSIS

Ground connection to an electrically conductive chassis or frame should be mechanically secured by soldering to a spotwelded terminal lug or by using a terminal on the ground wire that may be secured with a screw, nut, and lockwasher. The screw should fit in a tapped hole in the chassis or frame or it should be held in a through-hole by a nut. When the chassis or frame is made of steel, the metal around the screw hole should be plated or tinned to provide a corrosion-resistant connection. If alloys of aluminum or aluminum with a corrosion-resistant surface finish are used, the metal around the screw hole does not require masking if resistance of less than 0.002 ohm is measured through the coating.

6.8.4 HEAT

Limit direct contact with hot surfaces as follows (Ref. 41):

- 43 to 49°C (110 to 120°F) Accidental bare skin contact is acceptable, but contact should not be a normal part of display operation.
- 49 to 60°C (120 to 140°F)- Provide a guard if this surface must be handled.
- Above 60°C (140°F)--Provide a guard to prevent contact with surface.

6.8.5 MECHANICAL HAZARDS

Guards should be provided on all moving parts of machinery and equipment, such as pulleys, belts, gears, and blades, on which personnel may become injured or entangled. Nominal openings in a guard should not exceed 1.2 cm (0.5 in) (Ref. 41). Guards should resist deformation while in normal use.

Equipment design should be reviewed to ensure that the operator cannot inadvertently pinch or catch his fingers in some mechanism. Power-driven mechanisms in which there is a chance of injury and which cycle through an operation automatically without remaining under the operator's direct control increase the hazard. An example of such a device might be a light table that translates toward the operator after he momentarily depresses a pushbutton, and stops moving only when it contacts a limit switch.

Exposed edges should be rounded to a minimum radius of 1 mm (0.04 in), and exposed corners to 13 mm (0.5 in) (Ref. 41).

6.8.6 TOXIC SUBSTANCES

Toxic substances will seldom be encountered in displays. The most likely exceptions are materials used for cooling or cleaning the display or the imagery.

Personnel should not be exposed to toxic substances in excess of the threshold limit values in accepted standards, such as those published by the American Conference of Governmental and Industrial Hygienists (Ref. 42). In many cases, limits imposed by the Occupational Health and Safety Administration (OSHA) will also apply, as will the appropriate military standards.

Eye baths, showers, and other first aid equipment should be readily available in areas where toxic materials will be handled. Provision should also be made for neutralization or flushing of harmful materials spilled on equipment or personnel.

6.8.7 CATHODE RAY TUBES

The handling and use of a cathode ray tube (CRT) must be undertaken with considerable care, as it is constructed primarily of glass enclosing an evacuated space. Impact or scratching may cause tube implosion and serious harm to personnel. When not installed in equipment, CRT's should be stored in shipping cartons with covers closed (see Section 6.9.8).

Under certain conditions, a television monitor can emit low-intensity X-rays This occurs most frequently when high voltages such as those used in color monitors are involved. If there is any change of radiation, measurements should be made to determine if there is a potential hazard from prolonged exposure (see discussion of radiation limits in Section 6.8.2). If there is, it must be corrected with shielding or by modifying the set.

6.8.8 HIGH-ENERGY LIGHT SOURCES

Certain high-energy light sources, such as short-arc xenon or mercury lamps, involve special hazards. Danger of injury from radiant energy (Section 6.8.1) or direct contact with a hot lamp should be eliminated by providing adequate ventilation and a secure enclosure with an electrical interlock so that the lamp cannot be operated unless it is shielded from personnel.

Because of the high pressures generated in operation, adequate enclosures are essential for protection in event of explosive lamp failure. General Electric recommends 18-gauge sheet steel. Extreme caution must be exercised in handling these lamps. Protective cases are provided and should be removed only after installation and should be replaced before removal. Only trained, authorized personnel should have access to these lamps.

Additional hazards may result from contact with auxiliary cooling systems or coolants and toxic gases such as mercury-krypton, mercury-zinc, and hydrogen-cyanide (see Section 6.8.6).

SECTION 6.8 REFERENCES

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   It should be noted that suggestions of a biochemical or photochemical damage mechanism in the retina have been made previously, but this is apparently the first data that can be applied directly to the problem of setting exposure limits.

3. Based on personal communication with National Institute for Occupational Safety and Health (NIOSH) personnel, it is understood that Pitts (Ref. 8) is conducting additional research in this area.

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   Also see Appendix I of Ref. 19.

5. American National Standards Institude (ANSI). *The Safe Use of Lasers.* Standard Z136.1-1973, ANSI, New York, 1973.

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   Pitts, D. G., Bruce, W. R., and Tredici, T. J. A comparative study of the effects of ultraviolet radiation on the eye. SAM-TR-70-28, School of Aerospace Medicine, Brooks Air Force Base, Texas, 1970.

   Pitts, D. G., and Tredici, T. J. The effects of ultraviolet on the eye. *Am. Ind. Hygiene Assoc. J.* Vol. 32, 1971 pp. 235-246.

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10. Sliney, D. H. The merits of an envelope action spectrum for ultraviolet radiation exposure criteris. Paper presented at American Industrial Hygiene Conf., San Francisco, California, 1972.

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12. Stair, R. Spectral-transmissive properties and use of eye-protective glasses. *NBS Circular 471.* National Bureau Standards, 1948.

    Koller, L. R., *Ultraviolet Radiation* (2nd ed). Wiley, New York, 1965.

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15. See Table 6 of Ref. 5.

16. See Figure 5 of Ref. 10.

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Also see: Dalziel, C. F. Electric shock hazard. *IEEE Spectrum*, Vol. 9, February 1972, pp. 41-50.

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6.9 MAINTAINABILITY

6.9.1 Maintenance Information

6.9.2 Test Points

6.9.3 Disassembly and Reassembly

6.9.4 Access

6.9.5 Handling of Equipment

6.9.6 Fasteners

6.9.7 Connectors

6.9.8 Circuit Protective Devices

6.9.9 Hazards

6.9.10 Calibration and Adjustment

6.9.11 Preventive Maintenance

[redacted]

SECTION 6.9 MAINTAINABILITY

NOTE: Because this entire section consists of recommendations, they are not listed separately here.

Although a well designed display will seldom require maintenance, occasional failures are inevitable, particularly when light sources are involved. Therefore, it is essential to design a display so that the necessary maintenance can be performed rapidly and efficiently, by a minimum of personnel, using a minimum of tools and equipment. The modern term for this characteristic is *maintainability*.

A brief summary of the techniques and features that will increase the maintainability of a display appears in this section, and more extensive treatment is available (Ref. 1). However useful such lists of design techniques are, the only way to ensure that a display will be easy to maintain is for the designer to think through each possible maintenance operation early enough in the design phase to make improvements where they are required. As a part of this process, he should ask the following kinds of questions about each possible failure:

- Will the maintenance operation involve potential hazards to personnel or equipment?
- Do prominent labels provide a warning about each hazard?
- What information on equipment status will be required to diagnose this failure?
- Is this information conveniently available to maintenance personnel?
- How will maintenance personnel become aware of the need to seek this information?
- Is there adequate access to test, remove, replace, and adjust components?
- What provision has been made for lifting or moving each component?
- Have fasteners been selected for maximum maintenance efficiency?
- Would it be easier to place a part in the proper location if guide pins were added?
- Are any of maintenance procedures likely to be beyond the capability of typical maintenance personnel using easily available tools and equipment?
- Has every effort been made to minimize the need to depend on the maintenance manual?

6.9.1 MAINTENANCE INFORMATION

The two primary sources of maintenance information are manuals and labels on the equipment. Manuals are covered in Section 6.10. The following labels should be provided; where code numbers are mentioned, they must correspond to usage within the maintenance manual.

- Warnings of safety hazards
- Warnings of maintenance actions, such as the use of a certain kind of solvent for cleaning, that could cause equipment damage
- Warnings of unusual components that would not be obvious, such as a screw with a left-hand thread
- Warning, and if possible a description, of any required preventive maintenance.
- A code number at each test point, and if possible, the name and correct value of the test point signal.
- A code number on each socket and plug (Section 6.9.7).
- A code number on each cable and pipe if the display is sufficiently complex that these might help in identification.
- If space is available on inside panels, circuit diagrams and other important maintenance information.

6.9.2 TEST POINTS

Test points should be provided to facilitate measurement of information required for calibration and trouble-shooting. At a minimum, test points must be labeled with a code number keyed to the maintenance manual. The name and correct value of the signal at the test point is also very useful and should be included where space permits.

Test points should be easily accessible so that test leads inserted in them do not block essential controls or displays.

6.9.3 DISASSEMBLY AND REASSEMBLY

Maintenance usually requires disassembly and reassembly of at least part of the display. The following practices will speed this activity:

- Minimize blocking of one component by another. Where space constraints require some components to be blocked, provide easy access to those most likely to fail.
- Simplify replacement of components that may fail by mounting them on plug-in modules.
- For special components that cannot be plugged in, make the replacement procedure as obvious and simple as possible. For example, wiring might be precut to length and, if several wires are involved, tied into a bundle with the end of each wire in its proper relative position.
- Ensure that no component can be installed in the wrong position. For example, if several similar printed-circuit-card sockets are used, notches can be cut at different locations in each type of card and plastic inserts can be added to each socket to prevent improper insertion.
- Label each removable component and its position on the display with corresponding numbers.
- Unless absolutely unavoidable, require only standard hand tools.
- Provide for the easy replacement of components that fail frequently, such as lamps and fuses.

6.9.4 ACCESS

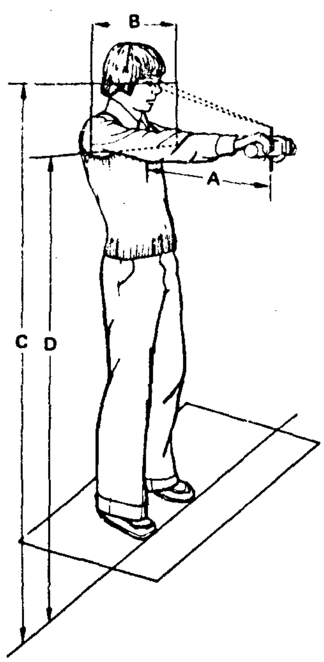
Access into the display is required for visual inspection, for connecting test leads, and for adjusting, removing, or replacing components. The openings needed to achieve manual access of varying degrees are summarized in Figures 6.9-1 through 6.9-4, and whole body clearances and optimum work areas for various work positions are summarized in Figures 6.9-5 and -6. The values in these six figures are intended to accommodate 90 to 95 percent of male maintenance personnel. These figures include only a small part of the data of this type that are available (Ref. 2 and Section 6.1.1).

Blocking of access to one component by another component should be avoided. If this is not possible, then the relative accessibility of different areas, from most accessible to least, should be as follows:

- Preventive maintenance points, such as oil holes
- Test points used for adjustment or troubleshooting
- Components that require the most frequent maintenance
- Components that should seldom require maintenance

If access covers are hinged, they should be stable in the open position so that maintenance personnel need not waste time holding them open.

Clearance around subassemblies should be adequate for easy removal (see Section 6.9-5). For large or heavy subassemblies, it is preferable that the case be designed to be removed from around the subassembly, rather than the subassembly from the case.



POSITION	DISTANCE							
	CENTIMETERS				INCHES			
	A	B	C	D	A	B	C	D
STANDING, FORWARD REACH, BOTH ARMS	48	50	176	132	19	20	69	52
STANDING, FORWARD REACH, PREFERRED ARM	51	31	176	132	20	12	69	52
STANDING, LATERAL REACH, PREFERRED ARM	55	26	176	132	22	10	69	52
SEATED ON CHAIR, FORWARD REACH, BOTH ARMS	38	47	119	86	15	19	47	34
SEATED CROSSLEGGED ON FLOOR, FORWARD REACH, BOTH ARMS	34	46	72	43	13	18	28	17

A = DEPTH OF REACH FOR SHORT-ARMED PERSON
B = WIDTH OF APERTURE TO CLEAR ARMS OF LARGE PERSON
C = HEIGHT OF APERTURE TOP TO ALLOW VISUAL ACCESS FOR TALL PERSON
D = HEIGHT OF APERTURE BOTTOM TO CLEAR ARM OF SHORT PERSON

Figure 6.9-1. Access Panel Dimensions (Ref., 3, X)

6.9.4 ACCESS (CONTINUED)

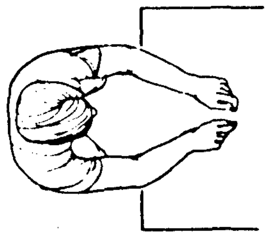
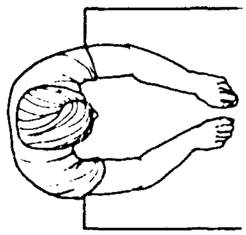
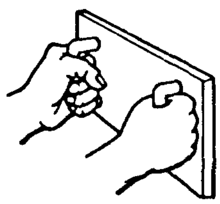
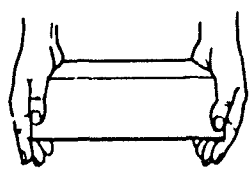
ACCESS		CLEARANCE REQUIRED
BOTH HANDS TO DEPTH OF 150 TO 490 mm (6 to 19 in)		WIDTH - DEPTH OF REACH [minimum of 200 mm (8 in)] HEIGHT = 125 mm (5 in)
BOTH HANDS, FULL ARM'S LENGTH (to shoulders)		WIDTH = 500 mm (19.5 in) HEIGHT = 125 mm (5 in)
INSERTING BOX HELD BY HANDLES		WIDTH = BOX + 25 mm (1 in) HEIGHT = BOX + 25 mm (1 in)
INSERTING BOX WITH HANDS ON SIDES		WIDTH = BOX + 115 mm (4.5 in) HEIGHT = BOX + 25 mm (1 in) [minimum of 125 mm (5 in)]

Figure 6.9-2. Opening Required for Two-Hand Access (Ref. 4,X)

6.9.4 ACCESS (CONTINUED)

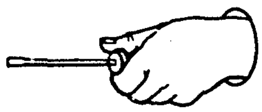
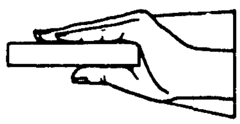
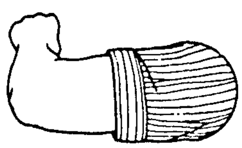
ROLLED HAND		DIAMETER = 95 mm (3.75 in)
FLAT HAND		HEIGHT = 55 mm (2.25 in) WIDTH = 100 mm (4 in)
CLENCHED HAND		HEIGHT = 95 mm (3.75 in) WIDTH = 125 mm (5 in)
HAND PLUS 25 mm (1 in) DIAMETER OBJECT		DIAMETER = 95 mm (3.75 in)
HAND PLUS OBJECT OVER 25 mm (1 in) DIAMETER		HEIGHT AND WIDTH = OBJECT PLUS 90 mm (3.5 in)
ARM TO ELBOW		HEIGHT = 100 mm (4 in) WIDTH = 115 mm (4.5 in) (or, 115 mm diameter)
ARM TO SHOULDER		DIAMETER = 125 mm (5 in)

Figure 6.9-3. Opening Required for One-Hand Access (Ref. 4,X)

6.9.4 ACCESS (CONTINUED)

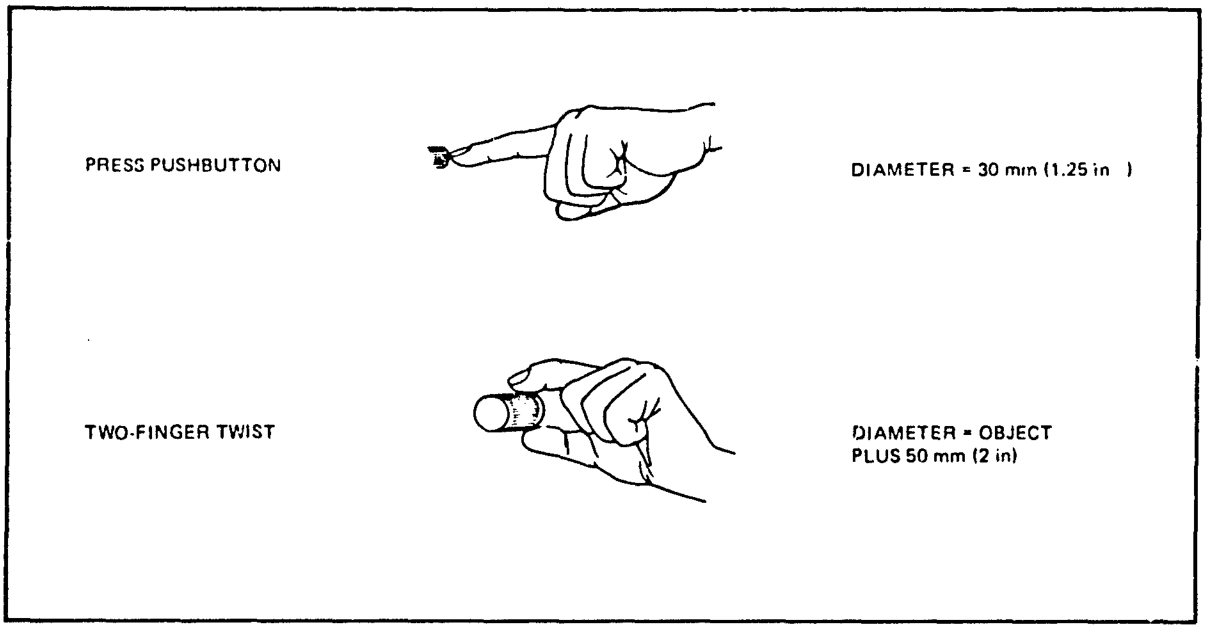
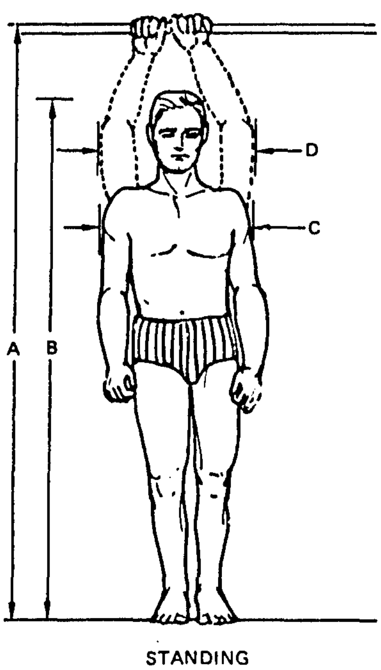


Figure 6.9-4 Opening Required for Finger Access (Ref. 4, X)



	MINIMUM CLEARANCE	
	cm	in
B	192	76
C	48	19
D	43	17
E	145	57
F	51	20

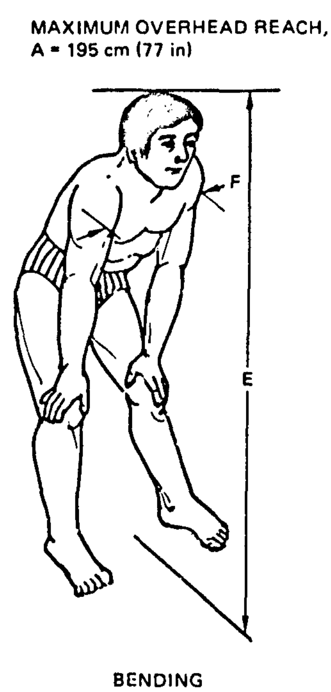
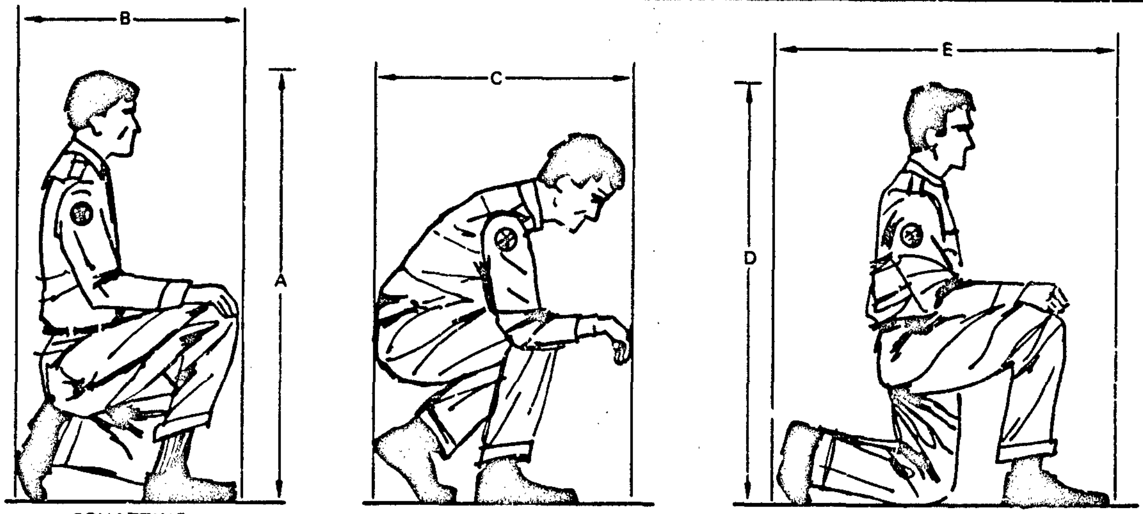
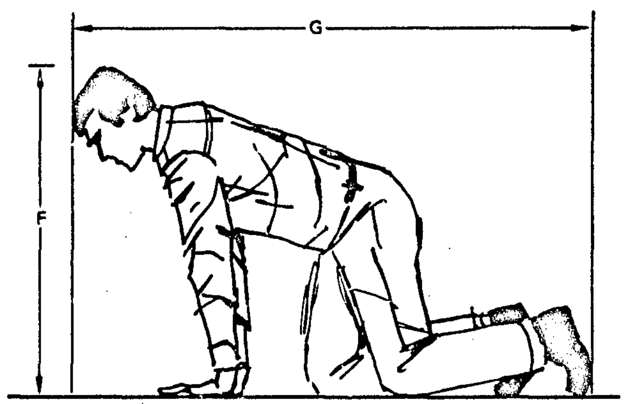


Figure 6.9-5. Clearances and Optimum Work Heights for Typical Work Positions (Ref. 5,X) (Continued on next page)

6.9.4 ACCESS (CONTINUED)



	MINIMUM CLEARANCE	
	cm	in
A	122	48
B	69	27
C	91	36
D	107	42
E	142	56
F	79	31
G	150	59
H	43	17
I	244	96



POSITION	HEIGHT OF VISUAL WORK AREA		HEIGHT OF MANUAL WORK AREA	
	cm	in	cm	in
SQUAT	68-110	27-43	48-86	19-34
STOOP	81-120	32-48	61-100	24-39
KNEEL	71-112	28-44	51-90	20-35

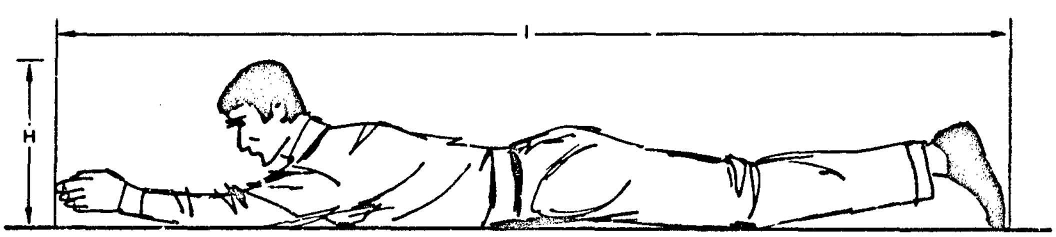


Figure 6.9-6. Clearances and Optimum Work Heights for Typical Work Positions (Ref. 5,X)

6.9.5 HANDLING OF EQUIPMENT

Equipment intended for carrying should be provided with handles or other suitable means for grasping. Minimum internal dimensions for a handle are 5 cm (2 in) deep by 11 cm (4.5 in) wide.

Equipment units up to 20 kg (45 lb) are suitable for handling by one man. From 20 to 40 kg (45 to 90 lb), provision should be made for handling by two men. Beyond 40 kg (90 lb), provision should be made for mechanical lift. Units over 20 kg (45 lb) should be labeled to show weight and over 40 kg (90 lb) to show lift points. If the center of gravity is not obvious from the external appearance of the unit, it should be clearly marked.

If an equipment unit is larger than 75 cm (30 in) in two or more dimensions, it is too bulky for handling by one man, even though it may weigh less than 20 kg (45 lb), and provision should be made for carrying by two men.

6.9.6 FASTENERS

Fasteners used to hold access covers, panels, or components in place should be selected according to the following goals:

- To reduce maintenance time, use the minimum number of fasteners and the minimum number of turns per fastener commensurate with strength requirements.
- To reduce maintenance time, use finger-operated fasteners in locations where the fastener must be removed frequently and where there is both sufficient space and no need for high torque.
- Use captive fasteners wherever a dropped fastener might be difficult or dangerous to retrieve or where it might cause equipment damage.
- To reduce tool requirements, use a minimum number of fastener head styles.
- To prevent fastener head damage in high torque applications, use allen or hex head styles. A slotted screwdriver style is acceptable for moderate torques, but should be combined with a hex or allen head for high torque applications. Phillips head screws are easily damaged and should be avoided, except perhaps for low torque applications where there is no chance the screw will freeze in place over time
- To reduce maintenance time, and fastener resupply problems, use a minimum number of fastener types. In particular, do not use fasteners that are so similar in appearance that an attempt might be made to insert one in the wrong location. For example, small differences in screw length or diameter, and different thread spacings on similarly sized screws, should be avoided.

6.9.7 CONNECTORS

Connectors are essential to the assembly and disassembly of equipment, both during the construction and check-out phase and later during maintenance. Unfortunately, connectors are less than totally reliable, and most are susceptible to damage. Hence, connectors should be used only where needed.

Connectors should be selected and mounted to facilitate rapid removal and replacement–without any need for excessive force–in the correct location and with no damage to the connector, the display, or personnel. The following practices will help achieve these goals:

- Where a locking mechanism is necessary to ensure positive seating of the plug in the socket and to ensure that the plug does not come loose, select an easily operated style. For example, a locking ring should not require more than part of a turn.
- To indicate where each plug belongs, place a code number on it and on the corresponding socket. For example, plug P73 would mate with socket S73.
- Where several connectors are in use, obviously different styles will avoid placement of plugs in the wrong socket. If there is a need for similar connectors, us keying pins to prevent incorrect positioning, an improve the labeling or even add a color code t make correct plug location more obvious.
- Use guide pins to aid plug insertion if there is an chance that misalignment will lead to pin damage.
- Multi-pin plugs must be rotated to the prope orientation before being inserted. Plugs and socket that provide a visual indication of orientation ar preferred. To reduce confusion, mount all sockets i the same orientation. It is usually preferred to plac the index mark toward the top, or away from th operator.
- Provide sufficient space around each connector f hand access. A nominal minimum value is a clearanc of 2.5 cm (1 in). For specific applications, refer t the figures in Section 6.9.5 or conduct an evaluatio on a mockup.
- To reduce potential hazards to personnel and equi ment install connectors so that separated, all-elect cal potentials are on female, rather than male, pins.

6.9.8 CIRCUIT PROTECTIVE DEVICES

Circuit breakers are preferable to fuses as a means of protecting electrical circuits because they eliminate the need to find a replacement fuse and they reduce the chance of equipment damage from use of too heavy a fuse.

A circuit breaker must provide positive indication that it has tripped. Indication that a fuse has blown is also desirable but less easily achieved. The loss of the power-on indicator lamp may provide a sufficient hi that a fuse may be blown.

Circuit breakers and fuse holders should be readi accessible for resetting or fuse replacement.

The correct fuse rating should be included on a lab next to each fuse holder. Holders for spare fuses are al desirable.

6.9.9 HAZARDS

Safety hazards are discussed in Section 6.8. Although these correctly apply both to operation and maintenance of the display, it is inevitable that maintenance personnel will on occasion be more directly exposed to certain hazards. For example, it may be impossible to design the display so that personnel performing troubleshooting will be always unable to make physical contact with a hazardous electrical potential. However, exposure to such hazards should be kept to an absolute minimum. Increasing the number of test points, for example, will reduce the need to probe directly within a circuit. Extremely dangerous circuits should be mounted in their own enclosure. An interlock to remove power from a particularly dangerous circuit when it is uncovered is very important. However, the interlock will inevitably be bypassed if that is the only way maintenance personnel can obtain the information necessary to determine if the circuit is operating properly. Hence, it is essential to provide safe access to this information.

Because mishandling can result in implosion, cathode ray tubes (CRT's) are particularly dangerous. During installation or removal, the weight of the tube should be supported at the heavy faceplate, with the neck held only for guiding the base pins into and out of the socket. Work tables or benches used for CRT servicing should be provided with siderails, boards, or guards to prevent CRT's from rolling off, striking other objects, or being inadvertently damaged by falling equipment, materials, or tools. Whenever the tubes must be placed in direct contact with the work surfaces, felt or other soft material (either fitted or permanently attached to the work surface), should be provided to reduce the possibility of scratching the glass surface of the tube. Scratches weaken the glass and increase the chance of implosion.

Removal of one or several subassemblies from the display, or sliding them out if they are supported like drawers, should not unbalance the display to the point where it might tip over.

6.9.10 CALIBRATION AND ADJUSTMENT

In order for maintenance personnel to adjust and calibrate display equipment, they must be provided with:

- Information on the procedures to use (Section 8.0).
- Access to information on equipment adjustment status. This might be the signal on a servo motor, or the height of a guide rail.
- The equipment necessary to perform the adjustment. This should be limited to standard tools and measuring devices.

6.9.11 PREVENTIVE MAINTENANCE

Preventive maintenance includes lubrication and adjustments required to increase the useful life of the display. Because preventive maintenance will not necessarily be performed properly or on schedule, the designer should depend on it only where no other approach is feasible.

If preventive maintenance is required, the display user must be made aware of this fact by prominent labels on the equipment. At a minimum, each label should indicate when maintenance is required and where the maintenance procedure is described. Ideally, each will also describe the tools and materials required, such as type of lubricant, and the procedure. If extremely critical maintenance must be performed on an exact schedule, the label should include space for the person performing the maintenance to record the date.

Preventive maintenance must be described in the maintenance manual (Section 8.0) provided with the equipment, as well as on a label.

SECTION 6.9 REFERENCES

1. Crawford, B. M. and Altman, J. W. Designing for maintainability. Chapter 12 in Van Cott, H. P. and Kinkade, R. G. (Ed.), *Human Engineering Guide to Equipment Design*. U.S. Government Printing Office, Washington D.C., 1972.

   Also, see Ref. 4.

2. See Ref. 4 and 5.

3. Kennedy, K. W. and Filler, B. E. *Aperture Sizes and Depths of Reach for One- and Two-Handed Tasks*. AMRL-TR-66-27, Aerospace Medical Research Lab, Wright-Patterson Air Force Base, Ohio, 1966. Cited in Ref. 5.

4. *Human Engineering Design Criteria for Military Systems, Equipment and Facilities*. MIL-STD-1472B, (proposed), U.S. Army Missile Command, May 1974.

5. Hertzberg, H. T. E. Engineering Anthropology. Chapter 11 in VanCott, H. P. and Kinkade, R. G. (Ed.) *Human Engineering Guide to Equipment Design*. U.S. Government Printing Office, Washington D.C., 1972. In slightly more than 100 pages this reference summarizes the information contained in about 190 references.

   Also see Ref. 4.

6.10 MANUALS

6.10.1 Content

6.10.1.1 All Manuals

6.10.1.2 Operating Manuals

6.10.1.3 Maintenance Manuals

6.10.2 Format and Style

6.10.3 Typical Manual Deficiencies

6.10.4 Manual Development

SECTION 6.10 MANUALS

NOTE: Because this entire section consists of recommendations, they are not listed separately her

Manuals provide personnel with the information necessary to operate and maintain equipment. The most important requirement imposed on a manual is that it impart the required information in a reliable and efficient manner.

Manuals must be accurate and must reflect the latest modifications to equipment. Users will lose trust in any manual in which they find errors.

When a manual is being prepared, the equipment designer is often the only individual with enough familiarity with the equipment to correctly describe how it should be operated. However, because of this familiarity, he also has difficulty appreciating the pr facing the individual who must use the manual. Fi user lacks the designer's technical background a experience with the equipment. Second, if it operating manual, the user's interest in the equip not likely to extend beyond its usefulness as a help him in carrying out his work. As a result, have a low tolerance for lengthy descriptions equipment that make no obvious contribution actually using it.

Most of the material in this section is derive Reference 1.

6.10.1 CONTENT

To the extent possible, each manual should be complete within itself, thereby eliminating the need to refer to more than one document in order to perform a particular task. A limited amount of redundancy between manuals is an acceptable penalty for achieving this goal.

When a particular operation or sequence of op must be performed in exactly the manner de these should be preceded by a warning note sta fact. The manual user will be much more likely this warning if he is also told why it is necessary.

6.10.1.1 ALL MANUALS

All equipment manuals should include the following material:

- Table of contents
- Lists of figures and tables
- Cross references to other manuals covering the same equipment
- A very brief general description of the equipment and its purpose, with a picture or drawing included as an aid in quickly identifying the equipment
- A summary list of equipment specifications, size, light level, magnification range, and requirements
- A nontechnical description of the equipment functions, and how it is operated
- A summary of the operating procedure, pref tabular form, at a level appropriate for revie already trained operator
- An index

6.10.1.2 OPERATING MANUALS

Specific items that should appear in an operating manual, in addition to the items in Section 6.10.1.1 above, include the following:

- Detailed, step-by-step operating procedures; a summary should appear at the beginning of any lengthy procedure so that the partially trained operator need not lose time reading the entire procedure again
- A list of unscheduled events and a descri what to do when they occur
- A description of any potentially hazardous si each prominently identified with a "WARN "CAUTION" label
- A description of any operator maintenance f

6.10.1.3 MAINTENANCE MANUALS

There are two common approaches to maintenance. One is to simply follow a prepared procedure, step by step, until the failed component is determined and repaired. The second requires the technician to use his knowledge of how the equipment functions to decide what action to take in response to a particular set of symptoms. The first approach requires less technician training and can be faster if the procedures are well prepared. However, since it is impossible to predict every possible failure mode, the maintenance manual must, at a minimum, include complete information on how the equipment functions. In order to reduce maintenance time, step-by-step procedures, or at least a troubleshooting guide, should also be included for the most likely failure modes.

Specific items that should appear in the maintenance manual, in addition to the items in Section 6.10.1.1 above, are:

- A detailed description of the equipment, including drawings and photos that identify the equipment components
- Circuit diagrams that identify the individual circuit elements
- A detailed description of how the equipment functions
- Normal test point values, such as voltage, current, resistance or signal waveform, with at least some indication of tolerance or allowable variation around these values
- A troubleshooting guide containing a list of symptoms, with each symptom followed by probable causes and corrective action
- Step-by-step test procedures in sufficient detail to determine what component must be repaired or replaced
- Repair/replacement procedures
- A parts list with sufficient detail to allow the new part to be procured

6.10.2 FORMAT AND STYLE

The first requirement imposed on manual format and style is to communicate effectively with the user. The second, which contributes indirectly to communication, is consistency with the manuals for other items of equipment used by the same organization. For equipment procured by a number of organizations with different style standards, revision of the manual to match the style in use by each organization may not be worth the cost.

An operator or maintenance technician will rely on a manual only to the extent that it is helpful in accomplishing his task. As soon as he understands the task sufficiently that the manual is not contributing, it will be discarded. Therefore, the format of the manual should be designed to provide quick access to needed information. Tabular or outline format is usually better for this purpose than a paragraph by paragraph narrative.

One of the most important features of a manual is the ease with which the user can locate information on a specific topic. Texts on how to study emphasize the need to read technical material several times in order to understand it. However, most manual users, particularly users of operating manuals, will read the entire manual no more than once, if that often. For any manual more than a few pages long, the user is therefore heavily dependent on manual section titles, the table of contents, and the index in order to find the information he needs.

Attempts have been made to use audiovisual devices to improve the presentation of the information normally found in a maintenance manual. The results indicate that the mode of presenting this information is much less important than the content, organization, and accessibility (Ref. 2,X).

Text material that must be used with a particular figure should be visible to the user at the same time as the figure. If not too long, this text can be on the same or the facing page. Otherwise, the figure should be printed on oversize paper so that when unfolded it lies outside the manual, where it can be viewed while reading the text. The portion of the figure page that remains inside the manual should be blank.

Space can contribute to making the manual easier to use. For example, in tables containing long columns, a space between every five is helpful. For columns in a table that are not separated by a vertical line, a separation of at least 4 mm (0.17 in) is recommended. Text material that

6.10.2 FORMAT AND STYLE (CONTINUED)

must be used with a particular figure should be positioned so that both are visible without turning pages, even if this means leaving a large amount of blank space in the manual.

The complexity of the writing should be on a par with the background and the interest of the manual user. Use short sentences and short words. Where technical terms are necessary, choose ones that are shortest and best known by the user populations. These are not necessarily the terms used by the designer.

Consistency in terminology is essential. The same term should always be used to refer to a particular equipment item or function. Where a term must be used that may not be well known, or where several terms in addition to the one used in the manual are common, this should be explained in a footnote, or, preferably, in a glossary. Terms and symbols in the manual should also match those used in equipment labels.

The binding method for manuals should permit fully opened manuals to lie flat and should facilitate revisions.

Use photographs and drawings to illustrate equipment features and operating and maintenance procedures. To emphasize certain features, add annotations and print less important features with less resolution or contrast.

To show the relationship between two or three variables, use a graph. To provide the user with discrete values, use a table.

Number pages, figures, and tables in a consistent manner. Preferred location for page numbers is the lower outside corner or lower center.

Present all quantitative information in immediately usable units, thereby eliminating the need for mathematical conversions. In most cases, use metric units followed by English units in parentheses. Always indicate the units.

Avoid acronyms and abbreviations wherever possible. If they must be used in order to keep the length of the manual within reason, define them when they are first introduced and in a list at the beginning of the manual.

To the extent possible, show components in data flow diagrams and test setups in their true relative positions.

Standard 216- by 279-mm (8.5- by 11-in) format is preferred, with the following exceptions:

- Pocket-size summary manuals
- Duplicate, oversize copies of frequently used charts intended for wall mounting
- Foldout charts

Manuals should be printed on material that will tolerate anticipated abuse. For example, figures that will be used frequently at a workbench, such as circuit diagrams required for repairing equipment, should be printed on sturdy, crease-resistant stock.

6.10.3 TYPICAL MANUAL DEFICIENCIES

The difficulties reported by technicians using U.S. Air Force maintenance manuals provide an indication of the most likely potential problems to watch for when preparing a new manual (Ref. 3).

- Manuals were out of date because of modifications to the equipment, or because the manual incorporated modifications that had not yet been made.
- The manuals contained errors.
- Critical information was ambiguous, difficult to find, or missing.
- The normal condition, such as a voltage on a test point, was given without any indication of the allowable variation; as a result, the user could not decide when a small deviation was significant.
- Troubleshooting lists were too incomplete to be worth using.
- Figures, particularly circuit diagrams, contained so many small details that they were difficult to use; tracing a single conductor across a circuit diagram was a particular problem.
- Frequently used diagrams were soon damaged.
- Locating needed information was time consuming; on an average 30 percent of total job time was spent looking for information (Ref. 4).
- Terms in the manuals were unfamiliar and were not clearly defined.
- Illustrations were often several pages from associated text material.

6.10.3 TYPICAL MANUAL DEFICIENCIES (CONTINUED)

- Several manuals were required to do a single job; cross-referencing between manuals wasted time.
- Procedural guides were too complicated.
- Procedures called for were not realistic and had obviously been prepared by personnel who were not familiar with maintenance procedures.
- The manual was too heavy and bulky to use effectively in the available workspace.

6.10.4 MANUAL DEVELOPMENT

The following procedure is suggested for development of manuals.

- Prepare a complete list of tasks to be performed by the individual on the job for which the manual is being prepared.
- Prepare a step-by-step procedure for each of the tasks listed.
- Examine each step of each task, and the task as a whole, to determine what information should be provided to the manual user prior to and during the performance of each task.
- Prepare a draft of the manual.
- Conduct a small-scale tryout of the manual with individuals comparable to the user population.
- Revise the manual as necessary.

SECTION 6.10 REFERENCES

1. Crawford, B. M. and Altman, J. W. Designing for maintainability. Chapter 12 in Van Cott, H. P. and Kinkade, R *Human Engineering Guide to Equipment Design*. Government Printing Office, Washington, D.C., 1972.

2. Shriver, E. L. and Trexler, R. C. *A Description and Analytic Discussion of Ten New Concepts for Electronics M nance*. Technical Report 66-23, Human Resources Research Office, George Washington University, Alexandria, 1966. Cited in Ref. 1.

3. Losee, J. E., Allen, R. H., Stroud, J. W., and VerHulst, J. *A Study of the Air Force Maintenance Technical Dat tem*. Report AMRL-TDR-62-85, Aerospace Medical Research Labs, WPAFB, Ohio, 1962. Cited in Ref. 1.

4. This value, 30 percent, is based on results with fairly complex electronic systems. Most displays are much simp and the time loss should be considerably less.

SECTION 7.0
FACILITIES

7.1 INTERPRETATION FACILITY LAYOUT

7.2 CHAIR DESIGN

7.3 AMBIENT ILLUMINATION

7.4 AIR CONDITIONING

SECTION 7.0 FACILITIES

Many characteristics of the work facility, though not under the direct control of the display designer, can have a considerable impact on how effectively the display will be operated. A few of the more important ones are summarized briefly in this section. A more complete treatment can be found in the references cited and in standard architectural and interior design sources.

The treatment of furniture here is limited to the display operator's chair. Other aspects of furniture design, such as work surface heights, appear in Section 6.1.

Excessive ambient noise can severely interfere with display use. In general, the same considerations discussed in Section 6.6 for a single display also apply to the ambient environment.

7.1 INTERPRETATION FACILITY LAYOUT

7.1.1 General Principles

7.1.2 Individual Workstations

7.1.3 Passages

SECTION 7.1 INTERPRETATION FACILITY LAYOUT

This section summarizes some of the principles involved in increasing the utilization and efficiency of the imagery interpretation facility. These involve proper positioning of workstations and individual items of equipment within the workstation as well as proper organization of the work flow through the facilit Finally, they include providing adequate space so th the interpreter (1) has access to each item of equipme he must use and (2) can move freely from his individu workstation to obtain work materials and information.

7.1.1 GENERAL PRINCIPLES

A number of formal techniques are available to aid in organizing an imagery interpretation workstation and to help integrate it into an entire imagery interpretation system (Ref. 1,X). Most of these involve diagramming some aspect of system, such as the flow of work materials or information the movement of personnel, or even the shifts in the interpreter's visual attention as he carries out his task.

For individual interpreter workstations, these types of techniques generally involve developing a work flow that shows the frequency and sequence of use for the several items of equipment and for the individual controls and displays on each item. This information is then used to position the most frequently used items in the most accessible locations. If certain items of equipment are often used in sequence, then these can be positioned so that a minimum amount of time is lost in moving from one to the other.

A comparable technique can be applied to a facility, or part of a facility, containing several interpreters and support personnel; it involves the following steps:

- Identify the materials and information that must move through the system.
- Determine the frequency of occurrence for each, and the amount of time each must spend at a particular workstation.
- Draw the flow path these materials and information must follow in moving through the system.
- Use these flow diagrams as an aid in reducing pa lengths, and to identify points that may becor overloaded and thereby limit the output of the ent system. Changes required may include relocati workstations to reduce time lost in moving mater between them, rerouting the work through existing workstations, increasing the number or capacity of overloaded workstations, and chang the function of under-utilized workstations.

Applying this sort of technique to an individual inter ter's workstation might involve the following steps:

- Identify the material and information required perform each work task. This includes an estimat the frequency and sequence in which each is requ
- If these are not to be delivered to the interpr determine where he must go to obtain them, and h long each trip will require.
- Diagram the path followed by the interpreter du some work interval.
- Relocate the interpreter or the materials he requ or redesign the work task, in order to reduce the path length (expressed as time, rather than li extent).

7.1.2 INDIVIDUAL WORKSTATIONS

The workspace requirements shown in Figure 7.1-1 are the best available general recommendations. The requirement for a specific situation will vary with the frequency of operator movement from one portion of the work-space to another, and with the seating provided.

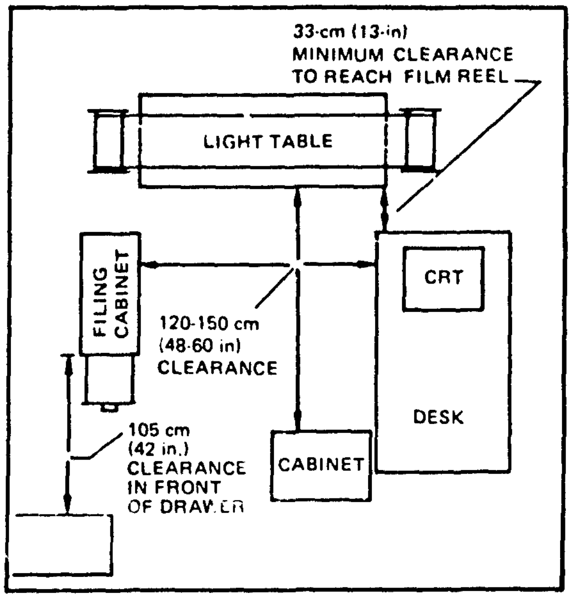


Figure 7.1-1. Working Space and Clearance at Display Workstation (Ref. 2,X). This figure shows the amount of clear space required to allow the display user to move freely from one item of equipment to another. An actual workstation would be likely to contain additional items, such as a map holder and a microfiche viewer for *collateral*, or reference, material.

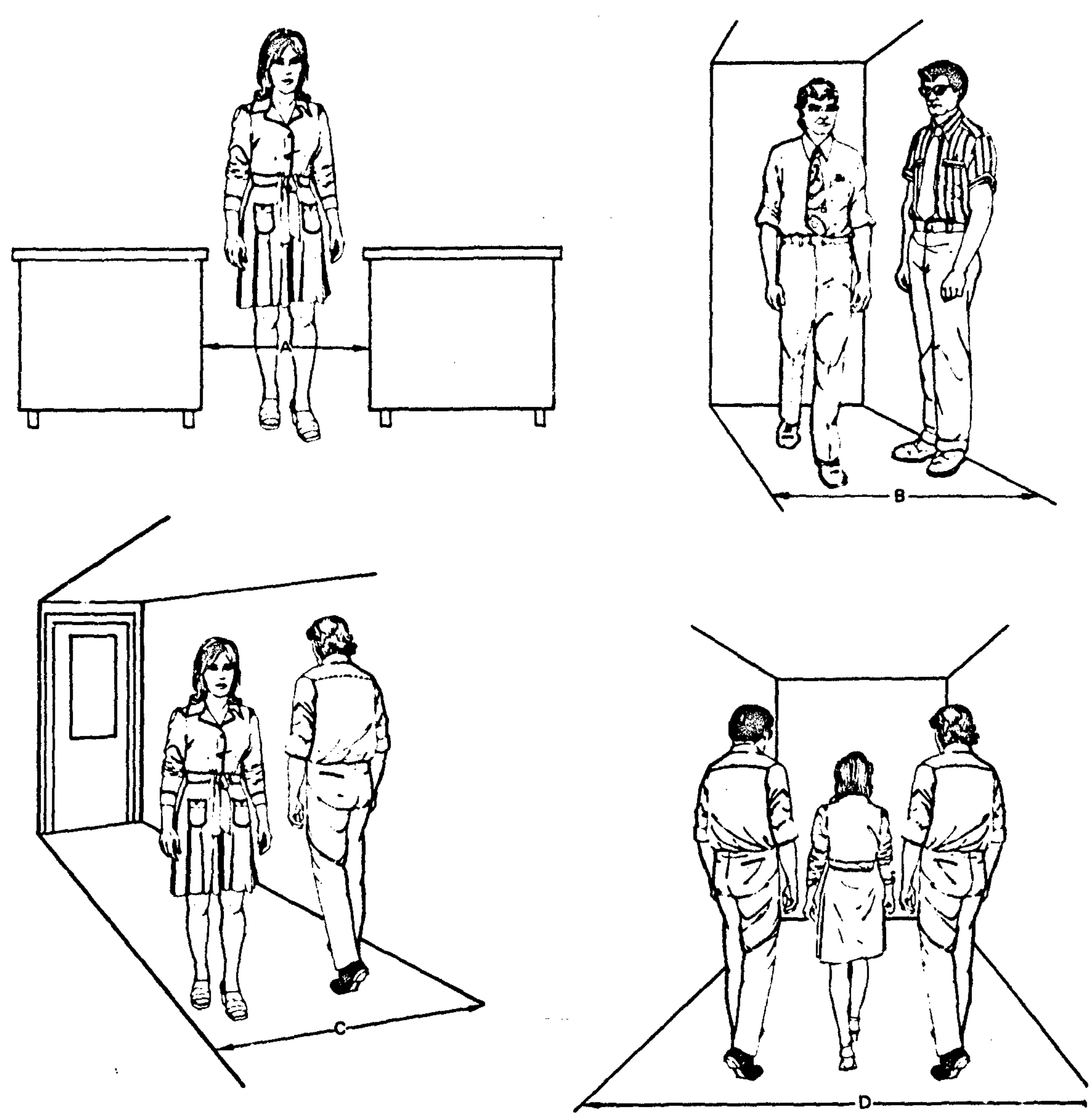
7.1.3 PASSAGES

Minimum passage dimensions depend on the frequency with which they are used and on whether the user will be carrying or moving bulky equipment. A door, for example, must be sized to clear the maximum size equipment anticipated, regardless of how many individuals will be using it.

Adequate layout of passages is nearly as important as their size. Detailed knowledge of work requirements and organization is essential to ensure that the layout will result in the most efficient personnel movement patterns. See Section 7.1-1.

Display users generally spend much more time working at their display than in walking from one area to another. Therefore, unless a passage is used quite frequently, it is better to reduce passage space to a minimum in order to provide adequate workspace.

7.1.3 PASSAGES (CONTINUED)



	MINIMUM cm (in)		RECOMMENDED cm (in)	
A ONE PERSON	51	(20)	61	(24)
B ONE PERSON PASSING; ONE AGAINST WALL	76	(30)	91	(36)
C TWO PERSONS PASSING OR ABREAST	112	(44)	137	(54)
D THREE PERSONS PASSING OR ABREAST	152	(60)	183	(72)

Figure 7.1-2. Aisle Dimensions (Ref. 2,X)

7.1.3 PASSAGES (CONTINUED)

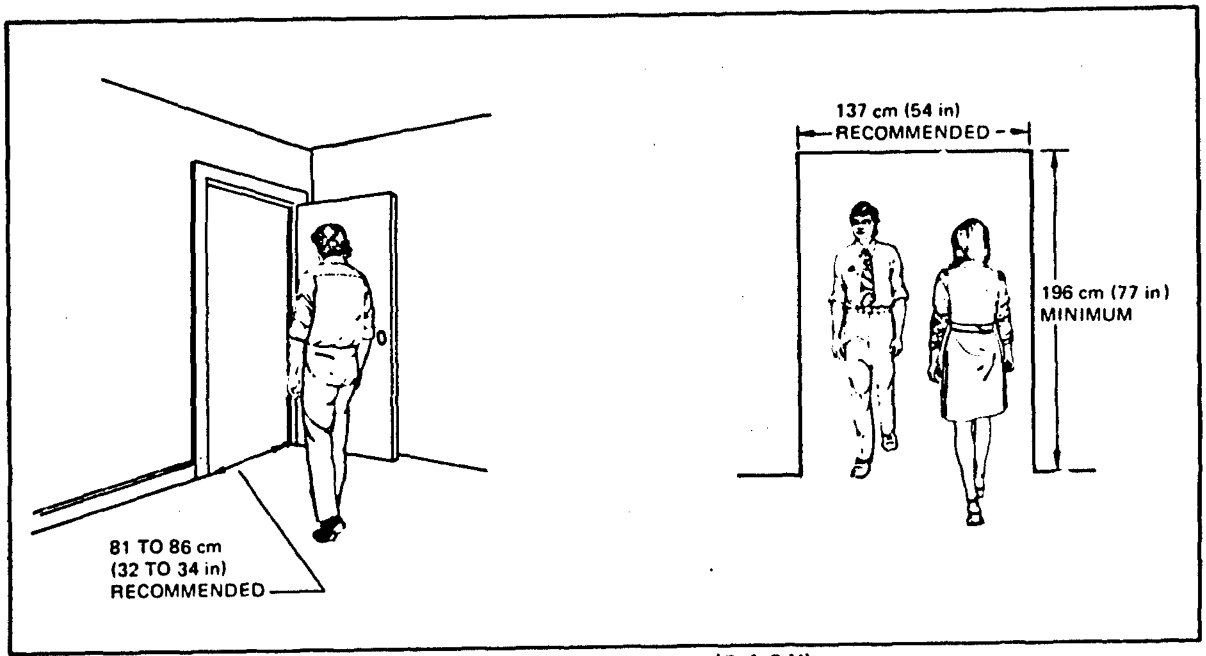


Figure 7.1-3. Doorway Dimensions (Ref. 2,X)

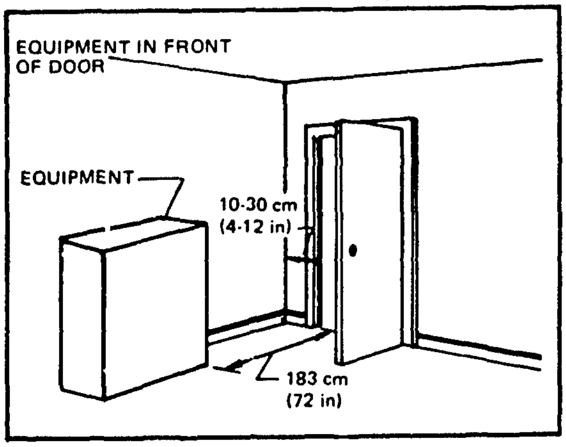


Figure 7.1-4. Clearance Around Doors (Ref. 2,X)

SECTION 7.1 REFERENCES

1. Kidd, J. S. and Van Cott, H. P. System and human engineering analyses. Chapter 1 in Van Cott, H. P. and Kinkade, R. G. *Human Engineering Guide to Equipment Design*. U.S. Government Printing Office, Washington D.C., 1972.

2. Thomson, R. M. Design of multi-man-machine work areas. Chapter 10 in Van Cott, H. P. and Kinkade, R. G. *Human Engineering Guide to Equipment Design*. U.S. Government Printing Office, Washington D.C., 1972.

7.2 CHAIR DESIGN

SECTION 7.2 CHAIR DESIGN

RECOMMENDATIONS:

Provide several chair styles so that the one most suitable for a particular body size and work habits can chosen by each display user.

Use chairs designed generally to the dimensions of Figure 7.2-3.

Provide a chair containing the following features:

- **A backrest that provides lower back support,**
- **Porous upholstery,**
- **A height adjustment that is easy to use, and**
- **An adjustable footrest if the user's feet may not rest on the floor.**

Provide a chair that will accommodate different operator work positions.

Few portions of a workstation have a greater impact on comfort than the operator's chair. It has been suggested, for example, that the proper positions for man are standing up or lying down, and anything in between, primarily sitting, is by necessity a compromise (Ref. 1). Nearly half the adult male population will at some time suffer from lower back pain, and this almost certainly is aggravated by the amount of time spent in a sitting position (Ref. 2).

This section summarizes a number of the factors that should be considered when designing or selecting a chair for use with an imagery display. Since in most instances it will be necessary to select from available designs, it is likely that some compromise will be required. Evaluation by individuals typical of the user population is desirable; these evaluations, however, make a significant contribution only if sufficiently extreme body sizes are considered. Similarly, the responses of individuals known to have mild back trouble or to be especially sensitive to chair design for some other reason, such as poor circulation, are more important than those of young, athletic individuals, who can tolerate almost any design. In addition, proper evaluation of a chair requires it to be used for several hours, not just a few minutes.

Design, or selection, of a chair is complicated by several factors. Users vary widely in body size and in work habits. They also vary in their sensitivity to a poor chair design. Some individuals can sit in almost any style of chair. Other individuals, particularly those with back trouble, will be uncomfortable unless the desig exactly right.

Chairs are so inexpensive, relative to the cost manpower and modern displays, that there is no ex for reducing the efficiency of a display operator forcing him to use a poorly designed chair. In partic when several chairs are being procured, it is possib make provision for variations among operators obtaining several different designs and allowing e operator to chose the one best for him. Unfortunat this benefit is usually lost because of the desires of logistics department to simplify the procurement p cess, and of management to establish a uniform decc each work area.

Two of the principal ways a chair can contribut discomfort are excessive compression of soft portion the body and inadequate support for the lower b These are summarized in Figures 7.2-1 and 7.2-2 bel A number of other factors are also important but are covered in detail here. For example:

- Too long a seat, relative to the length of the u leg, forces the back forward off the back rest.
- Too soft and deep a seat, or too rounded a places part of the support on the outer part of t thigh; this tends to rotate the thighs upward, pla an uncomfortable load on the hip joints (Ref. 1).

The chair adjustment mechanism must be easy to use, even by the smallest, weakest operator. This applies particularly to the vertical adjustment on chairs used with a fixed eyepoint display, where compensation for differences in trunk length must be made with the chair rather than with the display. Observation indicates that when a chair is difficult to adjust, users will tend to suffer in an uncomfortable position rather than struggle to adjust it.

It is essential that the chair seat be upholstered with a porous material in order to avoid problems with perspiration during prolonged use.

The mobility of the chair is important. In most work situations, the operator must frequently move from one display to another or move to text material lying on a nearby desk. This usually involves rotation of 90 to 180 degrees, plus some chair translation. Casters and a rotatable chair are therefore essential. The casters should not be too freewheeling or the chair will tend to roll back from the display whenever the operator rests his elbows on some portion of the display structure.

The chair base should extend toward the rear far enough to eliminate any possibility that the chair will tip over when the user leans back.

If the seat is too high for some user's feet to reach the floor, as with a display that incorporates a fixed eyepoint to floor distance (Section 6.1.2), the operator must be provided with a footrest to support his feet. Footrest height is determined by the seat-to-floor distance limit (K) in Figure 7.2-3. Proper size and horizontal positioning of the footrest has not been well documented. It should be large enough to prevent pressure points on the user's feet, and ideally it should allow some shifting in foot position. The possibility of shoe or stocking damage will be important to some users. The footrest must be convenient to use and not interfere with the free movement of the chair.

In theory, it seems desirable to spring-load a lumbar pad backrest and allow its position to vary to suit the user's needs. Unfortunately, in practice the spring tension is usually inadequate, with the result that the spring-loading causes more muscular tension and discomfort than it eliminates. Spring-loading should generally be avoided unless it includes adequate adjustment capability, and even then it should incorporate a backrest travel limit of 2 to 3 cm (1 in).

The chair should be designed to accommodate the several different positions the typical display operator may assume over a period of time. Some of these will be due to variations in work activity and others simply to his search for comfort. Four typical positions are given below.

- The operator is bent forward at the waist and is looking straight down, as when using a tube magnifier. The lumbar pad provides little if any back support. A significant portion of upper body weight is supported by the arms.
- The operator is bent forward slightly, with his eyes perhaps 30 to 60 degrees below horizontal, as when using a typical microscope, reading text, or writing. The lumbar pad helps maintain spinal curvature (Figure 7.2-1).
- The operator is erect and looking approximately horizontal, as when using a microscope with horizontal eyepieces or looking at a typical screen display. If an upper back support is provided on the chair, it can be used to support a portion of the operator's weight.
- The operator is leaning back in his chair to read material held in his hands, to converse with other personnel, or simply to think. The upper back support and arm rests contribute significantly both to supporting body weight and to maintaining a comfortable position.

Many useful articles on chair design have been published in addition to those discussed in this section (Ref. 3).

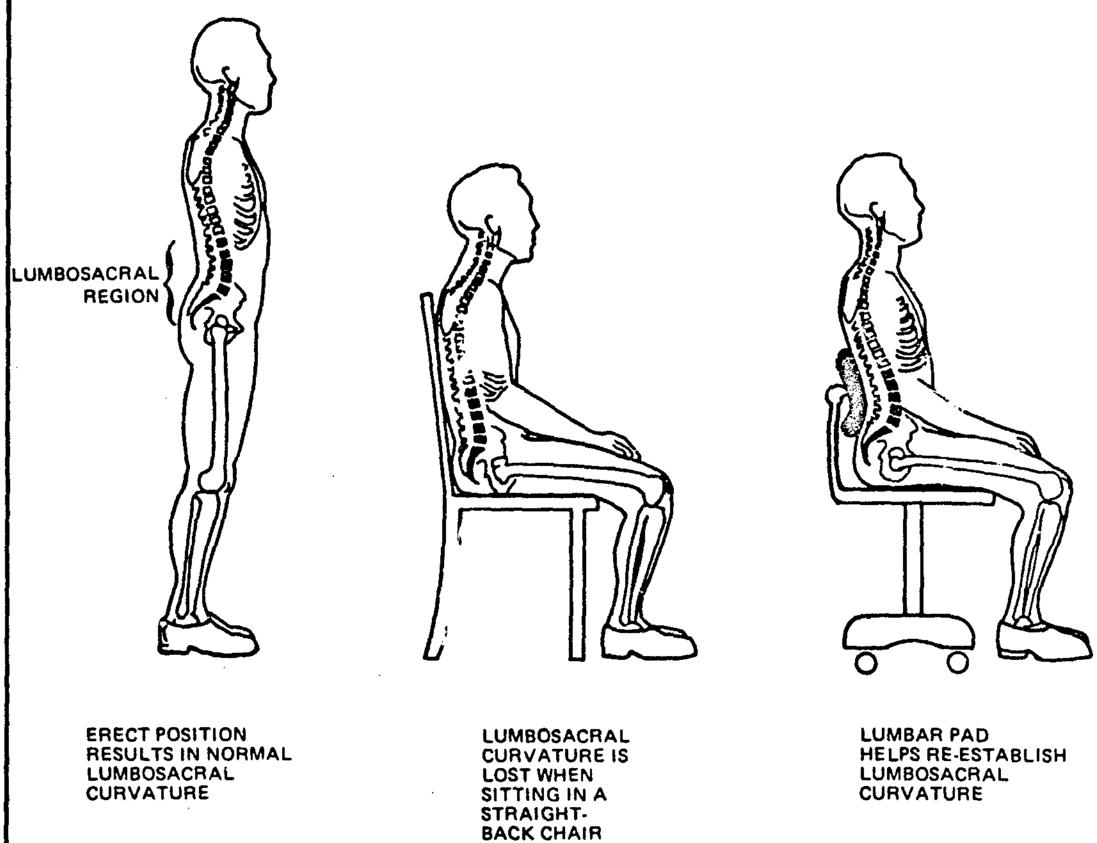


Figure 7.2-1: Curvature of the Lumbosacral Spine (Ref. 4). For most individuals, the lumbosacral portion of their spine has a slight forward curvature when they stand erect. Excessive deviation from this curvature, in either direction, can cause discomfort and pain, or even damage, in the lower back (Ref. 5). A back support in this region, sometimes referred to as a lumbar pad, helps to maintain proper curvature. It can also carry a slight portion of the body weight.

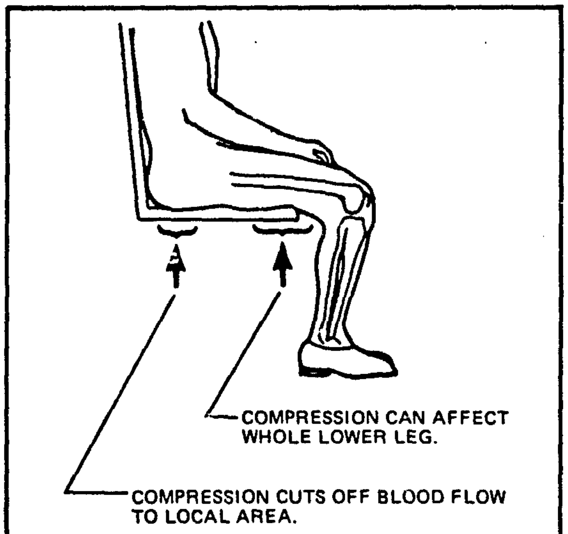


Figure 7.2-2: Excessive Compression by Seat Surface. When the pressure between the seat surface and the body exceeds the blood pressure, the blood vessels collapse and blood flow into that region ceases. This causes discomfort and, if prolonged, pain. With a flat, rigid seat pressures in the buttocks region of approximately 60 times blood pressure have been measured (Ref. 6). Addition of padding reduces maximum pressure by distributi the load over a greater area.

A similar problem occurs in the lower thigh. If the seat too high above the foot support surface, excessive pressure on the thigh anywhere from the knee to the middle of the upper leg can compress blood vessels or even the nerves to the lower leg. Again the result is discomfort or pain, or the sensation that the lower leg is "asleep."

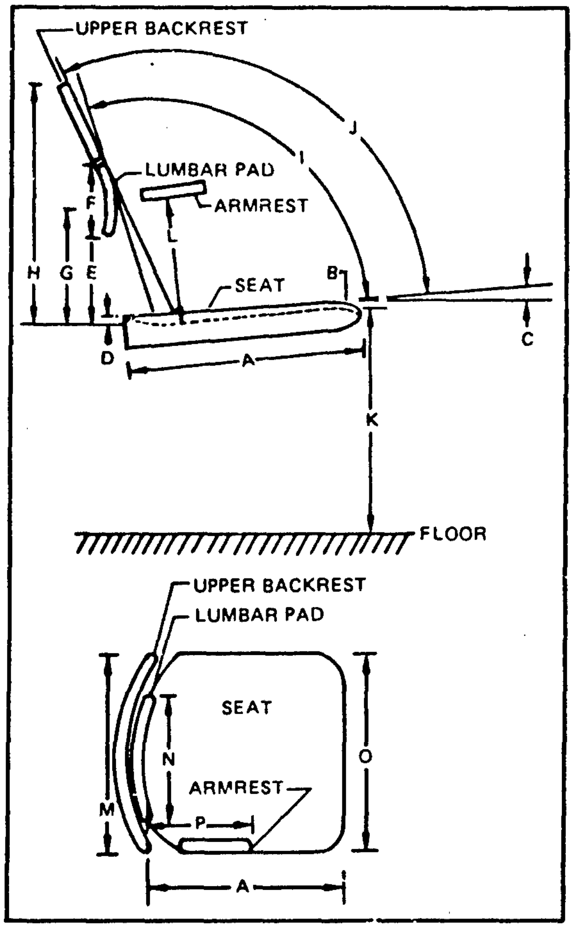


Figure 7.2-3: Chair Dimensions. The best available recommendations for the dimensions of a chair to be used by male and female imagery display operators are summarized here. They are based on nine sources, (Ref. 7), some of which describe original research and some of which are summaries of published research.

A – Seat depth, measured from the forward limit of the lumbar pad to the front edge of the seat should not exceed 43 cm (17 in), with a preferred limit of 41 cm (16 in); a longer seat may prevent some users from sliding back against the backrest.

B – The front edge of the seat should be rounded to reduce pressure on the thighs; unless the seat is thin, the front edge should taper underneath so that the user's lower legs can be swung back beneath the seat; the seat surface should be flat or only very slightly contoured (for a padded seat).

C – The seat should be horizontal or slanted back a maximum of 5 degrees.

D – The seat should be padded so that it compresses 2 to 5 cm (1 to 2 in) when used by an average size individual; elevation measurements are most properly made from the compressed seat surface.

E – The region below the lumbar pad should be open, or at least curved back sharply, to leave room for the portion of the body below the lumbar vertebrae (sacrum) when the lumbar region comes in contact with the backrest. This open or recessed region should extend 12 to 15 cm (5 to 6 in) above the compressed seat, with a minimum value of 10 cm (4 in).

F – The minimum vertical length of the lumbar pad is 12 to 15 cm (5 to 6 in).

G – The forward point of the lumbar pad should be 18 to 20 cm (7 to 8 in) above the compressed seat surface; adjustment over a range of 15 to 25 cm (6 to 10 in) is preferable.

H – The upper backrest should extend at least 46 to 50 cm (18 to 20 in) above the compressed seat surface.

I – In order to maintain proper back curvature, the upper portion of the lumbar pad should make an angle of approximately 105 degrees with the seat surface; a pivot behind the pad is a useful though not absolutely necessary method of adjustment.

J – The upper portion of the backrest should tilt back 105 to 115 degrees; a value approaching the maximum tilt is best for the present application, since it will increase the operator's ability to make use of the lumbar support in the lower portion of the backrest while keeping his arms and shoulders free to work at the light table.

K – Although most fixed height seats are 43 to 46 cm (17 to 18 in) above the floor, a better dimension is 38 to 41 cm (15 to 16 in), since it is easier to accommodate to a seat that is too low than to one that is too high; where eye positioning is critical, adjustment over a range of 36 to 50 cm (14 to 20 in) in increments no larger than 2 cm (1 in) should be possible.

L – The armrest height above the compressed seat surface should be adjustable from 20 to 25 cm (8 to 10 in); if armrest height must be fixed, the preferred value is 25 cm (10 in) (Ref. 8).

M – The upper backrest should be at least 50 cm (20 in) wide; it should have little or no lateral curvature; the minimum radius of curvature is 41 cm (16 in).

N – The lumbar pad should be at least 30 cm (12 in) wide; it should have little or no lateral curvature; the minimum radius of curvature is 19 cm (7 in).

O – The seat should be at least 43 cm (17 in) wide, with a preferred value of 46 to 48 cm (18 to 19 in).

P – If the armrest does not extend more than 19 cm (7.5 in) in front of the forward limit of the lumbar pad, it will not interfere with moving the chair close to the display for any user with a waist thickness greater than that of a 5th percentile male.

1. Diffrient, N. Between standing up and lying down. *The American Way.* Vol. 3, Oct. 1970, pp. 5-8. This is an article on aircraft seats published by American Airlines.

2. The value of half the population is given in Ref. 1, without citation of an original source. Back problems become more common, and more severe, with age, making this an overestimate of the problem for a typical population of young adult interpreters.

3. Grandjean, E. (Ed.) *Proceedings of the Symposium on Sitting Posture.* Zurich, Switzerland, 1968. Taylor & Francis, London, 1969. In addition to considerable test data, this excellent book contains many helpful photographs and drawings.

   Floyd, W. F. and Roberts, D. F. Anatomical and physiological principles in chair and table design. *Ergonomics,* Vol. 2, 1958, pp. 1-16.

   Ridder, C. A. *Basic Design Measurements for Sitting.* Bulletin 616, Agricultural Experiment Station, Univ. of Arkansas, October, 1959.

   Bex, F. H. A. Desk heights. *Appl. Ergonomics,* Vol. 2.3, 1971, pp. 138-140.

4. This figure is adapted from Figures 1 and 2 of Ref. 5.

5. Keegan, J. J. Alterations of the lumbar curve related to posture and seating. *J. Bone and Joint Surgery,* Vol. 35A, 1953, pp. 589-603. This article contains numerous tracings from X-rays of the spines of individuals in different positions, and good diagrams illustrating the mechanics of spinal disc displacement. Chair design recommendations, based on the spinal X-rays, are provided.

6. Hertzberg, H. T. E. *The human buttocks in sitting: Pressures, patterns and palliatives.* Paper 72005, Society of Automotive Engr. (SAE) Automotive Engr. Cong., Detroit, 1972. (Also available as Report AMRL-TR-71-107, Aerospace Med. Res. Lab.)

7. Akerblom, B. Chairs and sitting. *Proc. of the Ergonomics Research Society Symposium on Human Factors in Equipment Design,* Vol. 2, 1954, pp. 29-35.

   Ayoub, M. M. *Posture in Industry.* Unnumbered report, Texas Tech. Univ., 1970.

   Burandt, U. and Grandjean, E. Sitting habits of office employees. *Ergonomics,* Vol. 6, 1963, pp. 217-228.

   Damon, A., Stroudt, H. W. and McFarland, R. A. *The Human Body in Equipment Design.* Harvard Univ. Press, Cambridge, Mass., 1966.

   Dreyfuss, H. *The Measure of Man.* Whitney Library of Design, New York, 1960.

   Grandjean, E., Hunting, W., Wotzka, G. and Scharer, R. An ergonomic investigation of multipurpose chairs. *Human Factors,* Vol. 15, 1973, pp. 247-255.

   Keegan, J. J. Evaluation and improvement of seats. *Industrial Medicine and Surgery,* Vol. 30, 1962, pp. 137-148.

   Kroemer, K. H. E. and Robinette, J. C. *Ergonomics in the Design of Office Furniture–A Review of European Literature.* Report AMRL-TR-68-80, Aerospace Med. Res. Lab., 1968. (Also available as AD 848621.)

   Also, see Ref. 5.

   The recommendations in these nine studies were seldom in complete agreement. The dimensions in Figure 7.2-3 are based on a rough assessment of the validity and relevance of the data supporting each author's recommendations.

8. A fixed armrest height of 20 to 23 cm (8 to 9 in) has been recommended by some authorities but the test data to support this value are not reported and anthropometric data for male and female civilian and military personnel suggest that 10 inches is a better choice. This would require some users to slide their arms forward or to sit with their shoulders somewhat raised, but it should allow nearly everyone to reach the armrest.

7.3 AMBIENT ILLUMINATION

7.3.1 Units

7.3.2 Quantitative Requirements

7.3.3 Spatial Distribution

SECTION 7.3 AMBIENT ILLUMINATION

The term "ambient illumination" includes all sources of illumination except those used to display imagery or as signals. In most cases this means ceiling-mounted light fixtures and desk lamps. The two major requirements imposed on ambient illumination, quantity and spatial distribution, are summarized in Sections 7.3.2 and 7.3.3 below.

The spectral and temporal distribution of the ambient illuminations are also important. For most applications, any common illumination source with a spectral distribution that yields nominally white light is acceptable. Most critical color discrimination will involve comparisons between colors in the imagery being interpreted an colors in reference samples on the same type of film. I this case, the imagery illumination spectral distributio recommendations of Section 3.2.9 apply. If reflectiv materials are used as color references, they should b illuminated by a special limited-area source that mee these same requirements, rather than by the ambien illumination.

Temporal variation in ambient illumination must n result in the sensation of flicker. The factors involved a essentially the same as for display illumination and a discussed in Section 3.2.10.

7.3.1 UNITS

Two terms are used in this section to refer to the quantity of light, *luminance* and *illuminance*. As is discussed in Section 3.2.1, illuminance refers to the quantity of light falling on a given surface area and luminance refers to the quantity of light reflected from or passing through a given surface area and traveling in a given direction.

For surfaces that are nonspecular and diffuse incident light evenly in all directions rather than reflecting it in one direction like a mirror, luminance is determined by the illuminance and the reflectance of the surface. In the preferred International System (SI) units, illuminance in lux multiplied by R/π, or 0.318 R, where R is the reflectance, yields the luminance in candelas per squar meter (cd/m^2, or nits). In the more common Englis units, illuminance in footcandles (fc) multiplied by yields the luminance in footlamberts (fL). The Englis to metric conversion factors are:

- 1 footcandle (fc) = 10.76 lux
- 1 footlambert (fL) = 3.426 cd/m^2

The term "illumination" was formerly used to refer the quantity now known as illuminance. The prefer usage, which is followed in this document insofar possible, is to use the term "illumination" to refer to process, rather than a quantity (Ref. 1).

7.3.2 QUANTITATIVE REQUIREMENTS

RECOMMENDATIONS:

In rooms where imagery displays are used, provide general illuminance of approximately 330 lux (30 fc); the preferred value is 55 to 550 lux (5 to 50 fc), adjustable by the user.

On areas such as a desk, where the display user reads printed material or writes reports, provide an illuminance of approximately 550 lux (50 fc); preferred value is 110 to 1100 lux (10 to 100 fc), adjustable by the user.

Do not allow the luminance resulting from these two recommendations to exceed the maximum display image luminance available when imagery of typical density is being viewed.

On areas used for viewing paper prints that serve as reference material, provide an illuminance of approximately 2750 lux (250 fc); the preferred value is 550 to 5500 lux (50 to 500 fc), adjustable by the user.

Unlike the situation with imagery displays discussed in Section 3.2.6, there is no shortage of highly authoritative recommendations for the illuminance that should be provided in almost any work environment (Ref. 2). Some of these are summarized in Figures 7.3-1 and -2. These recommendations have on occasion been challenged as excessive (Ref. 3), perhaps more because they have usually been made by individuals and organizations supported by the lighting industry than because good test data exist to refute them (Ref. 4). Given the available test data, they are probably as reasonable as any such general recommendations can be.

The quantitative requirements imposed on ambient illumination have been developed from much of the same data that is summarized in Section 3.2.6.1, and the summary statements made at the beginning of that section apply here also:

- Over a limited range, visual performance increases with the illuminance provided.
- After a certain point, each successive increase in illuminance on the visual task yields a successively smaller increment in visual performance; once an adequate performance level is achieved, the cost of sufficient light to improve performance further may not be justified.
- The illuminance necessary for maximum visual performance increases with task difficulty; for example, maximum performance in reading large, high-contrast printed text will occur at a much lower illuminance than will maximum performance reading the same text if it is small and has very low contrast.

It is important to keep these facts in mind when designing a lighting environment, and to remember that the spatial distribution of the light can be as important as the amount. Spatial distribution is discussed in Section 7.3.3

If the luminance viewed by the display user near the display differs considerably from the display image luminance, the display user will require a brief interval to *adapt* to the new luminance each time he shifts to or away from the display. (See the two paragraphs immediately preceding Figure 3.2-52.) Therefore, the ambient illuminance should yield a luminance in this area approximately equal to the display image luminance when imagery of typical density is being displayed. In practice, it is usually necessary to reduce the luminance of most areas near the display well below this level in order to eliminate reflections (Sections 7.3.3 and 4.4.2).

7.3.2 QUANTITATIVE REQUIREMENTS (CONTINUED)

AREA	IES RECOMMENDED LUMINANCE	
	lux	fc
DRAFTING ROOMS		
DETAILED DRAFTING AND DESIGNING,	2200	200
CARTOGRAPHY	1600	150
ROUGH LAYOUT DRAFTING	1600	150
ACCOUNTING OFFICES		
AUDITING TABULATING, BOOKKEEPING, BUSINESS MACHINE OPERATION, COMPUTER OPERATION	1600	150
OFFICES		
READING POOR REPRODUCTIONS, BUSINESS MACHINE OPERATION	1600	150
READING HANDWRITING IN HARD PENCIL OR ON POOR PAPER, READING FAIR REPRODUCTIONS	1100	100
READING HANDWRITING IN INK OR MEDIUM PENCIL ON GOOD QUALITY PAPER	750	70
READING HIGH-CONTRAST OR WELL-PRINTED MATERIALS	330	30
CONFERRING AND INTERVIEWING	330	30
CONFERENCE ROOMS		
CRITICAL SEEING TASKS	1100	100
CONFERRING	330	30
NOTE-TAKING DURING PROJECTION (VARIABLE)	330	30
CORRIDORS	220*	20*

*ILLUMINANCE IN CORRIDORS SHOULD BE AT LEAST 20 PERCENT OF THE ILLUMINANCE IN ADJOINING AREAS

Figure 7.3-1: IES Recommended Office Illuminance. This chart summarizes the current (1973) Illuminating Engineering Society (IES) recommendations for ambient illuminance in offices (Ref. 5). The numbers given here are intended to be increased if there is sufficient glare or veiling luminance present to reduce visibility (Ref. 6). This should not occur in a well-designed imagery display work area. (See Section 7.3.3.)

7.3.2 QUANTITATIVE REQUIREMENTS (CONTINUED)

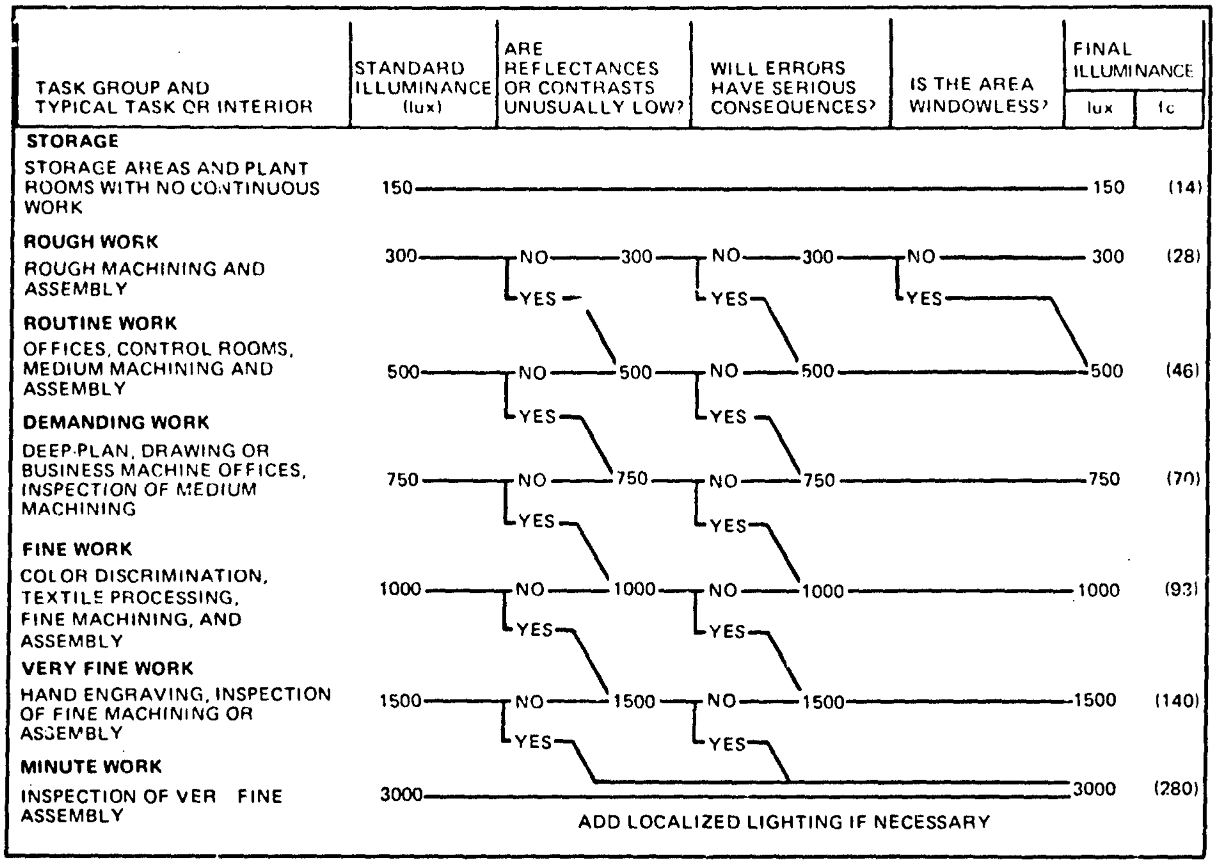


Figure 7.3.2: Impact of Working Conditions on Required Illuminance. This flow chart shows one published scheme for using work conditions to determine ambient illuminance requirements (Ref. 7). Many of the concepts embodied in this chart were used to derive the values in Figure 7.3-1.

This chart is included here to show relative effects, not as a set of specific design recommendations.

7.3.3 SPATIAL DISTRIBUTION

RECOMMENDATIONS:

Provide the maximum illuminance in the primary visual work area. Make the remainder of the visual environment slightly darker and fairly uniform. The following actions are helpful in eliminating extremely bright and dark areas:

- **Direct the light from any luminaire within the visual field of the display user downward onto the wor surface where it is required, rather than into his eyes (Figures 7.3-4 and -6).**
- **If light from a luminaire strikes a wall or similar surface, reduce the reflectance of the wall to the point where the wall luminance is not objectionable.**
- **Eliminate specular surfaces that might provide an image of a high luminance area such as a luminaire c illuminated wall; or, if this is not possible, eliminate the high luminance area (Figures 7.3-4, -5, and -6)**
- **Eliminate large, extremely dark areas close to the immediate visual work area; for example, replace a dark surfaced desk with one that has a reflectance slightly less than is typical for white paper.**

The spatial distribution of light in the work environment can be almost as important as the quantity. As the recommendations in this section indicate, the goal is to eliminate extremely bright and extremely dark areas that can act as a source of glare or produce a distracting contrast close to the visual work area.

Typical recommendations for the reflectance surfaces in offices and similar work spaces are as follows (Ref. 8):

- Ceiling finish–80 to 92 percent (integrated reflectance may be somewhat lower for acoustic materials).
- Walls–40 to 60 percent
- Furniture and equipment–26 to 44 percent
- Floors–21 to 39 percent

Excessively dark areas can be as troublesome as excessively bright ones. At one time, dark tops were common on office desks. The resulting high contrast at the edge of the white paper that contained the user's visual task was distracting and led to the use of much lighter surfaces. Desk surfaces with reflectances equal to that of white paper were also evaluated, but were found to be less desirable, apparently because they tended to obscure the edge of the sheet of paper being viewed (Ref. 9).

As was discussed in Section 3.2.12, glare results both from a large surround area that has a much different luminance than the visual work area and from a small area that is extremely intense. In the latter situation, the glare effect is a function of the product of the luminan and the apparent area of the intense source; this produ is equivalent to the photometric quantity *lumino intensity* and provides a measure of the quantity of lig reaching the eye. The glare effect of a small source also directly related to the proximity of the source the visual work area. A limiting distance from the vis axis of 30 to 45 degrees is sometimes given (Ref. 10).

These recommendations are intended to provide a fai uniform luminous environment. If specular surfac such as directly viewed film, the front surface of a re projection screen, or a cathode ray tube are present, may be more important to reduce reflections by maki the room quite dark, rather than just a little darker th the image in the imagery display. If printed mater must also be viewed, limited area illumination sour such as desk lamps or highly directional ceiling lu naires such as those described in Figures 7.3-5 and must be provided.

A considerable amount of material has been written making the luminous environment uniform. One use source, the *IES Handbook* (Ref. 11) also includes quantitative approach developed by that group. addition to being more than slightly complicated, i not obvious exactly how this technique should applied in a work environment involving imagery plays, where one of the most important consideratio elimination of reflections.

7.3.3 SPATIAL DISTRIBUTION (CONTINUED)

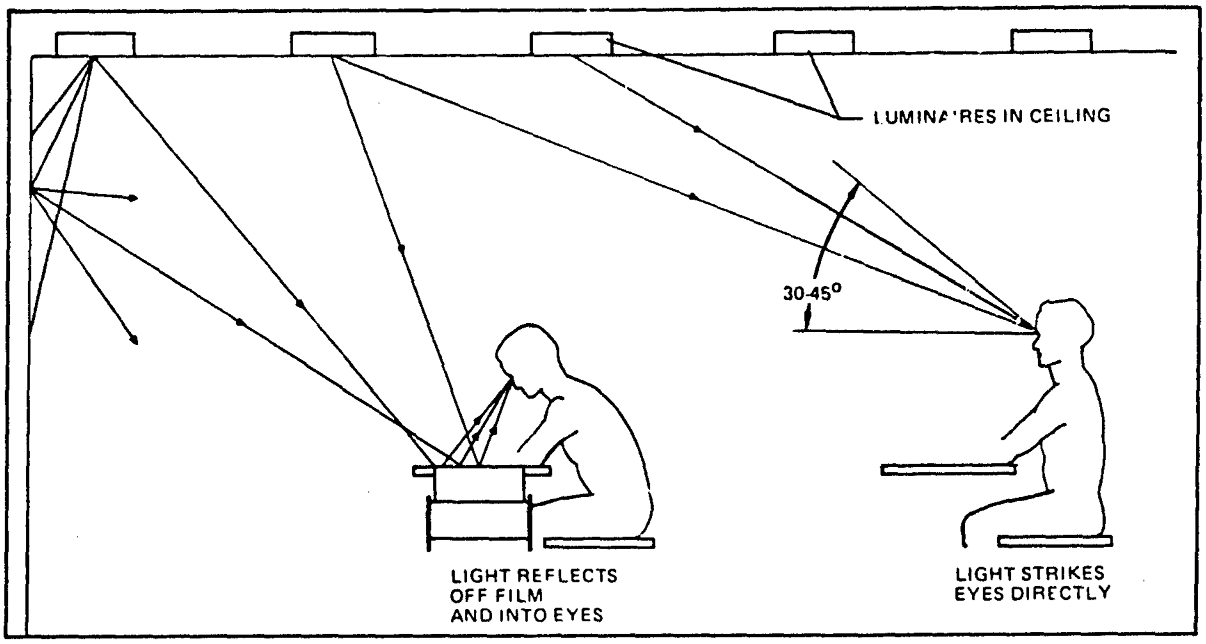


Figure 7.3-3: Glare From Ceiling Luminaires. Light from ceiling luminaires can strike the display user's eyes directly or after reflection from a specular surface such as film, a rear projection screen, or a cathode ray tube. If this light reaches the eye from within 30 to 45 degrees of the line of sight, it acts as glare and it can be annoying and reduce visual performance (Section 3.2.12, Ref. 10) If it is from a reflection located on the line of sight, it also constitutes a veiling luminance that reduces the luminance of the image being viewed (Section 3.2.13).

Although it is not included in this illustration, light reflected from walls or from other surfaces in the work area can cause the same problems as light coming directly from a luminaire.

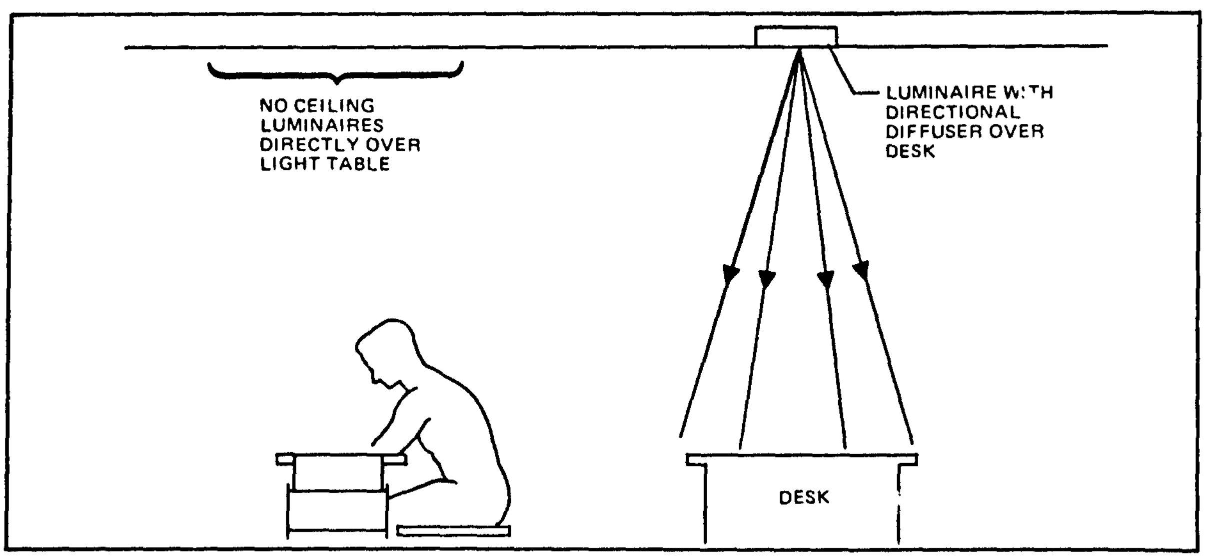


Figure 7.3-4: Elimination of Glare by Use of Collimated Luminaires in Selected Locations. One approach to reducing both direct and reflected glare is to eliminate ceiling luminaires over the light table and use highly collimated luminaires over desks and similar areas where printed material must be viewed. An alternative is to eliminate all ceiling luminaires and provide desk lamps where they are needed.

7.3.3 SPATIAL DISTRIBUTION (CONTINUED)

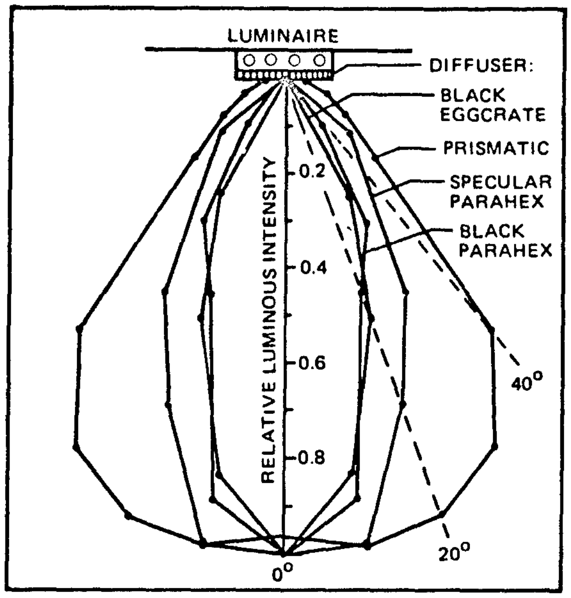


Figure 7.3-5: Light Distribution for Four Diffusers. Diffusers used with common 40-watt fluorescent lamp luminaires vary widely in the extent to which they spread light or direct it downward. Relative *luminous intensity* measurements made on four diffusers are shown here in polar coordinate form, much as they appear in the *IES Handbook* (Ref. 12) or a manufacturer's data sheet (Ref. 13,C). The four diffusers are (Ref. 14):

- Prismatic—A typical translucent plastic diffuser with a raised prismatic pattern on the lower surface
- Specular Parahex—A hexagonal grating with a mirroı finish; the inner surface of each hexagonal opening i: curved to limit spreading of the light
- Black Parahex—Specular Parahex painted flat black
- Black Eggcrate—A 12-mm (0.5-in) square, 12-mm (0.5-in) thick grid, painted flat black

As the figure illustrates, the best diffusers for limiting light to a small area such as a desk are the two painted black; the specular Parahex is the next best choice. All three provide considerable improvement ov the prismatic diffuser.

If it is essential to minimize luminaire energy consump tion, the specular Parahex may be the better choice. T maximum luminous intensity for this diffuser, relative the maximum for the prismatic diffuser, was 0.90, ver only 0.55 for the black Parahex and 0.65 for the black eggcrate.

7.3.3 SPATIAL DISTRIBUTION (CONTINUED)

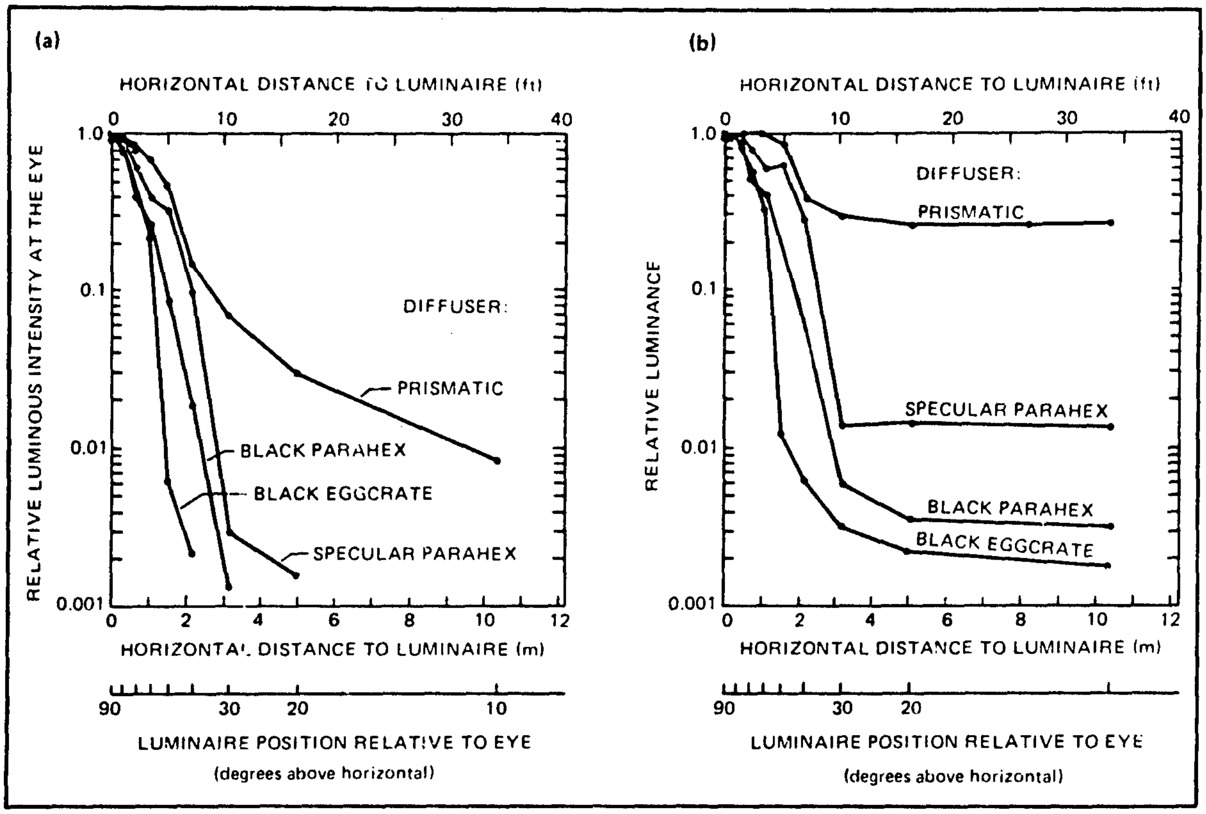


Figure 7.3-6: Glare and Luminance for Four Diffusers. The relative amount of glare caused by each of the four diffusers described in the previous figure is shown here as a function of the horizontal distance to the luminaire. The luminaire is assumed to be 2m (6 ft) above eye level and the luminaire is assumed to be 0.6m (2 ft) wide.

The bottom scale shows luminaire position expressed as angular distance above horizontal. Assuming a horizontal line of sight, and that a glare source is significant within 30 to 45 degrees of the line of sight, the luminaire would be a potential source of glare when it was further than 2 to 4m (6 to 12 ft) away.

Part (a) of this figure shows relative *luminous intensity* and therefore provides the best indication of the glare caused by the luminaire. Comparing the four diffusers at an angle of 30 degrees or less above horizontal, the prismatic diffuser causes at least 10 times as much glare as any of the other three. If this comparison is made at 45 degrees, the specular Parahex is only slightly better than the prismatic diffuser.

Another way of comparing the four diffusers is to assume that the display user looks directly at the luminaire. In this case, his eyes adapt to the luminance of the luminaire, which should not be much greater than the luminance of the image in his display (see the discussion of glare in Section 3.2.12). Part (b) of this figure shows the relative luminance of the luminaire. The luminance of a typical fluorescent lamp luminaire, viewed from directly below, might be from 1700 to 5000 cd/m^2 (500 to 1500 fL), and a desirable value for the display user to view might be 1 to 2 percent of this. Again the black eggcrate is the most effective diffuser, with the black Parahex and specular Parahex following in that order.

SECTION 7.3 REFERENCES

1. Meyer-Arendt, J. R. *Introduction to Classical and Modern Optics.* Prentice-Hall, Englewood Cliffs, New Jersey, 1972.

2. Kaufman, J. E. and Christensen, J. F. (Ed.) *IES Lighting Handbook* (5th ed.) Illuminating Engineering Society, N York, 1972. This handbook is revised every 5 years or so. Section 9 contains illuminance recommendations. Much the recent evolution of these recommendations can be traced by working back through the Blackwell references cited in Section 3.

3. Weston, H. C. Rationally recommended illumination levels. *Illum. Engr. Soc. Trans.*, Vol. 26, 1961, pp. 1-16.

   Faulkner, T. W. and Murphy, T. J. Illumination: A human factors viewpoint. 15th Annual Meeting of the Human Factors Society, October, 1971, New York.

   Also, see Ref. 4.

4. Ringgold, P. C. In the interest of illumination—An IES editorial. *Lighting Design and Application,* Vol. 2, Novem 1972, pp. 1a-6a. This is a vigorous defense of the Illuminating Engineering Society (IES) approach to establishing recommended illuminance levels. It does not directly address the criticisms presented in 7.3-3.

5. See Figure 9-80, page 9-87 of Ref. 2.

6. Techniques to determine the illuminance increase necessary to correct for glare or veiling luminance appear on pa 3-17 to 3-23 of Ref. 2 and in the references below. Their use will not be obvious to the casual reader.

   A Unified Framework of Methods for Evaluating Visual Performance Aspects of Lighting. Publication CIE No. 1 (TC.3.1), The International Commission on Illumination (CIE), Paris, 1972.

   Blackwell, H. R. The evaluation of interior lighting on the basis of visual criteria. *Appl. Optics,* Vol. 6, 1967, pp. 1443-1467. This is an early summary of the principles involved.

7. Collins, J. B. The IES Code 1973. *Light and Lighting and Environmental Design,* Vol. 66, No. 2, February 1973, 36-39. The author was chairman of the committee that derived the illuminance recommendations in Ref. 2.

8. See Figure 11-9 of the fourth edition of Ref. 2.

9. Oetting, R. L. *Thesis on Reflectance Recommendations.* University of Wisconsin, 1948. Partially reprinted as: C walls be too bright?, *Lighting Design and Application,* Vol. 1. December 1971, pp. 30-33.

10. Section 11 of the fifth edition of Ref. 2 suggests that glare is important within about 30 degrees of the line of sig while the fourth edition uses a value of 45 degrees.

11. See Ref. 2, particularly Section 3.

12. See the front part of Section 9 in Ref. 2.

13. Gane, M. *Specialized Partial Collimated Lighting Systems Test Report.* Document D2-114112-1. The Boeing Com pany, Seattle, Washington, 1967. This is the laboratory test report from which the data in Figures 7.3-5 and -6 w extracted.

    Kraft, C. L., Decker, T. A. and Booth, J. M. *Improved Lighting Systems for Image Interpreters Work Spaces.* Doc ment D2-114125-1. The Boeing Company, Seattle, Washington, 1967. This report analyzes lighting systems utiliz diffusers of the type represented in Figures 7.3-5 and -6 in terms of their impact on the interpreters' visual enviro ment and their (1967) cost.

14. The four diffusers were:

Prismatic – Stock No. 12478U2, Lightolier, Inc., Jersey City, New Jersey. A solid sheet of plastic, approximately 0.7 by 1.3m (2 by 4 ft) in size. Probably similar to the diffusers on Luminaires 3 and 7, Figure 9-4 in the fourth edition of Ref. 2.

Specular Parahex – Stock No. PHS 684-4SRS, Globe Illumination Co., Gardenia, Calif. A plastic mirror-finish grid. The hexagonal grid openings are smaller at the top than at the bottom, and are vertically curved to limit the angular area illuminated, much as the following article: Dobras, Q. D. and Phillips, D. R., Designing low brightness luminaires for higher lighting levels. *Illum. Engr.*, Vol. 54, October 1959, pp. 627-633.

Black Parahex – Specular Parahex, painted flat black, paint No. TT-E-527B, on inner surfaces and on the bottom, but not on the top surface.

Black Eggcrate – Part No. 8351, Plastic Louver Suspended Ceiling Panel, Sears, Roebuck and Co. A plastic grid, 13 mm (0.5 in) thick, with 13 mm (0.5 in) square openings. Painted flat black, paint No. TT-E-527B, on all surfaces.

7.4 AIR CONDITIONING

7.4.1 Ventilation

7.4.2 Temperature

7.4.3 Relative Humidity

NOTE: Because this entire section consists of recommendations, they are not listed separately here.

Air conditioning is required to remove objectionable impurities from the air and to maintain the temperature, humidity, and airflow rate within acceptable limits. The values given here are based primarily on military human engineering standards (Ref. 1), and one summary paper on thermal comfort (Ref. 2). More complete treatment of thermal comfort is available (Ref. 3), and more extensive standards are available in the publications of the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) (Ref. 4).

7.4.1 VENTILATION

The amount of air introduced to a work area depends on the number of persons present and on their work activity. The recommended amount of air for adults engaged in moderate physical activity ranges from 0.14 to 0.85 m^3 (5 to 30 ft^3) per minute per person, with approximately two-thirds of this consisting of new, outside air (Ref. 5).

Air velocity past individuals should be between 3 and 20m (10 and 65 ft) per minute. Higher velocities may cause personnel to feel a draft, and lower ones may cause complaints of stuffiness (Ref. 2).

7.4.2 TEMPERATURE

The preferred temperature varies with relative humidity, so it is common to combine the two into an effective temperature, ET. To be even more precise, one can also include airflow velocity and wall temperature in the determination of effective temperature (Ref. 2).

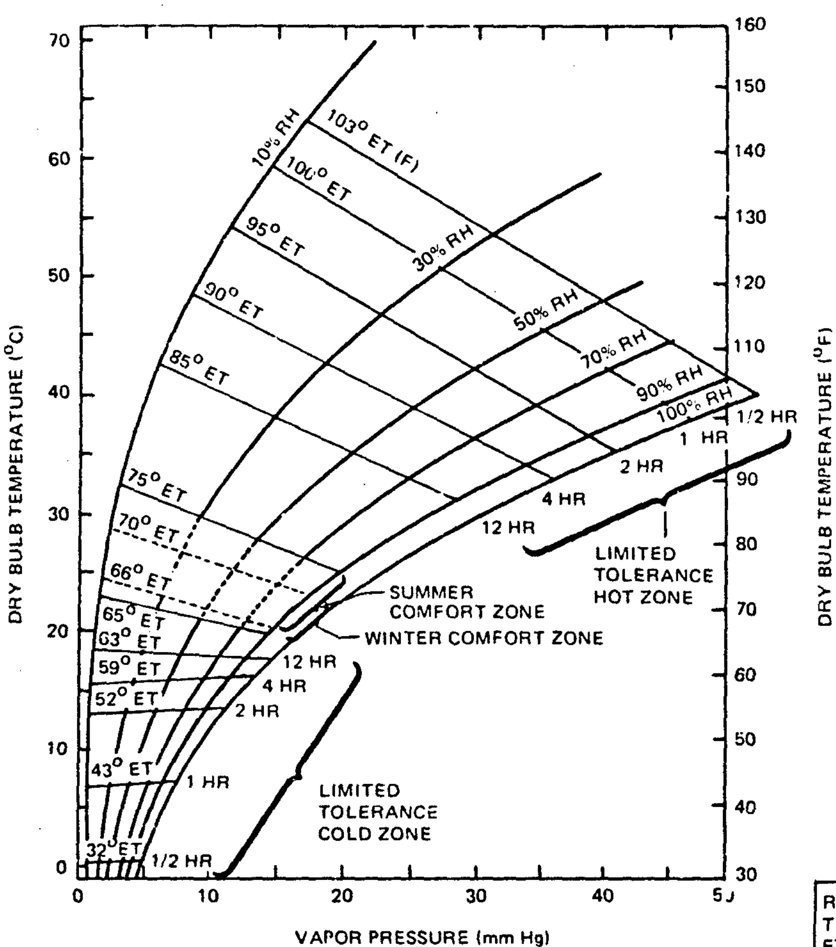
Preferred temperature apparently does not vary from summer to winter, so long as the insulation value of the clothing worn by the individuals being tested is held constant (Ref. 2). However, since individuals tend to wear lighter clothing during hot summer weather, higher temperatures are acceptable. The desire to reduce energy consumption may also make temperatures closer to outdoor temperatures more acceptable, but there are no known test data available.

As Figure 7.4-1 illustrates, the preferred effective temperature is 18.3 to 21.1°C (65 to 70°F) in the winter and 18.9 to 23.9°C (66 to 75°) in the summer (Ref. 1,X).

In some buildings, a reduction in the energy required for summer cooling can be achieved by using cool night air to remove some of the heat from the interior of the building and by allowing the temperature to rise several degrees throughout the day. It is not known if personnel tolerance limits for temperature variations of this kind have been published.

The temperature should be relatively uniform throughout the work area. A maximum variation, measured from floor to head level, of 5.5°C (10°F) has been suggested (Ref. 1,X).

7.4.2 TEMPERATURE (CONTINUED)



EFFECTIVE TEMPERATURE	
°C	°F
39.4	103
37.8	100
35.0	95
32.2	90
29.4	85
23.9	75
21.1	70
18.9	[illegible]
18.3	65
17.2	63
15.0	59
11.1	52
6.1	43
0.0	32

ASSUMPTIONS:

Sitting person dressed in conventional clothing (insulation value = 1 clo) doing light manual work

Air motion equals 60 m/min (200 ft/min) for tolerance zones and 6 m/min (20 ft/min) for comfort zones.

CONVERSION OF FAHRENHEIT TO CENTRIGRADE: (Celsius) $T_C = \frac{5}{9}(T_F - 32)$

RH	=	Relative humidity
T	=	Temperature
ET	=	Effective temperature (°F)
C	=	Centrigade (Celsius)
F	=	Fahrenheit
HR	=	Hour

Figure 7.4-1: Thermal Comfort and Tolerance Zones (Ref. 1,X). This figure illustrates the region of thermal comfort, and the tolerance times outside this zone, for a seated person wearing conventional office clothing and performing light manual work. Air velocity in the comfort zone is 6m (20 ft) per minute. In the tolerance zones it is 60m (200 ft) per minute.

7.4.3 RELATIVE HUMIDITY

The preferred value for relative humidity is 45 to 50 percent; the acceptable range is 35 to 65 percent (Ref. 1, 2,X). A relative humidity below 15 percent will dry the eyes, skin, and respiratory tract sufficiently to cause discomfort, while values over 70 percent can lead to mold growth and condensation on cool surfaces.

SECTION 7.4 REFERENCES

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2. McIntyre, D. A guide to thermal comfort. *Appl. Ergonomics*. Vol. 4.2, 1973, pp. 66-72.

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SECTION 8.0
GLOSSARY

SECTION 8.0 GLOSSARY

This section contains definitions of many of the terms used in the handbook. In some instances, more complete treatment of a term appears where it is defined or explained in the text of the handbook, or in the references following each section. Figure 8.0-1 summarizes the conversion factors used in the text. Rounding errors will occasionally cause small deviations from the values shown here. Figures 8.0-2 and -3 list the symbols, acronyms and abbreviations that appear in the text separated from their definitions.

DISTANCE:

1 meter (m)	= 10^2 centimeters (cm)	= 10^3 millimeters (mm)
	= 10^6 micrometers (μm)	= 10^9 nanometers (nm)
	= 10^{10} Angstrom (A°)	
1 inch (in)	= 2.54 centimeters (cm)	= 25.4 millimeters (mm)

FORCE:

1 gram (g)	= 0.0352 ounce (oz)	= 0.0022 pound (lb)
1 lb	= 16 oz	= 453.6 g
1 dyne	= 10^{-5} newtons	= 0.00102 gram (or more correctly, gram weight)

TORQUE:

1 gram-meter (g-m)	= 1.39 ounce-inches (oz-in)	= 0.087 pound-inch (lb-in)
1 kilogram-meter (kg-m)	= 7.23 pound-feet (lb-ft)	

POWER:

1 watt (W)	= 1 joule (J) per second	
1 horsepower (hp)	= 550 foot-pounds per second	= approximately 745.7 watts

$P = VI = V^2/R = I^2R$, where P = power in watts,
V = potential in volts, I = current in amps and R = impedance in ohms.

ILLUMINANCE:

1 lux	= 0.0929 footcandle (fc)
1 fc	= 10.76 lux
E	= AL, where E is retinal illuminance in trolands (Td), A is pupil area in square millimeters (mm^2) and L is scene luminance in candela per square meter (cd/m^2) (See Section 3.2.2.)

LUMINANCE:

1 cd/m^2	= 0.292 fL	= 0.314 mL
1 fL	= 3.426 cd/m^2	= 1.076 mL
1 mL	= 0.929 fL	= 3.183 cd/m^2

(cd/m^2 = candela per square meter, or nits; fL = footlambert; mL = millilambert)

TYPE SIZE:

1 point	= 0.35 mm	= 0.0138 in

Figure 8.0-1. Conversion Factors

A, B, C, D, X	=	(when following a reference) a reference rating; described in Section 1.4
C_m, C_l, C_d	=	contrast as defined in Figure 3.1-10
cd/m^2	=	candelas per square meter
cm	=	centimeter
D	=	diopter
dB	=	decibel
dBA	=	sound pressure level in decibels weighted according to curve A in Figure 6.6-4
E	=	illuminance
fc	=	footcandle
fL	=	footlambert
ft-lb	=	foot pound (work)
g	=	gram
g-m	=	gram meter (torque)
Hz	=	Hertz
I	=	intensity
in-oz	=	inch ounces (work)
J	=	joule
^oK	=	degrees Kelvin
KHz	=	kilohertz
kV	=	kilovolts
m	=	meter
mA	=	milliampere
mg	=	milligram
MHz	=	megahertz

Figure 8.0-2. Symbols

min	=	minutes
mJ	=	millijoule
m·Kg	=	meter kilogram (work)
mm	=	millimeter
mW	=	milliwatt
n	=	index of retraction
nits	=	candelas per square meter
nm	=	nanometer
N/m^2	=	newtons per square meter
nsec	=	nanosecond
oz·in	=	ounce inches (torque)
R	=	megabaud; reflectance; numerator of remainder from an arithmetical division
R_λ	=	spectral reflectance
Sinc	=	$\frac{\sin x}{x}$
T	=	transmittance
T_λ	=	spectral transmittance
Td	=	troland
W	=	watts
X, Y, Z	=	CIE primaries
X, Y, Z	=	tristimulus values for X, Y, and Z primaries
$\bar{x}, \bar{y}, \bar{z}$	=	spectral tristimulus values
$\bar{x}_\lambda, \bar{y}_\lambda, \bar{z}_\lambda$	=	spectral tristimulus values for a specific wavelength, λ
x, y, z	=	chromaticity coordinates
λ	=	wavelength
μA	=	microamperes
μm	=	micrometers
μsec	=	microseconds
μwatt	=	microwatts
σ	=	standard deviation

NOTE: This list includes only those symbols not defined on the page where they are used.

Figure 8.0-2. Symbols (Continued)

ANSI	=	American National Standards Institute
bit	=	Binary digit
CCDI	=	Color contrast discrimination index
CFF	=	Critical flicker frequency, critical fusion frequency, critical frequency for fusion.
CRI	=	Color rendering index
CRT	=	Cathode ray tube
DPCM	=	Differential encoded pulse code modulation
IEEE	=	Institute of Electrical and Electronics Engineers, Inc.
IPD	=	Interpupillary distance
LBR	=	Laser beam recorder
LCD	=	Liquid Crystal Display
LED	=	Light emitting diode
M	=	Magnification
MAN-1	=	Trade name for a seven-segment LED
MTF	=	Modulation transfer function
NA	=	Numerical aperture
NC	=	Noise criterion curves
NCA	=	Noise criterion curves, alternate
NTSC	=	National Television Standards Committee
OSHA	=	Occupational Safety and Health Administration
PCM	=	Pulse code modulation
PNL	=	Perceived noise level
PSIL	=	Preferred-frequency speech interference level
RETMA	=	Radio-Electronics-Television Manufacturers Association
rms	=	root mean square
RPA	=	Resting point of accommodation
SIL	=	Speech interference level
SNR	=	Signal-to-noise ratio
SPL	=	Sound pressure level
SP_{ref}	=	Reference sound pressure level
TV	=	Television
UCS	=	Uniform chromaticity scale

NOTE: This list includes only those acronyms and abbreviations not defined on the page where they are used.

Figure 8.0-3. Acronyms and Abbreviations

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Aberration: Any deviation from perfect reproduction so that a point is not imaged as a point, a straight line as straight, or an angle as an equal angle.

Absorption coefficient: The fraction of the incident intensity absorbed per unit thickness of a transmitting medium.

Accommodation (visual): Specifically, the dioptric adjustment of the eye to attain maximal sharpness of the retinal image for an object of regard. Focusing of the eye.

Accommodative amplitude: The difference, expressed in diopters, between the farthest point and the nearest point of accommodation with respect to the spectacle plane, the entrance pupil, or some other reference point of the eye.

Accuracy: The degree to which the average of a set of measurements agrees with the true value.

Achromatic color: Sensory or perceptual components possessing a brightness level but no hue; white, gray, and black.

Achromaticness: Brightness or lightness (see achromatic color).

Actinic: Pertaining to wavelengths of radiant energy which produce chemical changes, especially those beyond the violet end of the visual spectrum.

Action spectrum: A curve showing the relative spectral effectiveness of radiant energy in causing undesirable effects.

Active portion (TV line): The portion of the time allotted to a single active TV line which is not devoted to horizontal retrace; approximately 83 percent for most current displays.

Active TV lines: The number of lines actually scanned on the photosensitive element of the camera or the CRT phosphor in a single frame, in distinction to the total number of scan periods per frame, including those needed for vertical retrace.

Adaptation (to light or dark): The adjustment, occurring under changes in illumination, in which the sensitivity to light (or light threshold) is increased or reduced.

Additive color: Superposition or other nondestructive combination of light of different chromaticities.

Aerial image displays: An image, especially a real image, formed by an optical system but perceived by alignment of the viewing eye with the path of light emerging from the optical system, instead of being focused first as an image on a receiving screen. Typical aerial image displays are the microscope, or a screen viewed with a magnifier.

Airy disc: The bright diffuse spot of light, surrounded by a series of concentric dark and light rings, that makes up the image of a point source of light in a diffraction limited display.

Aliasing: In communications theory, the generation of spurious signals caused by sampling a signal at a rate lower than twice its frequency. In electro-optical imaging devices, the sampling rates refer to the spatial frequencies of the scene on the photosensor. Aliasing in these systems can result in the creation of artificial spots, gradients, or patterns in the imagery.

Alignment (of images): The positioning of images one to the other in binocular viewing, expressed in units of visual angle.

Alternate noise criterion (NCA) curve: A set of curves which specify noise limits at each of eight octave bands (illustrated in Figure 6.6-10). These curves differ from noise criterion (NC) curves in that an increase in the noise level of the lower frequency octaves is allowed.

Ambient illumination: Light from the surroundings, as opposed to light from the display itself.

Anaglyph: Two related photographs or drawings, superimposed and laterally displaced, each outlined in a color complementary to that of the other (usually in red and blue-green) to be viewed through filters of the same colors, one to each eye. If the corresponding parts of the drawings have been properly displaced, or the photographs are of a single scene taken from two directions, when properly fused the anaglyph will give rise to the percept of relief or stereopsis.

Analog signal: A signal that is solely dependent upon magnitude to express information content. Generally continuously variable in strength between specified limits, as opposed to a digital signal which can only assume discrete values.

Anamorphic magnification: Magnification in a single direction perpendicular to the optical axis, so that the image appears to stretch in one dimension.

Angular subtense: The angle formed by the linear extent of some dimension of an object with the eye at the vertex.

Aniseikonia: A relative difference in size and/or shape of the ocular images. It can be measured by using an instrument to present a different object to each eye and measuring the relative difference in the visual angles which causes the objects to appear equal in size, or equal in distance from the point of binocular fixation.

Anisometropia: A condition of unequal refractive state for the two eyes, one eye requiring a different lens correction from the other.

Anode potential: In TV cameras and CRT's the difference in voltage between the electron gun and the scanned element (camera target or phosphor surface).

Anomaloscope: An instrument to test the color sense. It usually consists of a viewing tube with a circular bipartite field, one-half of which is illuminated with yellow, the other with a mixture of green and red. The yellow half is not variable except for brightness, while the other may be varied continuously from red to green. The color sense is tested by mixing the colors of the variable color field until it subjectively matches the yellow field. A certain combination in the variable field is considered normal, and specific variations indicate the type or the degree of anomalous color vision present.

Anomaly quotient (AQ): A measure used to represent degrees of deviation from normal in the proportion of red and green mixed to make yellow in the anomaloscope.

Aperiodic interlace: A staggered interlace system in which different times are allotted each field.

Aperture: An opening that permits light, electrons, or other forms of radiation to pass through. In an electron gun, the aperture determines the size, and has an effect upon the shape, of the electron beam.

Aperture equalization (television): Electrical compensation for the signal distortion introduced by the size of the scanning aperture.

Aperture grill (CRT): A grill used as a physical barrier to the electron beams in color CRT's in order to avoid excitation of any one color phosphor by the electron beams not associated with that color.

Aperture mask (CRT): A metal plate with accurately formed openings, placed closely behind the phosphor in a tricolor picture tube. It insures that each of the three electron beams excites only the desired color phosphor.

AQ (see anomaly quotient)

Aqueous humor: The clear, watery fluid which fills the portion of the eye between the cornea and the lens. This region is also known as the anterior (forward) chamber.

Artificial eye photometer: See Figure 3.2-20.

Artificial pupil: A perforation in a diaphragm or disk to be held or mounted in front of the eye to effect a small or constant pupil size.

Aspect ratio of a raster: The ratio of the frame width to the frame height.

Astigmatism: 1. A condition of refraction in which rays emanating from a single luminous point are not focused at a single point by an optical system, but instead are focused as two line images at different distances from the system, generally at right angles to each other. In the eye, a refractive anomaly due to unequal refraction of the incident light in different meridians. It is generally caused by a cylindrical component in the anterior (front) surface of the cornea or, of less degree, by other ocular refracting surfaces, or by the obliquity of incidence of the light entering the cornea or the crystalline lens. 2. A monochromatic aberration in which light rays from a point located off the optical axis come to focus as a line radial to the optical axis at one distance along the axis and as a segment of an arc circumferential to the axis at another distance.

Audiometric monitoring: Measurement of hearing acuity on a continuing basis to ensure that hearing loss is not occurring (due to noise exposure).

Average spot luminance (CRT): The luminance of a spot (CRT) averaged over the area of the spot. Spot size (area) must be defined.

Backlash: The range of control movement after reversing direction that does not result in a system response. In microscopes, the maximum focus control rotation that will not cause the stage to move.

Badal principle: An optical technique for obtaining an image of constant angular size but adjustable vergence (viewing distance). It involves viewing a target object through a positive lens positioned with its focal point at the eye (properly, at the anterior nodal point of the eye). The angular size of the target is the same as if the target was located in the plane of the lens, and the vergence in diopters varies linearly with the distance of the object from the lens.

Banding: A periodic anomaly in the image generated on a CRT or optical line scan printer caused by uneven spacing of the scan lines. It gives the visual appearance of stripes or bands in the image.

Bandwidth: The range of frequencies over which the performance of a device is within specified limits. In this handbook the term refers to the performance of the electronics associated with electro-optical displays and is expressed in megahert (MHz).

Baudrate: A unit of signaling speed equal to the number of discrete conditions or signal events per second expressed as bits per second.

Beam current: The current emerging from the final aperture of the electron gun.

Beam modulation (in CRT's): 1. The ratio of the highlight signal current to the dark current. 2. The variation in beam current corresponding to variations in the signal voltage.

Bezold-Brücke phenomenon: A change in perceived hue of some, but not all, spectral colors with change in intensity.

Bifocals: Spectacles containing lenses which are divided to provide two focal points (points of focus).

Binary data: A numbering system using the base 2 (instead of the base 10 in the common decimal system).

Binocular: 1. Pertaining to both eyes; 2. The use of both eyes simultaneously in such a manner that each retinal image contributes to the final image.

Biocular: A binocular optical system in which both eyes share an optical element with a single axis of symmetry. See Figure 3.7-1.

Bit: An abbreviation of binary digit; one element in a binary number, where only the digits 0 and 1 are allowed.

Blackbody (see Planckian radiator)

Blanking (in CRT's): The process of cutting off the electron beam during retrace.

Blemish: Nonsystematic variations in screen luminance caused by a CRT defect.

Blind spot: A portion of the visual field where nothing is seen because the corresponding retinal area is without receptors. This occurs at the point where the optic nerve exits the eye.

Bracketing: A technique for obtaining the optimum setting of a continuously adjustable control by moving it back and forth through the optimum to a point on either side where setting is apparently worse. A position midway between these settings is then selected as optimum. Bracketing is frequently used for microscope focusing.

Break-even voltage: Anode potential at which the luminescence produced by a CRT is equal for aluminized and non-aluminized screens.

Brightness: The subjective attribute of any light sensation giving rise to the perception of luminous intensity, including the whole scale of qualities of being bright, light, brilliant, dim, or dark. More popularly, brightness implies the higher intensities, dimness the lower. At one time the term brightness was also used for the quantity luminance; this usage is no longer correct.

Broad-band noise: In electronic circuits, noise covering a range of frequencies equal to, or substantially equal to the bandwidth of the circuit.

Buffer: In data processing and computation, a storage device used to compensate for a difference in the rate of flow of information or time of occurrence of events when transmitting information from one device to another.

Candela: The unit of luminous intensity in the CIE photometric system. It is 1/60 of the luminous intensity of 1 cm^2 of a blackbody radiator at the temperature of solidification of platinum. The term is intended by the CIE to be used in place of candle, international candle, and new candle.

Cathode luminescent (phosphor) (see cathodoluminescence)

Cathode ray charge-storage tube: A charge-storage tube in which the information is written by means of a cathode ray. In charge-storage tubes, the information is retained on the storage surface in the form of a pattern of electric charges.

Cathode ray tube (CRT): A tube in which the electrons emitted by a heated cathode are focused into a beam and directed toward a phosphor-coated surface that becomes luminescent at the point where the electron beam strikes it.

Cathodoluminescence: The property of emitting light when bombarded by electrons.

CDI (see color discrimination index)

CFF (critical flicker frequency, critical fusion frequency, critical frequency for fusion): The rate of presentation of intermittent, alternate, or discontinuous photic stimuli that just gives rise to a fully uniform and continuous sensation obliterating the flicker.

Chip: An individual piece or fragment. For photographic imagery, frame or portion of a frame, as distinct from a roll. Color chips are individual samples of selected colors.

Chroma: The dimension of the Munsell system of color which corresponds most closely to saturation.

Chromatic aberration: Aberration produced by unequal refraction of different wavelengths or colors. The typical manifestation of chromatic aberration in a simple optical system is a colored fringe on the border of an image.

Chromaticity coordinates: The ratios of each of the tristimulus values to the sum of the three. Symbols: *x*, *y*, and *z*. Defined in Figure 5.2-8.

Chromaticity diagram: A plane diagram formed by plotting two of the three chromaticity coordinates against one another, thus constituting a graphical representation of stimulus characteristics derived from color mixture data. Illustrated in Figure 5.2-9.

Chromaticness: The attributes of chromatic color sensation, hue and saturation collectively, as distinguished from intensity.

Chrominance: A color term defining the hue and saturation of a color. Does *not* refer to brightness.

Chromostereopsis: Stereopsis resulting from the lateral displacement of retinal images of objects of different wavelengths. Discussed in Section 5.2.6.

CIE (Commission Internationale de l'Eclairage): An international organization devoted to studying and advancing the art and science of illumination. It is variously referred to as C.I.E., or I.C.I. from the English translation, International Commission on Illumination.

CIE chromaticity diagram (See chromaticity diagram or Figure 5.2-9)

CIE chromaticity system: Described in Section 5.2.1.3.

Clipping: The loss or elimination of signals greater or less than a defined amplitude, or the display (at a single level) of amplitude above or below a defined amplitude.

C_m, C_l, C_d, C_r: See Figure 3.1-10.

Coherent illumination: Electromagnetic radiation in which all the propagated energy is in phase, the maxima and minima of all waves being coincident; the energy being propagated from each point at the emitter is in phase with every other point.

Collateral material: In photointerpretation work, materials other than the latest photographic coverage, which aid the PI to report out the contents of the imagery.

Collimate: 1. To render a bundle of rays parallel. 2. To adjust an optical instrument so that its mechanical and optical axes are coincident or parallel.

Collimated luminaire: A luminaire (light fixture) in which the direction of light is restricted or modified to produce nearly parallel rays.

Color: 1. A sensory or perceptual component of visual experience, characterized by the attributes of *hue, brightness,* and *saturation*, and usually arising from, or in response to, stimulation of the retina by radiation of wavelengths between about 380 and 760 nm. Sensory components, such as white, gray, and black, which have neither hue nor saturation are properly, but are not always, included with colors. Variously synonymous with *hue, tint,* or *shade*. 2. A stimulus or a visual object which evokes a chromatic response.

Color adaptation: An altered sensitivity to color which produces apparent changes in hue or saturation. It may be induced, for example, by varying levels of illumination or by prolonged exposure to a specific color.

Color blindness: A common but misleading synonym for color defect.

Color defect: A variation from the normal response on a test that measures luminosity and chromaticness in various parts of the visual spectrum, such as the anomaloscope. Discussed in Section 5.2.2.1.

Color discrimination index (CDI): A measure of the average perceived difference between the colors in a standard set when viewed under a test illuminant.

Color fields: The portion of the visual field within which color can be perceived, the field for any given color being smaller than, and roughly concentric with, the visual field for white. The field for each color varies greatly with variation in such factors as target size, saturation, brightness, and contrast.

Color frame: In sequential color TV systems, the completion of one scanning cycle through the three primaries (three scanning fields).

Color matching function: The energy fluxes of the three chosen primary wavelengths required to match the unit energy flux of a given monochromatic test wavelength. Also known as "spectral tristimulus values."

Color picture: In sequential color TV systems, the completion of two color frames (six scanning fields). See also, color frame.

Color preference index (CPI): An indication of the degree to which a set of colors in a standard set viewed under a test illuminant provide their preferred appearances; i.e., red "looks" red.

Color rendering index (CRI): A measure of the degree to which, under specified conditions, the perceived colors of objects illuminated by the source conform to those of the same objects illuminated by a standard source.

Color temperature: The temperature of a blackbody radiator. For an illuminant that is not a blackbody radiator, the "correlated" color temperature is the temperature of a blackbody radiator that yields the same chromaticity.

Color wheel: A system of hues represented on a circle; the spectral colors in their original order arranged on a circle, with the purple hues connecting the extremes of the visible spectrum.

Coma: An oblique monochromatic aberration of an optical system in which the image of a point off the optical axis appears comet-shaped.

Comparator: A device used to measure distance on imagery.

Complementary wavelength: The wavelength of the color that is on the opposite side of the white point in the chromaticity diagram.

Composite video signal: A TV signal that results from combining a picture signal with the synchronizing signal; the TV signal as transmitted from a TV station.

Conductance: The inverse of the measure of resistance to the flow of electricity.

Cone: A type of photoreceptor cell in the retina of the eye involved in color vision, high visual acuity, and photopic (daylight) vision. There are about 6 or 7 million in each retina, the greatest proportion of which are located in the fovea.

Cone blindness (see congenital total color blindness)

Congenital total color blindness: A rare form of defective vision characterized by total inability to discriminate any of the ordinarily differentiated hues. Presumably, all hues are seen as varying shades of gray, black, or white.

Conjunctiva: The delicate membrane lining the eyelids and covering the anterior (forward) portion of the eyeball.

Contrast: 1. The difference in brightness between two areas. 2. Any one of several ways of mathematically expressing the difference in luminance of two areas; the more common ways are defined in Figure 3.1-10.

Contrast ratio: See Figure .1-10.

Contrast threshold: The contrast associated with the minimum luminance difference between two areas which can be perceived as having different brightnesses.

Convergence angle (eye): The angle between the two visual axes.

Convergence angle (in color CRT's): The angle at which electron beams from separate color guns of a color CRT display come together at the phosphor.

Convergent stereo photography: Stereo photography collected with the camera axes tilted to intersect approximately at the object being photographed.

Converging disparity: Disparity associated with an object nearer than some reference object. Also known as "crossed disparity." Illustrated in Figure 5.1-2.

Cornea: The transparent anterior (front) portion of the fibrous coat of the eye.

Correlation: A number which describes the closeness of association of two variables; the range is from -1 (an exact inverse relationship) to +1 (an exact relationship). (More properly, the "coefficient of correlation.") The most frequently used coefficient of correlation is the Pearsonian, or product-moment.

CPI (see color preference index)

CRI (see color rendering index)

Critical angle: In optics, that angle of incidence which results in the refraction of a ray passing from one medium to another at an angle which causes the ray to travel along the surface between the two media. Any angle greater than the critical angle results in total reflection.

Critical flicker frequency (see CFF)

Critical fusion frequency (see CFF)

Crossed disparity (see converging disparity)

CRT (see cathode ray tube)

Crystalline lens: A semi-elastic lens located between the aqueous and vitreous humors and just behind the iris. Through the action of the ciliary muscle, this lens changes curvature and thus refractive power in bringing the image to a focus on the retina as viewing distance changes.

Cyclic banding: Cyclic variation in line spacing in CRT's or in transparencies generated by optical line scan printers.

Daily noise dose: A recommended limit on the level and duration of exposure to noise.

dB (see decibel)

Dead voltage: Anode potential below which no luminescence is produced in a CRT phosphor.

Decibel (dB): Ten times the logarithm to the base 10 of the ratio of two powers. Defined also in Section 6.6.2. With P_1 and P_2 designating two amounts of power and n the number of decibels denoting their ratio, $n = 10 \log_{10} (P_1/P_2)$. When the conditions are such that ratios of currents or ratios of voltages (or analogous quantities in other fields) are the square roots of the corresponding power ratios, the number of decibels by which the corresponding powers differ is expressed by the following equations:

$$n = 20 \log_{10}(I_1/I_2)$$
$$n = 20 \log_{10}(V_1/V_2)$$

where I_1/I_2 and V_1/V_2 are the given current and voltage ratios respectively. By extension, these relations between numbers of decibels and ratios of currents or voltages are sometimes applied where these ratios are not the square roots of the corresponding power ratios; to avoid confusion, such usage should be accompanied by a specific statement of this application.

Deflection angle: In a CRT, the angle between the electron beam and a line between the last element of the electron optics and the center of the CRT screen.

Density: The logarithm of the ratio of incident to transmitted light. Stated another way, density (D) is the logarithm of the reciprocal of the transmittance (T):

$$D = \log_{10} 1/T = -\log_{10} T$$

Depth of field: The variation in the object distance of a lens or an optical system which can be tolerated without incurring an objectionable lack of sharpness in focus. The greatest distance through which an object can be moved and still produce a satisfactory image.

Depth of focus: Same as depth of field but in image space.

Detent: In a control, a mechanism that causes a noticeable change in required actuation force, or which tends to keep a control in a fixed position.

Deuteranomaly: A form of anomalous trichromatism in which an abnormally large proportion of green is required in a mixture of red and green light to match a given yellow. In the green to red region of the spectrum, hue discrimination is poor, and colors appear relatively more desaturated to the deuteranomal than they do to the normal trichromat, leading to confusion of light tints or of very dark shades of these colors. The degree of the defect covers a range from nearly normal to nearly deuteranopic. A sex-linked hereditary defect, it is the most common of all color vision deficiencies, occurring in about 5 percent of all males and 0.25 percent of all females.

Deuteranopia: A form of dichromatism in which relative spectral luminosity does not differ noticeably from normal, but in which all colors can be matched by mixtures of only two primary colors, one from the long wavelength portion of the spectrum (yellow, orange, or red), the other from the short wavelength portion (blue or violet). A neutral point (colorless or white) occurs at a wavelength of about 497 nm, and it is in this region that hue discrimination is best. Light of shorter wavelengths appears blue; of longer wavelengths, yellow, with saturation increasing toward the ends of the spectrum. Thus, red, orange, yellow, and green cannot be differentiated when their brightness and saturations are made equal. Similarly, blue, violet, and blue-purple differ only in brightness and saturation, but not in hue. It is a sex-linked hereditary defect and occurs in about 1 percent of all males and only rarely in females.

Dichroic: Producing two different colors; associated with different directions of transmission of light, different directions of viewing, different thicknesses or concentrations of the transmitting substance, differences between color of transmitted and reflected light.

Dichromatism: A form of defective color vision requiring only two primary colors, mixed in various proportions, to match all other colors. The spectrum is seen as comprised of only two regions of different hue separated by an achromatic band. Dichromatism may occur as protanopia, deuteranopia, tritanopia, or some irregular form such as tetartanopia.

Differential encoded PCM: A technique of digital transmission in which the change in signal level, and not the level itself is transmitted. (See also pulse code modulation.)

Differential gain (TV): The difference between the ratio of the output amplitudes of a small high-frequency sine-wave signal and unity at two stated levels of a low frequency signal on which it is superimposed. In this definition, level means a specified position on an amplitude scale applied to a signal waveform.

Differential phase (TV): The difference in output phase of a small high-frequency sine-wave signal at the two stated levels of a low-frequency signal on which it is superimposed.

Differential pulse code modulation (see differential encoded PCM)

Diffraction: The tendency of light to deviate from a straight line path in an isotropic medium. In complete wavefronts, this tendency is canceled through mutual effects of the neighboring points on the wavefront. At the edge of a wavefront, as when a wavefront passes by an edge or through a slit, the canceling effects are eliminated on one side and the wavefront at that point bends in the direction of the removed portion of the wavefront.

Diffraction limited display: A display in which the image quality is not reduced beyond the limit set by diffraction. This limit is considered in Section 3.3.2.

Digital system: A system that operates on the basis of discrete numerical techniques in which the variables are represented by coded pulses or discrete states.

Diopter: 1. A unit expressing two equivalent (and identical) quantities for a bundle of light rays. These are first, the vergence, or angular relationship between the rays, with diopters being the reciprocal of the distance to the point of intersection of the rays, the distance being in meters; and second, the reciprocal of the radius of curvature of the wavefront, with the radius being in meters. (For diverging light rays, vergence in diopters will be positive, and for converging rays it is negative.) When used in this sense, the diopter is a useful unit for expressing the distance to an object being viewed because it indicates the amount of eye accommodation required to focus the object on the retina. Also see the discussion in Figure 3.6-1. 2. The refractive power of a lens, expressed as the reciprocal of the lens focal length in meters. 3. See prism diopter.

Dioptric power: The vergence power of an optical system.

Diplopia: The condition in which a single object, or the haploscopically presented equivalent of a single object, is perceived as two objects rather than as one; double vision.

Discontinuous phosphor: A CRT tube coating where the phosphor is applied to the faceplate in stripes or in a matrix rather than in a continuous coat.

Disparity: Defined in Section 3.7.1.

Displacement joystick: A joystick control in which the output signal varies with the position of the control. (Compare with "isometric joystick.")

Display Contrast Ratio (see contrast ratio)

Display field: The field of view, measured in terms of visual angle, as defined by the edges or limits of an image display.

Distortion: 1. An aberration resulting from unequal magnification of object points not on the optical axis of a line system. Barrel distortion is produced by decreasing magnification with increasing distance of object points from the axis of an optical system. With this distortion, the corners of the image of a square are closer to the center than expected, with a resulting barrel-shaped appearance. Pincushion distortion results from increasing magnification with increasing distance of object points from the axis of an optical system. With this distortion, the corners of the image of a square are farther from the center than expected, with a resulting pincushion appearance. 2. Any change in which the image does not conform to the shape of the object, such as when viewed through a cylindrical lens.

Dither: The addition of a high frequency, low amplitude noise or square wave pulse to a signal being quantized. The effect is to "blur" edges and, for low levels of quantization, to improve the subjective quality of the image.

Diverging disparity: Disparity associated with an object farther away than some reference object. Also known as "uncrossed disparity." Illustrated in Figure 5.1-2.

Dominant wavelength: The spectral wavelength which, on proper mixing with white, will match a given sample of color.

Dot interlacing: A method of placing dots on a television screen to form the complete picture. During the first scanning of each line, the dots are separated by one or more dot widths, and on the following scans of the line, the dots are placed to fill the spaces in between.

Dot pattern: The pattern of locations (dots) exposed or energized in the display or printing of an image formed by a two-dimensional sampling system.

Dwell time: In a TV camera or CRT, the time the electron beam spends on a given screen location.

Dynamic convergence: A means whereby the three beams in a color television picture tube are caused to maintain correct convergence over the entire face of the tube by use of electromagnetic fields modulated by waveforms occurring at the horizontal and vertical rates.

Dynamic focusing: The process of varying the focusing electrode voltage for a color picture tube automatically so the electron-beam spots remain in focus as they sweep over the flat surface of the screen.

Dynamic range: The difference, in decibels, between the overload level and the minimum acceptable signal level in a system or transducer. This minimum is ordinarily fixed by one or more of the following: noise level, low level distortion, interference, or resolution level.

Dynamic visual acuity: Visual acuity measured with a moving target.

Echo: A reflection of a transmitted television picture, appearing as a "ghost" on the screen of a monitor or receiver.

Edge sharpening: An image manipulation technique in which edges and lines are narrowed or made more distinct.

Effective temperature (ET): A measure which combines temperature with relative humidity and other factors related to comfort. Used in Section 7.4.

Effectivity ratio: An expression for the ratio between effective pupil area and true pupil area, effective pupil area being a figure which takes into account the Stiles-Crawford phenomenon.

Electromagnetic spectrum: The total range of frequencies or wavelengths of electromagnetic radiant energy, extending from the longest radio waves to the shortest known cosmic rays.

Electron beam: A narrow stream of electrons moving in the same direction under the influence of an electric or magnetic field.

Electron gun: An electrode structure that produces, and may control, focus, deflect, and converge one or more electron beams in an electron tube.

Electro-optical imagery display: A display in which information in the form of an electronic signal is converted, by electronic and optical means, to an image.

Emmetropia: The visual condition wherein, at minimum eye accommodation (minimum eye refractive power) an object at infinity is in focus on the retina. Also called "normal vision."

Empty magnification: Typically, any value in excess of 1000 times the numerical aperture (NA). In a more general sense, any increase in magnification which does not result in an increase in what the user can see. Discussed in Section 3.3.2.

Entrance pupil: The image of the aperture stop formed by the portion of an optical system on the object side of the stop.

Errors of commission: Reports of targets where they do not exist or, in some studies, misidentifying one type of target for another.

Errors of omission: Failure to report existing targets.

Erythema: Redness of the skin (congestive or exudative) caused by hyperemia (excess of blood in a part). Typically seen, for example, in response to excessive exposure of the skin to ultraviolet radiant energy.

Esophoria: The inward turning, or the amount of inward turning, of the two eyes relative to each other as manifested in the absence of a fusion stimulus, or when fusion is made impossible, such that the lines of sight cross at a point in front of and nearer to the eyes than a given point of reference, this point of reference usually being the point of binocular fixation prior to the phoria test or, more arbitrarily, at an infinite distance. Also see Figure 3.7-30.

ET (see effective temperature)

Exit pupil: The image of the aperture stop formed by the portion of an optical system on the image side of the stop. Illustrated for one type of optical system in Figure 3.6-1.

Exophoria: The divergent turning, or the amount of divergent turning, of the two eyes relative to each other as manifested in the absence of a fusion stimulus, or when fusion is made impossible, such that the lines of sight cross at a point behind the eyes or at a point in front of the eyes beyond a given point of reference, this point of reference usually being the point of binocular fixation prior to the phoria test or, more arbitrarily, at an infinite distance. Also see Figure 3.7-30.

Eyepiece: The lens or a combination of lenses in a telescope, microscope, or other optical instrument to which the human eye is applied in order to view the image formed by the objective system.

Eye pupil: The aperture formed by the iris of the eye. See Figures 3.1-1 and -7.

Eye relief: The distance between the last mechanical surface and the exit pupil in an optical instrument.

Faceplate: The front transparent elements of a CRT.

Far point (of the eye): Image distance for which the eye is focused when accommodation (refractive power of the eye) is at a minimum. In an emmetrope, the far point is at infinity.

fc (see footcandle)

Field (in CRT displays): One of the equal parts into which a television frame is divided in an interlaced system of scanning. One vertical scan, containing many horizontal scanning lines, is generally termed a field.

Field curvature: An aberration of refractive and reflective optics wherein a curved image surface results from a plane object, due to each object point being a different distance from the refracting or reflecting surface.

Fixation point: The point in space to which one or both eyes are consciously directed. In normal vision its image is on the fovea.

fl: (see footlambert)

Flash (in phosphors): A high level of luminance associated with the fluorescence of a phosphor during excitation.

Flat field (luminance): A CRT display in which all lines (or spots) are driven by an equal or constant signal strength electron beam or beams.

Flat field ripple modulation (CRT): The variations in luminance caused by overlapping of the line spread functions when the frames are scanned with a beam of uniform current. The variations approximate a sinc wave distribution for most common line spacings.

Flicker: Perceptible temporal variation in luminance.

Fluoresce (in CRT's): Emitting light as the result of the excitation of the phosphor by the electron beam.

Fluoresce (in the eye): The emitting of light by parts of the eye, such as the aqueous humor or lens, as a result of excitation by radiant energy of a different wavelength. The most common excitatory wavelength region is the near ultraviolet.

Fluorescence: Emission of electromagnetic radiation that is caused by the flow of some form of energy into the emitting body and which ceases abruptly when the excitation ceases. In CRT's, fluorescence is in the form of light generated by an electron beam striking a phosphor-coated surface.

Flying spot: A moving spot of light used to scan an image or transparency, the intensity of the transmitted or reflected light being sensed by a photoelectric transducer.

Focus control: An adjustment for bringing the electron beam of a camera pickup tube or picture tube to a minimum size spot, producing the sharpest image. Also the control used to vary the position of lenses in an optical device relative to the object.

Focusing coils: An assembly producing a magnetic field for focusing an electron beam.

Focal point: The point of intersection on the axis of an optical system of those light rays that either enter or exit the system parallel to the axis. The anterior focal point is the point of intersection for those rays that exit the system parallel, and the posterior focal point is the point of intersection for the rays that enter parallel.

Footcandle (fc): A unit of illumination equal to uniformly distributed flux of 1 lumen per ft^2. Other units and conversion factors: 1 *lux* (*lumen/m^2*) = 0.0929 fc; 1 *metercandle* = 0.0929 fc; 1 *phot* = 929 fc.

Footlambert (fL): A unit of luminance equal to $1/\pi$ candela per ft^2 or to the average luminance of a surface emitting or reflecting light at the rate of one lumen per ft^2. The average luminance of any reflecting surface in footlamberts is the product of the illumination in footcandles and the reflectance of the surface. Symbol: fL. Other units and conversion factors: 1 *millilambert* = 0.929 fL; 1 *stilb* (candela per cm^2) = 2919 fL; 1 *candela* per ft^2 = 3.142 fL; 1 *nit* (candela per m^2) = 0 2919 fL; 1 *apostilb* = 0.0929 fL.

Fovea: A small pit in the center of the retina in which the density of photoreceptors is greatest and which controls perception of fine detail.

Foveal vision: Vision achieved by looking directly at objects so that the image falls on or near the fovea.

Frame (CRT): One complete scan of the image area by the electron beam. A frame may consist of several fields.

Frame rate (CRT): The number of frames produced per second; expressed in Hertz (Hz).

Gamut (color): The range of colors that can be obtained with a particular set of primaries or materials.

Gaussian distribution (see normal frequency distribution)

Ghost image (CRT): A spurious image resulting from an echo in the transmission of a video signal.

Glare: Relatively bright light, or the dazzling sensation of relatively bright light, which produces unpleasantness or discomfort, or which interferes with optimal vision.

Glossiness (as a dimension of color): An attribute of the appearance of a surface dependent upon the type and the amount of reflection. Low glossiness is characteristic of rough diffusing surfaces and high glossiness of smooth surfaces that give a shiny or lustrous effect.

Grain: The developed silver particles in a photographic image.

Grating: A set of parallel bars, usually of equal width; illustrated in Figure 3.1-11. (A grating can also consist of two sets of parallel bars arranged crosswise to each other to form a latticework. Such a configuration is seldom used in visual science.)

Gray: A color that is achromatic, or without hue, and which ranges from white to black.

Gray scale: A series of achromatic tones having varying proportions of white and black to give a full range of grays between white and black. These are usually regularly spaced with regard to reflectance or transmittance, and can be in either linear or log steps.

Gray scale color coding: Assigning colors to selected transmittance levels in black-and-white imagery to improve the detection of contrast levels. Also called pseudocolor encoding.

Ground distance per line pair: The distance on the ground corresponding to a line pair (bar and space) of a resolution target on the image. Ground distance per line pair equals scale factor (1/scale) times line pair image dimension.

Halation (CRT): An annular area surrounding a spot that is due to the light emanating from the spot being reflected from the front and rear sides of a CRT faceplate.

Head-up display (HUD): A display which permits the observer to view it without restricting his view of the rest of the visual field. An example would be the projection of information on a combining glass with collimated light to an airplane pilot who wants to maintain his view out of the window.

High order (CRT interlace system): An interlace system in which more than two fields are employed; e.g., 3:1, 4:1 interlace.

Horizontal aperture equalization (see aperture equalization)

Horizontal resolution (CRT): The number of individual picture elements that can be distinguished in a horizontal scanning line within a distance equal to the picture height. See Figure 4.1-6.

Horizontal retrace (CRT). Return of the electron beam to the start of the next line of the field being written in the CRT.

HUD (see head-up display)

Hue: The attribute of color sensation ordinarily correlated with wavelength or combinations of wavelengths of the visual stimulus and distinguished from the attributes brightness and saturation.

Hyperopia: The visual condition wherein, at minimum eye accommodation (minimum eye refractive power) an object at infinity is focused behind the retina. Some individuals with this condition will accommodate in order to focus on objects at infinity while others will require a positive corrective lens. Also known as farsightedness or hypermetropia.

Hyperphoria: Synonymous with vertical phoria.

IES (see Illuminating Engineering Society)

Illuminance: The photometric term for the intensive property of the luminous flux passing through a cross section of a beam or falling on a surface; the density of luminous flux incident on a surface. It is the quotient of the luminous flux divided by the area of the surface when the flux is uniformly distributed. Common units are lumen per ft^2 (footcandle) or per m^2 (lux, metercandle).

Illuminance sensor: Defined in Section 3.2.1.

Illuminants A, B, or C: Light sources having specified spectral distributions, adopted by the CIE in 1931 as international standards in colorimetry. A is a tungsten lamp operated at a color temperature of 2854° K and approximates a blackbody operating at that color temperature. B is illuminant A in combination with a specified filter and approximates noon sunlight, having a color temperature of 4800° K or a blackbody operating at that color temperature. C is illuminant A in combination with a specified filter and approximates daylight provided by a combination of direct sunlight and clear sky, having a color temperature of approximately 6500° K.

Illuminating Engineering Society: A technical association dedicated to the collection and dissemination of information on good lighting practices.

Image: 1. In general, a likeness, a copy, a replica, a symbol, or a mental representation of an object. 2. The optical counterpart of an object produced by a lens, a mirror, or other optical system. 3. The perceived counterpart of a viewed object subjectively projected in visual space. (For a discussion of how the term image is used in this handbook, see the introduction to Section 3.0.)

Image curvature: 1. The apparent curvature of the image seen in a display. In Section 3.4.5 it is suggested that in many cases the image appears curved because of distortions. 2. Image curvature is sometimes used synonymously with field curvature.

Image defects (CRT): Degradation in image quality caused by improper operation of equipment or by transmission difficulties.

Image distance: The distance to the image as seen by the display user. Defined in the introduction to Section 3.6 and in Figure 3.6-1. Image distance is frequently expressed in diopters (the reciprocal of the distance in meters).

Image orthicon: A camera tube in which an electron image is produced by a photo-emitting surface and focused on a separate storage target, which is scanned on its opposite side by a low-velocity electron beam

Image quality (of a display): The extent to which a displayed image duplicates the information contained in the imagery (object) in a form suitable for viewing by the interpreter.

Image space: The space occupied by the image. For explanation of its importance in optical systems; see Figure 3.6-1.

Imagery (reconnaissance): A representation, usually in the form of a permanent record on a material such as film or magnetic tape, of some aspect such as reflectance of a ground scene. (For a discussion of how the term imagery is used in this handbook, see the introduction to Section 3.0.)

Imagery scale (see photographic scale)

Index of refraction, relative and absolute: The index of refraction is the ratio of the speed of light in vacuum, air, or other medium of reference, to the speed of light in a given medium, obtained by Snell's law as the ratio of the sine of the angle of incidence to the sine of the angle of refraction, and usually designated by the letter *n*. The index of relative refraction is the ratio of the speed of light in a medium of reference other than vacuum to the speed of light in a given medium. The index of absolute refraction is the ratio of the speed of light in vacuum to the speed of light in a given medium.

Infrared: Radiant energy in the wavelength range of about 760 nm to 10^6 nm (1mm). The wavelength region between visible and microwave radiant energy.

Instrument myopia: A tendency to focus an image in a microscope at a distance considerably closer than infinity.

Interlace (CRT): A scanning process in which the distance from center to center of successively scanned lines is two or more times the nominal line width, and in which the intervening lines are scanned during subsequent fields.

Interline flicker (see small field flicker)

Interlock: A device or arrangement by means of which the functioning of one part is controlled by the functioning of another, as for safety.

Intermediate image: An image before the final image perceived by the display user. In a compound microscope, the image of the object (imagery) formed by the objective lens approximately at the focal point of the eyepiece.

Interpupillary distance: The distance between the centers of the pupils of the eyes. Unless otherwise specified, it refers to the distance when the eyes are fixated on an object at infinity, so that the eye convergence angle is zero.

Inverted stereo: The image obtained when the two photos in a stereo pair are interchanged, or rotated 180 degrees, so that the direction of the disparity is reversed. Discussed in Figure 5.1-6.

IPD (see interpupillary distance)

Iris: The circular pigmented membrane located on the anterior (front) surface of the lens of the eye and which forms the eye pupil.

Isomeric colors: Colors of identical spectrophotometric composition and chromaticity. Contrasted with metameric colors in Section 5.2.1.6.

Isometric joystick: A joystick control which is essentially fixed in position and in which the output signal varies with the force exerted on the joystick by the operator. Also known as a "force joystick." (Compare with "displacement joystick.")

Jitter: Small deviations in the size or position of the elements of a repetitive display. Frequently caused by faulty mechanical and electronic systems. Generally continuous, but may be random or periodic.

j.n d. (see just noticeable difference)

Judged image quality: A subjective assessment of image quality performed by human observers in terms of some pre-established criterion. Objective measures of image quality employ physical measures or measure performance on a relevant task; e.g., target identification.

Jump scan (CRT): A scanning method whereby the electron beam "jumps" from one phosphor point to another point as opposed to continuously sweeping on a line by line basis.

Just noticeable difference: The least difference in value between two stimuli which, in a given individual, gives rise to two different sensations; or which gives rise (statistically) to a perceived difference as often as it does not.

Just perceptible difference (see just noticeable difference)

Kell factor: The factor by which the number of active TV lines are multiplied to give an estimate of the actual vertical resolution. It can be applied to other one-dimensional sampling systems as well. The factor is always less than 1 due to the effect of the sampling process.

Kelvin scale: A temperature scale in which the triple point (freezing point) of water is 273 degrees and the boiling point of water is 373 degrees.

Keratoconjunctivitis (see photokeratitis)

Lag (TV cameras): In TV camera tubes, a persistence of the electrical charge image for a small number of frames.

Lambertian radiator: A radiator in which the intensity of emitted light is a function of the cosine of the angle a given ray makes with a line perpendicular to the surface of the radiator.

Landolt ring: An incomplete ring, similar to the letter C in appearance, used as a test object for visual acuity. The width of the ring and the break in its continuity are each one fifth of its over-all diameter. The break or gap is placed in different meridional positions with its location to be identified by the observer as evidence of its perception. The visual angle is represented by the subtense of the gap at the eye. Illustrated in Figure 3.1-9.

Large field flicker (CRT): Flicker appearing over all or substantially all portions of the CRT tube face.

Laser beam recorder: A variety of line-scan image generator using a laser beam to expose the film.

Lateral alignment: The convergence angle or angle between the visual axes, necessary for the display user to fixate on corresponding points in the two images.

Lateral disparity: Defined in Section 3.7.4.4.

LBR (see laser beam recorder)

Lens (of the eye) (see crystalline lens)

Light: 1. Radiant energy, approximately between 380 and 760 nm, that gives rise to the sensation of vision on stimulating the retina. 2. The sensation of vision produced by stimulating the retina.

Light pen: A tiny photocell or photomultiplier, mounted with or without fiber or plastic light pipe in a pen-shaped housing; it is held against a cathode ray screen to make measurements from the screen or to change the status of the display.

Lightness: An attribute of object colors whereby they can be rated on an achromatic scale from black to white for surface colors, or from black to colorless for transparent spatial colors. It implies a direction on the scale opposite to that implied by darkness. Also see Figure 5.2-1.

Limiting aperture: The aperture in a system which serves to define either the diffraction limit and/or the field size.

Line crawl (CRT): A subjective effect in which interlaced raster lines appear to move either up or down the image frame. In addition to the necessary influence of an interlaced raster structure, the occurrence of line crawl also depends upon line luminance and the visual angle subtended by adjacent lines.

Line frequency (TV): The number of times per second that a fixed vertical line in the picture is crossed in one direction by the scanning spot. Scanning during vertical return intervals is counted.

Line luminance (CRT): The luminance of a scan line averaged over its area.

Line number (TV): 1. The total number of line scan periods per TV frame. Not all of these periods are used to scan the image (in the camera) or the phosphor (in the CRT), a portion are used in vertical retrace. 2. The sequential numbering of the active TV lines on the sensor or phosphor surface.

Line pairing (TV): In television, imperfect spatial interlace of the lines composing the two fields of one frame of the picture. The lines from one field do not lie precisely between the lines from the second field.

Line raster system: An electro-optical system where the image or scene is scanned on a line by line basis (one-dimensional sampling).

Line scan period: The length of time between the start of writing for two successive TV lines in a field; i.e., the active portion plus horizontal retrace time.

Line-scan transparency: A film transparency (image) produced by successive exposure on a line by line basis.

Line spread function: A mathematical description of the distribution of light across the image of an infinitesimally narrow bright-line object. In TV cameras and CRT's, the mathematical description of the distribution of current across a scan line, or for CRT's the distribution of luminance across a scan line.

Linear interpolation: A mathematical function used to calculate the signal level at a point between two known points under the assumption that the three points lie on a straight line.

Long-persistence phosphor: A phosphor which emits light for a relatively long time due to phosphorescence (persistency of 100 msec to 1 sec). Very long persistence phosphors are those having emittance times of 1 second or greater.

Luminance: Luminous flux per unit of projected area per unit solid angle either leaving or arriving at a surface at a given point and in a given direction. Formerly known also as brightness. Common units are nits (candela per square meter, or cd/m^2), footlamberts (fL) and millilamberts. (Conversion factors appear in Figure 3.2-14.)

Luminance gradient: A change in luminance over distance. The rate of change in luminance over distance.

Luminance sensor: A device for measuring luminance. Illustrated in Section 3.2.1.

Luminosity curve (see luminosity function)

Luminosity function: The relative brightness-producing capacity of light of different wavelengths measured by the reciprocals of the amounts of radiant flux required at each wavelength region to produce the same brightness. Illustrated in Figure 3.2-2.

Luminous efficiency (of phosphors): The ratio of the energy emitted by a phosphor (in the form of ultraviolet, visible and infrared radiation) to the energy in the exciting beam. Also defined, in a more restricted sense, as the ratio of the energy of the visible light output, weighted for the luminosity curve, to the electron energy of the input.

Luminous flux: The time rate of transfer of radiant energy, evaluated spectrally according to its ability to produce a visual sensation (using the luminosity function for the eye illustrated in Figure 3.2-2). The common unit is lumens. Also called luminous power.

Luminous intensity: In a given direction, the ratio of the luminous flux emitted by a source, or by an element of a source, in an infinitesimal cone containing this direction, to the solid angle of this cone. Luminous flux per unit solid angle in a given direction.

Luminous power (see luminous flux)

Magnification: (1) The ratio of image to object size. (Discussed in Figure 3.3-1.) (2) Enlargement.

Magnifying power: The ratio of retinal image size of an object in a particular viewing situation to its retinal image size when located at a standard or reference distance from the eye (normally 250 mm or 10 in). (Discussed in Figure 3.3-1.)

Mark-sense: A method of interfacing with a computer using sheets or cards marked by hand with a (usually) special pencil.

Mean (arithmetic): An average, or measure of central tendency, obtained by summing the values and dividing by the number of cases.

Median: An average, or measure of central tendency; specifically, the value of that item in a set for which there are an equal number of items of greater and of lesser magnitude.

Median frequency (TV): The middle frequency of a specific range of frequencies.

Megabaud: One million bauds, designated by the symbol R.

Megahertz: One million cycles per second.

Mensuration: The act or process of obtaining measurements of length, width, height, orientation or distance from imagery.

Mesopic: Pertaining to vision at a luminance range in which both rods and cones function.

Metameric colors: Colors of different spectrophotometric composition which appear the same under given conditions. Appearance is often defined in terms of chromaticity. Metameric colors are compared with isomeric color in Section 5.2.1.6.

MHz (see megahertz)

Microstereoscope: A binocular microscope which provides for viewing pairs of stereoscopic photographs.

Misregistration (see registration)

Mode: The most frequently occurring value in a defined set.

Modulation. Mathematically, the absolute value of the difference between two quantities, such as voltage or luminance at two times or at two locations, divided by their sum. Strictly speaking the variation in the value of the quantity should be sinusoidal, in which case the maximum and minimum value are used to calculate modulation. Modulation is one of several ways of expressing luminance contrast, and is identified as C_m in Figure 3.1-10 and in many other figures in this handbook.

Modulation sensitivity: A statement of ability to distinguish differences in luminance, with these luminance differences expressed as modulation.

Modulation transfer factor: The ratio of output to input modulation at a given spatial or temporal frequency.

Modulation transfer function (MTF): The curve or the mathematical expression describing the curve generated by a series of modulation transfer factors taken over a range of frequencies; usually from a frequency of zero to the frequency at which the modulation transfer factor drops to zero.

Monitor: A television display connected to the output of camera or other image generating device.

Monochromatism: The condition of being unable to differentiate between the hues of the visible spectrum and in which all parts of the visible spectrum supposedly produce varying shades of gray.

Monocular: 1. Pertaining to or affecting one eye. 2. Pertaining to any optical instrument which is used with only one eye.

Monoscopic (see monocular)

mrem: Abbreviation for milliroentgen equivalent man, a measure of radiation dosage corrected for absorption characteristics of body tissue. A dosage of any ionizing radiation whose absorption effects are equivalent to 1/1000 of a roentgen of X rays.

MTF (see modulation transfer function)

Munsell color system: A series of about one thousand standard color samples, each designated by a letter-number system. The series represents various combinations of hue, saturation, and brightness and includes variations of brightness of the achromatic colors which have neither hue nor saturation. Illustrated in Figure 5.2-5.

Myopia: The visual condition wherein, at minimum eye accommodation (minimum eye refractive power) an object at infinity is in focus in front of the retina because the eye has too much refractive power. Individuals with this condition are unable to focus on distant objects and hence are known as nearsighted. Myopia is corrected with a negative lens.

Nanosecond: One-billionth of a second; also 10^{-9} second.

Narrow-band noise: In electronic circuits, noise covering a small range of frequencies relative to the bandwidth of the circuit.

National Television Systems Committee (NTSC): A group impaneled to set standards for commercial television in the United States.

Natural pupil: The pupil formed by the iris of the eye, as opposed to an artificial pupil.

NC (see noise criterion curve)

NCA (see alternate noise criterion curve)

Near point (of the eye): Image distance for which the eye is focused when accommodation (refractive power of the eye) is at a maximum. Typically measured by moving a test target closer to the eye until it cannot be kept in focus. For most individuals the near point is much more variable than the far point.

Neutral density filter: A filter which transmits all visible wavelengths in approximately equal but reduced amounts.

Nit: A unit of luminance equal to 1 candela per m^2 (cd/m^2). Also see "footlambert."

Nodal points: A pair of points on the axis of an optical system which have the property that any incident ray directed toward the first, the anterior nodal point, leaves the system as though from the second, the posterior nodal point, and with its direction unchanged; i.e., parallel to the incident ray.

Noise: Unwanted disturbances superposed upon a signal that tend to obscure its information content.

Noise criterion curve (NC): A set of curves that specify noise limits at each of eight octave bands. Illustrated in Figure 6.6-9.

Nonspectral color: A color such as purple that is not visible in the spectrum.

Normal frequency distribution: A continuous frequency distribution often encountered in biological or other data. It is symmetrical, the central classes are the most numerous, and a decrease in frequency is obtained toward both larger and smaller class values according to a relatively simple mathematical law. Also known as Gaussian frequency distribution.

NTSC (see National Television Systems Committee)

Numerical aperture: An expression designating the light-gathering power of microscope objectives; the product of the index of refraction of the object space and the sine of the half-angle of the incident cone.

Object (in an optical display): Typically the imagery of which the display is to provide an image..

Object space: The space occupied by the object. For explanation of its importance in optical systems, see Figure 3.6-1.

Objective lens: The lens in a telescopic or microscopic system nearest the object.

Obliquity: An oblique aerial photograph is one taken with the camera axis directed between the horizontal and the vertical.

Octave: The interval between two frequencies having a ratio of 2:1.

Ocular: 1. An eyepiece; 2. Pertaining to or about the eye.

One-dimensional sampling: In electro-optical imaging systems, generating a continuous signal representing one dimension of the imagery and a discontinuous signal representing the other dimension. A conventional TV system is an example of a one-dimensional sampling system.

OPS (see optical power spectrum)

Optic axis (of the eye): An imaginary straight line that, in theory, passes perpendicularly through the midpoint of the refracting surfaces of the eye. Because of irregularities in the structure of the eye, the optic axis can only be approximated. Also known as the optical axis.

Optic disc: The portion of the optic nerve which is formed by the meeting of all the retinal nerve fibers. It is insensitive to light, corresponds to the physiological blind spot, is pinkish in color, due to its many capillaries, and, normally, has a central depression, the physiological cup.

Optical line-scan image generator (see optical line-scan printer)

Optical line-scan printer: A device used to expose film on a line by line basis. See Figure 4.1-16.

Optical path: The path followed by light in an optical device, normally represented by the chief ray.

Optical power spectrum (OPS): A description of imagery content. The spectrum represents relative image modulation contrast as a function of spatial frequency. Also known as Wiener spectrum.

Optometer: A device for measuring the refractive state of the eye.

Orthicon (see image orthicon)

Orthophoria: The condition in which the lines of sight, in the absence of an adequate fusion stimulus, intersect at a given point of reference. This point of reference is usually the point of binocular fixation prior to the phoria test.

Paired (pair) comparison: A method used in judgment of affective preference of colors, etc., in which each member of a series is compared individually with every other member in respect to a given quality, the judge indicating the member he prefers in each pair so that a graded scale of the entire series is obtained.

Parallax: The apparent change in direction or lateral displacement of a viewed object when the eye is moved from one position to another, or when the object is viewed first with one eye and then with the other.

Parfocal: An optical system in which magnification can be changed without varying the focus of the instrument.

Partial color blindness (see dichromatism)

PCM (see pulse code modulation)

Peak luminance (CRT): The luminance at the center of the scanning spot where the current density is greatest in the impinging electron beam.

Peak signal strength: Expression of the maximum instantaneous signal power or voltage as measured at any point in a system.

Peak-to-trough voltage: The difference in signal voltage between the maximum and minimum points of a cyclical signal.

Perceived noise level (PNL): The level in decibels assigned to a noise by means of a calculation procedure that is based on an approximation to subjective evaluations of "noisiness."

Periodic staggered interlace: Staggered interlace in which the time allotted for each field is the same.

Periphery (visual field): Noncentral portions of the field.

Phase (of a periodic phenomenon f(t), for a particular value of f): The fractional part t/P of the period P through which t has advanced relative to an arbitrary origin. Note: The origin is usually taken at the last previous passage through zero from the negative to the positive direction.

Phoria: The direction or orientation of one eye, its line of sight, or some other reference axis or meridian, in relation to the other eye, manifested in the absence of an adequate fusion stimulus, and variously specified with reference to parallelism of the lines of sight or with reference to the relative directions assumed by the eyes during binocular fixation of a given object.

Phosphor: Any substance that becomes luminous as a result of exposure to radiant energy or bombardment by atomic particles. This may cease with the exciting stimulus (fluorescence) or may persist (phosphorescence). In electro-optical systems, the term is used most commonly to denote those cathodoluminescent substances used for the coating of cathode ray tube screens.

Phosphor persistence: The length of time required after the removal of excitation for the luminance of an excited phosphor to drop to 10 percent of its peak value.

Phosphorescence: Emission of radiation as a result of previous absorption of radiation of other wavelengths. The emission may continue for a considerable time after the excitation has ceased, in contrast to fluorescence which stops within approximately 10^{-8} seconds after the removal of the excitation.

Photoconductivity: Electrical conductivity of certain insulators and semiconductors, such as selenium, induced by radiation of suitable wavelength.

Photogrammetry: The science or art of obtaining measurements of objects by means of photography.

Photographic scale: The ratio of the size of a feature in a photograph to the size of this same feature on the ground. A "large scale" photograph shows less ground area and hence smaller details on the ground than a "small scale" photograph of the same size.

Photokeratitis: Inflammation of the conjunctiva and cornea caused by exposure to ultraviolet radiant energy.

Photometry: The measurement of light, contrasted with radiometry, which is the measurement of radiant energy.

Photopic: Pertaining to vision at a sufficiently high luminance that cone receptors are involved. An opposite meaning word is scotopic, for night seeing.

Photosensor: The element of an electro-optical camera which changes its electrical characteristics in response to variations in incident illumination. The photodetector.

PIC (see pseudo-isochromatic chart)

Picture (CRT): The CRT image produced by complete scanning of all fields (and frames in a sequential color system).

Pitch (of a raster): In line-scan imaging systems the ratio of the line spacing to the standard deviation of the line spread function.

Pixel: The smallest discrete subsection of a digital image matrix.

Planckian radiator: A surface from which the spectral distribution of emitted radiant energy varies with temperature according to Planck's radiation formula. The standard material is carbon, but the tungsten filament of an incandescent lamp provides a good approximation. Also known as blackbody radiator.

PNL (see perceived noise level)

Point raster system: A system in which sampling is two dimensional.

Point scan: A technique of scanning whereby points rather than lines are illuminated; sampling is in two dimensions.

Point spread function: 1. A mathematical description of the distribution of light in a cross section of the image of an infinitesimally small, bright, point object, hence a description of the point-imaging characteristics of an optical system. 2. In CRT's, the mathematical expression describing the distribution of current in a longitudinal section of the electron beam. The distribution is most commonly Gaussian.

Position joystick (see displacement joystick)

Power (see dioptric power)

Preferred-frequency speech interference level (PSIL): See speech interference level (SIL). The PSIL differs from the SIL only in that the three-octave bands are centered at 500, 1000, and 2000 Hz. For typical noises, PSIL is 3 dB greater than SIL.

Presbyopia: A reduction in accommodative ability occurring normally with age and necessitating a plus lens addition for satisfactory seeing at near distances, sometimes quantitatively identified by the recession of the near point of accommodation beyond 20 cm.

Primary colors: Any set of colors, such as red, green, and blue, from which other color sensations can be produced by additive mixing. Although it is most common to speak of three primaries, some theorists contend that there are no fewer than four.

Primary flash (in CRT's): Term sometimes used to describe the very bright fluorescence of a cathodoluminescent phosphor when it is being bombarded by the electron beam of a CRT.

Principal plane: A plane in an optical system, perpendicular to the optical axis, at which refraction of the incident or emergent light may be considered to take place.

Principal ray: The line connecting the principal point of an image and the perspective center of the imaging lens.

Prism diopter: A measure of the deviation, or bending of light by a prism, equal to 100 times the tangent of the angle of deviation. Thus, a prism of 1 prism diopter will deviate light 1 cm at a distance of 1m.

Prismatic: Produced by, pertaining to, or resembling, a prism or its action or effect.

Protanomaly: A condition characterized by relatively lowered luminosity for long wavelength lights and, concomitantly, by abnormal color matching mixtures in which an excess of the red primary is necessary.

Protanopia: A form of dichromatism characterized by decreased luminosity for long wavelengths and an inability to differentiate the hues of red, orange, yellow, and green, or blue and violet, or blue-green and a neutral gray. A sex-linked, hereditary form of color blindness occurring in about 1 percent of the male population.

Prototype: The first of a kind–normally one that serves as a model for later issues.

Pseudocolor: Defined in Section 5.2.5.

Pseudo-isochromatic chart (PIC) color test: A color vision test which requires the discrimination of hues for a "normal" response and which permits differential diagnosis of color defect on the basis of responses which are not "normal."

PSIL (see preferred frequency speech interference level)

Pulse code modulation (PCM): In digital systems, a set of techniques for encoding quantized signal strength as a series of discrete pulses. These techniques are especially resistive to noise-induced errors.

Pupil (of the eye): The aperture in the iris, normally circular and contractile, through which the image-forming light enters the eye.

Purity (color): A measure of the degree of freedom of a color from achromatic content; or, the degree to which a color approaches the condition required for maximum saturation. Various purity scales are used, all of which can be expressed as some mathematical function of the ratio of the spectral to the achromatic components of a color mixture. One is illustrated in Figure 5.2-10.

PW (see sound power)

Quadratic interpolator: A spot-spread function which produces interpolated values which follow a best-fit parabola between three successive image samples.

Quantize: To subdivide the range of values of a variable into a finite number of nonoverlapping subranges or intervals, each of which is represented by an assigned value within the subrange.

Quantizing errors: The difference between the actual value of a variable and the level assigned to it in the quantizing process.

Radian: The angle subtended by an arc of a circle equal in length to the radius of the circle. One radian is equal to 57.3 degrees.

Radiant energy (electromagnetic): Energy associated with electro-magnetic waves, which are characterized by temporal variations of electrical and magnetic fields.

Radiant flux: Time rate of transfer of radiant energy. The most common unit is the watt. Also called radiant power.

Radiant power (see radiant flux)

Radiometry: The measurement of radiant energy.

Raster (TV camera or CRT): A predetermined pattern of scanning lines that provides substantially uniform coverage of an area.

Raster crawl (see line crawl)

Raster luminance (CRT): the luminance of an extended area on the face of the CRT.

Rayleigh criterion: A distance equal to the radius of the first dark ring in the Airy disc.

Real image: An optical image that can be received on a screen; one formed by the meeting of converging rays of light.

Real pupil (of the eye): The pupil of the eye formed by the iris, as opposed to the two images of the real pupil, the entrance and exit pupils of the eye. Illustrated in Figure 3.1-7.

Recognition: In image interpretation, the assignment of an object (as seen on a display) to a class of objects; e.g., tank.

Recognition latency: The period of time elapsing between the first appearance of a target in an imagery display and a response by the observer (interpreter) indicating he has located and recognized it.

Red-green color blindness (see dichromatism)

Reflectance: The ratio of reflected flux to incident flux.

Refraction: 1. The altering of the pathway of light from its original direction as a result of passing obliquely from one medium to another of different index of refraction. 2. The refractive and muscular state of the eyes, or the act or process of determining and/or correcting it.

Refractive difference (between the two eyes) (see anisometropia)

Refractive error: The dioptric power of the correcting lens which, together with the dioptric system of the eye, converges parallel rays to focus on the retina, with accommodation fully relaxed. Hence, if the eye has too much refractive power, the refractive error is negative.

Refresh rate: The frequency with which the electron beam of a CRT display returns to a given phosphor spot. Nominally assumed equal to the frame rate.

Registration: Any of several measures of the degree to which two images on binocular display are coincident. See also alignment, disparity.

Relative luminosity: The ratio of the luminous efficiency for a given wavelength to the value at the wavelength of maximum luminous efficiency.

Resolution (TV): A measure of ability to delineate picture detail. Resolution in cathode ray tubes is usually expressed as the number of scan lines in the vertical dimension of the raster (i.e., the direction perpendicular to the scan lines). A line of TV resolution is either the light or dark portion of a periodic target, as opposed to the designation of resolution as the number of line pairs (both the light and dark portions of a periodic target) used in optics. Two lines of TV resolution are required to equal one line pair of optical resolution.

Response latency: The lapse of time between the presentation of the stimulus and the occurrence of the response.

Resting position (of accommodation): The refractive state of the eye when there is no stimulus to focus at any given distance. Traditionally spoken of as being zero diopter (accommodation to infinity), it is now more often placed nearer at about 0.5 to 2 diopters (2 to 0.5 meters); this is presumed to be the basis for night or empty field myopia. See Section 3.6.2.

Reticle: A very small, transparent scale, gratelike pattern, or system of lines in the front focal plane of the eyepiece of an optical instrument, for direct observation of the apparent image size or position in the field of view.

Retina: The portion of the eye which contains the photoreceptors.

Retinal illuminance: The luminous flux incident per unit area on the retina.

Reliability: The coefficient of correlation obtained from two applications of the same test. (Properly, the coefficient of reliability.)

Retrace (in CRT's): Return of the beam on the cathode ray tube to its starting point after the completion of a line or a field; also that portion of the sweep waveform that returns the spot to its starting point.

Reverberation: 1. Reverberation is the persistence of sound in an enclosed space as a result of multiple reflections after the sound source has stopped. 2. The sound resulting from reverberation.

Reverberation time: The reverberation time of a room is the time that would be required for the mean squared sound pressure level therein, originally in a steady state, to decrease 60 dB after the source is stopped.

Ripple modulation (CRT): The variations in luminance in a flat field caused by the line spread function of the overlapping of scan lines. Ripple modulation generally approximates a sine-wave function for normal line spacing.

rms noise: The square root of the average of the squared values of nonsystematic variations about a mean signal level.

Rod: In contrast with the cones, the rods function at lower light levels, are located more in the periphery of the eye, and are more sensitive to movement. About 130 million rod cells exist in a human retina.

Sampling: Process of obtaining a sequence of instantaneous values of a wave at regular or intermittent intervals.

Saturation: 1. The quality of visual perception which permits a judgment of different purities of any one dominant wavelength; the degree to which a chromatic color differs from a gray of the same brightness. 2. In CRT's the level of excitation of the phosphor where further excitation does not produce an increase in luminance.

Scale (see photographic scale)

Scale number: Reciprocal of scale or photographic scale. Also called scale factor.

Scan line (TV camera and CRT): A single continuous narrow strip that is determined by the process of scanning (the process of directing a beam of energy successively over the elements of a given region, e.g., a CRT tube).

Scanning field: a cycle defined by a complete (top to bottom) sweep of one electron beam over the display. Two or more sweeps may be required to produce a picture.

Schematic eye: A simple schematic system designed to have the same optical properties as the average human eye. Also known as the reduced eye. Usually given for a condition of relaxed accommodation.

Scintillation: A subjective visual sensation of sparks or quivering flashes of light.

Scotopic: Pertaining to vision at relatively low luminance so that only rod receptors are involved.

Screen display: An image display in which the optical element closest to the eye is a diffusing surface or screen on which the image is formed. Also see aerial image display.

Screen image (see screen display)

Second derivative: The derivative is the slope of the curve $y = f(x)$ at a given point, C. The second derivative is the rate at which the slope of that curve changes. The second derivative of the original video signal was subtracted from that video signal to give the edge sharpened signal.

Self-scanning: In photodetectors, which consist of arrays of small, single photosensitive elements from which the signal is taken by means of individual connections to each element, the process of obtaining the signal through systematically switching from one element to another in a manner programmed in the electronic circuitry of the device. No electron beam is employed.

Sequential interlace (TV cameras and CRT's): A scanning process in which the lines from successive fields are written immediately adjacent to the those of the preceding field.

Shading: In electro-optical images, a large area brightness gradient in the reproduced picture not present in the original scene.

Shadow mask: A thin, perforated metal mask mounted just back of the phosphor-dot faceplate in a three-gun color picture tube; the holes in the mask are positioned to ensure that each of the three electron beams strikes only the phosphor dot of the correct color.

SI (Systeme Internationale): A system of physical units given official status and recommended for universal use by the General Conference on Weights and Measures. Known in French as Systeme International d'Unites, abbreviated as SI.

Signal mixing (TV cameras): Errors in a television camera signal for moving images caused by the time between the scans of a particular spot. During the time between scans the illumination from several spots in the scene falls on a single spot on the photodetector, resulting in a signal which is some weighted average of the signals for each spot in the scene. Analogous to the smear caused by uncompensated image motion in conventional cameras.

Signal strength: Amplitude of a signal, generally expressed in volts.

Signal-to-noise ratio (SNR): In electro-optical systems, the ratio of the value of the signal to that of the noise. The method used to measure the signal and the noise must be defined. A common definition in television systems is the peak signal voltage divided by the rms noise voltage. Root-mean-square signal voltages are sometimes used, as are amperages in lieu of voltages.

SIL (see speech interference level)

Sinc: Term designating the mathematical expression sin X/X.

Sine modulation: Variation in signal amplitude according to a sine function.

Sinusoidal grating: A target of alternating dark and light bars where some characteristic such as luminance varies according to the sine function.

SL (see sound level)

Small field flicker: Variation in perceived brightness of elements in single lines or small groups of lines having a visual angle approximately that of foveal vision (a solid angle of about 3 degrees).

Small field tritanopia: A normal reduction color discrimination for blue wavelengths for small color fields (nominally smaller than about 20 arc minutes), with the result that all colors can be matched by a mixture of two primaries, and purplish blues and greenish yellows are confused with neutral and with each other.

Snellen visual acuity: Measured by the ability to correctly read a standard set of letters of graduated size. Expressed as a comparison of the distance at which a given set of letters were correctly read to the distance at which the letters would be read by someone with clinically normal eyesight. A value of 20/80 indicates that an individual read at 20 feet the letters normally read at 80 feet. Also defined in Figure 3.1-12.

Snow (in CRT displays): A varying, speckled background, caused by noise.

SNR (see signal-to-noise ratio)

Sound level (SL): A measure of the overall loudness of sounds based on approximations of equal loudness of pure tones. It is a weighted measure, expressed in decibels, obtained by the use of a meter with specific weightings across the sound frequency spectrum.

Sound pressure (SP): The extent of the variation in atmospheric pressure produced by a sound wave. Measured in newtons/square meter (N/m^2) and normally used to mean the effective root-mean-square sound pressure.

Sound pressure level (SPL): The root-mean-square sound pressure expressed in decibels relative to a standard reference pressure (normally 2×10^{-5} N/m^2). See Section 6.6.2.

Spatial acuity: A general term referring to the visual ability to discriminate between targets on the basis of their relationships in space.

Spatial distribution: Allocation or apportionment of a quantity throughout a linear, areal or spatial extent, such as cycles per millimeter or candelas per square meter. In distinction to temporal distribution, which is the apportionment of a quantity over a time period, such as cycles per second (Hz).

Spatial frequency: A measure of the number of cycles in a grating or target of alternating light and dark bars as a function of their linear extent. Normally measured in terms of cycles/millimeter or cycles/degree of visual angle. Used in distinction to temporal frequency (usually designated simply frequency) which is expressed in units such as cycles per second (Hz).

Specific resolution: Smallest resolvable target size times the area of the pupil. Used in analyses such as the one in Section 3.3.2.

Spectral color: 1. A color corresponding to light of a single wavelength. Monochromatic color. (The spectral colors are listed in Figure 5.2-2.) 2. A color represented by a point on a straight line in the chromaticity diagram connecting the achromatic point (usually, the illuminant) and a spectral color as defined in (1) above.

Spectral distribution (of radiant energy): The relative or absolute amount of radiant energy at each wavelength along some portion of the electromagnetic spectrum. Portrayed as a continuous curve where the Y axis represents percentage, proportion, or absolute amount of energy and the X axis represents wavelength.

Spectral locus (see spectrum locus)

Spectral tristimulus values: Tristimulus values obtained when a (monochromatic) spectral color is matched to the three primaries. Usually identified as $\bar{x}$, $\bar{y}$ and $\bar{z}$ and listed or illustrated as in Figure 5.2-7 for a series of wavelengths along the visible spectrum.

Spectrum, electromagnetic, visible (see electromagnetic spectrum; visible spectrum)

Spectrum locus: Curve connecting points in chromaticity diagram that represent various (monochromatic) wavelengths of the spectrum.

Specular reflection: Reflection of electromagnetic waves where the direction of the incident and reflected waves makes equal angles with a line perpendicular to the reflecting surface and lies in the same plane with it.

Specular surface: A surface which provides a specular reflection, a shiny surface.

Speech interference level (SIL): The average in decibels of the sound pressure levels of the noise in three octave bands of center frequency 850, 1700, and 3400 Hz; if the 425-Hz octave has an SPL of more than 10 dB above the 850-Hz octave, it is also included in the average. See also preferred speech interference level (PSIL).

Spherical aberration: A monochromatic aberration occurring in simple refraction at a spherical surface, characterized by peripheral and paraxial rays focusing at different points along the axis. In the Gaussian theory, the focus of the system is identified with the paraxial rays, the peripheral rays being regarded as aberrant when they fail to intersect at the focal point of the paraxial rays.

Spot: In television cameras, CRT's, and optical line scan printers, the area covered by the electron or light beam on a surface such as the photodetector, phosphor or film. Also the area of luminance or film density caused by such a spot.

Spot shape: The geometric shape of a spot (see definition for spot). Also used to refer to the distribution of current, intensity or energy within a spot, this latter however is more properly called the spot spread function.

Spot size: The size of a spot defined in terms of a proportion of its maximum intensity level. Spot size is frequently expressed as the diameter in millimeters or inches of the spot at its 50 percent intensity level (see Figure 4.1-9).

Spot spread function: Distribution (in two dimensions) of current or light within the spot (see definition for spot).

Spot wobble: A process whereby a scanning spot is given a small periodic motion transverse to the scanning lines at a frequency above the picture signal spectrum.

Spread: See line spread function, point spread function or spot spread function.

Square-wave grating: A grating or target of alternating dark and light bars. The luminance (and color) across each bar is constant.

Stage (for aerial image display): That portion of a microscope or similar aerial image display which holds the film being viewed.

Staggered interlace: An interlace technique whereby lines in succeeding fields are intermixed rather than being contiguous as in the sequential interlace system.

Standard deviation: In statistics, the degree of deviation of scores from the mean, computed by taking the quadratic mean of the individual deviations from the arithmetic mean of these values, thus the root-mean-square of the deviations from the arithmetic mean. It is denoted by σ and the formula for its computation is:

$$\sigma = \left(\frac{\Sigma(x^2)}{N}\right)^{1/2}$$

where σ = standard deviation
x = deviation from arithmetic mean
N = total number of items

Standard observer (data): A set of color vision data obtained from a group of "normal" color vision subjects. A single average set of values based on the performance of this group was defined by the CIE as the standard observer.

Stereo acuity: The ability to perceive depth by the faculty of stereopsis, represented as a function of the threshold of stereopsis.

Stereo photogrammetry: The science or art of obtaining measurements of objects using stereoscopic imagery.

Stereopsis: 1. Binocular visual perception of three-dimensional space based on retinal lateral disparity; 2. Visual perception of depth or three-dimensional space.

Stereoscopic: Pertaining to or producing stereopsis.

Stiles-Crawford effect: The difference in stimulus effectiveness (brightness) of two pencils of light incident on the same retinal point, one passing through the center of the pupil and the other through an eccentric part of the pupil, the central pencil producing a more intense response.

Subcarrier: A carrier wave of constant amplitude and phase frequency used to generate a modulated wave that is applied, in turn, to modulate another carrier.

Subtractive color: Color produced by dyes or pigments that selectively absorb the radiant energy in a portion of the spectrum.

Surface color: Color perceived as belonging to a surface of a stimulus object as opposed to transparency or volume color.

Sweep circuit: A circuit that produces, at regular intervals, linear, circular, or other specified movement of the beam in a TV camera or CRT. Most commonly the beam movement is linear, and in a horizontal direction in systems used for image interpretation.

Temporal modulation: Time varying instead of spatially varying modulation.

Thick lens: A lens that is so thick that it must be represented in a ray trace diagram as having two nodal points and two principal planes.

Thin lens: A lens that is sufficiently thin that it can be represented in a ray trace diagram by a single nodal point and a single principal plane.

Third-field decay lag: The signal strength left on the scanned element of a television camera after the third scan subsequent to the removal of a specified illumination divided by the signal strength obtained during the illumination (also called third field lag).

Three-dimensional color space (for CRT's): A three-dimensional space defined by the amount of each of the three primary colors (red, blue, green) present on the display.

Threshold: The statistically determined point on the stimulus scale at which occurs a transition in a series of sensations or judgements.

Threshold contrast (see contrast threshold)

Total color blindness (see monochromatism)

Trackball: A continuous position control used to command the position of a cursor on a display. The control consists of a ball or sphere, normally of 3-4 inches in diameter, which is rotated about its center.

Transmission: The passing of radiant energy through a medium or space. See transmittance.

Transmittance: The ratio of radiant flux transmitted through a body to that incident on the body.

Transmittance histogram: A graphical representation of a frequency distribution of transmittance values by a series of rectangles which have, for one dimension, a distance proportional to a definite range of transmittance values and for the other dimension, a distance proportional to the number of times the transmittance values in each range appear in an image.

Transparency (as dimension of color): Attribute of appearance that permits perception of object or space through or beyond a surface.

Triad (in color CRT's): A grouping of three colored phosphor dots (red-, blue- and green-emitting) on the face of a CRT.

Tri-bar test target: A target consisting of three equal-sized bars of defined length and width. Spacing between the bars is usually equal to bar width. The most frequently used tri-bar target is illustrated in Figure 3.1-11.

Trichromatism: Color vision in which mixtures of three independently adjustable primaries (e.g., red, green, and blue) are required to match all perceived hues.

Trinitron: A type of color CRT with the aperture mask in the form of a grill.

Tristimulus values: The amounts of each of three primaries required to match a color. Symbols: X; Y; Z. See Section 5.2.1.3.

Tritanopia: A form of dichromatism in which all colors can be matched by suitable mixtures of only a red primary and a green (or blue) primary. Brightness (luminosity) of all colors is within normal limits. Sensitivity to differences in hue of blues, blue-greens, and greens is greatly reduced, but discrimination of short wavelength violets appears to be superior to that of normal observers.

Troland: A unit of retinal illuminance equal to that produced by viewing a surface having a luminance (photometric brightness) of 1 candle per sq. m. through a pupil having an area of 1 sq. mm. Originally called *photon* by Troland and later renamed in his honor to differentiate it from a photon of light energy. The relationship between scene luminance and retinal illuminance with a natural pupil is shown in Figures 3.2-14, -15 and -16.

TV line number: The number of scan periods per complete image scan (525 for U.S. commercial broadcast TV). The actual number of lines scanned on the camera image or CRT phosphor surface are less than the number of scan periods because of vertical retrace requirements. The lines actually scanned are referred to as the active lines.

Two-dimensional sampling: Sampling in both the horizontal and vertical directions.

Ultraviolet: Any radiant energy within the wavelength range about 10 to 380 nm.

Uncrossed disparity (see diverging disparity)

Uniform chromaticity scale (UCS): A CIE chromaticity diagram designed to provide a more uniform representation of smallest discriminable color differences. Illustrated in Figure 5.2-11.

Value (in the Munsell color system): A color dimension in the Munsell system corresponding to lightness or darkness.

Variance: A measure of the variability in a set of observations. Equal to the mean of the square of the differences between the observations of a random variable and the mean of the observations of that random variable. Equal to the standard deviation squared.

Veiling luminance: A non-patterned addition of light to the image such as to occlude the scene or diminish the contrast in the image. This could arise, for example, in situations where a bright light to one side precludes the perception of detail in the remaining portion of the field, or through the diffuse reflection of ambient illumination from the phosphor surface of a CRT.

Vergence: 1. The angular relationship between the rays of light from a single object point. Usually expressed in diopters (1/apparent distance, in meters, to the source of the light rays). 2. In some sources, the angle between the visual axes of the two eyes. In this handbook, this angle is referred to as the "eye convergence angle," not as vergence.

Vernier acuity: Visual acuity based on the ability to detect the alignment or the nonalignment of two lines, as in the reading of a vernier scale.

Vertex: The point of intersection of the optical axis with a refracting or reflecting surface.

Vertical alignment: The vertical position of two images relative to each other. Vertical alignment is usually expressed as misalignment, or the deviation from a condition of perfect alignment (see Section 3.7.1).

Vertical aperture equalization (see aperture equalization)

Vertical disparity (defined in 3.7.4.3)

Vertical phoria: The relationship, in the vertical direction, between the visual axes of the two eyes in the absence of a binocularly viewed fixation object.

Vertical resolution: 1. The number of active TV lines. 2. The number of distinct horizontal lines, alternately black and white, that can be seen in the CRT image of a television test pattern; it is primarily fixed by the number of horizontal lines used in scanning and by the Kell factor (see Figure 4.1-6).

Vertical retrace: The return of the electron beam to the top of the picture tube screen or the camera tube target at the completion of the field scan.

Vidicon: A camera tube in which a charge-density pattern is formed by photoconduction and stored on the surface of the photoconductor which is scanned by an electron beam, usually of low-velocity electrons.

Viewing distance: The distance to the image being viewed. Same as image distance in a display. Defined for aerial image displays in Figure 3.6-1. Usually expressed in this handbook as the vergence of the light rays entering the eye, in diopters.

Vignetting. 1. A graduated reduction in illumination at the edges of an image due to a series of stops in the lens system selectively blocking obliquely incident light. 2. The photographic process of gradually blending the picture with the surrounding ground.

Virtual image: An optical image that cannot be received on a screen; one formed by the backward prolongation of diverging rays to the point of apparent origin. The image seen by the user of an aerial image display is usually virtual.

Visible spectrum: The portion of the electromagnetic spectrum which contains wavelengths capable of stimulating the retina, approximately between 380 and 760 nm.

Visual acuity: 1. Ability to resolve or separate detail in a small high contrast target. 2. A unit equal to the reciprocal of the smallest resolvable target detail in arc minutes (see Figure 3.1-12).

Visual angle: The angle subtended by the extremities of an object at the entrance pupil or other point of reference of the eye.

Visual axis: 1. The line joining the point of fixation and the anterior (front) nodal point of the eye. 2. The line connecting the fovea to the point of fixation and passing through the nodal points of the eye. Since it connects both nodal points, it is a broken, not a single, straight line. In practice, the two nodal points are regarded as coincident, in which case it is a straight line. 3. In practice, the visual axis is often approximated by a line connecting the fixation point to the center of the eye entrance pupil.

Visual field: The area or extent of physical space visible to an eye in a given position.

Visual spectrum:(see visible spectrum)

Vitreous humor: The gelatinous, colorless, transparent substance filling the portion of the eyeball behind the lens. Illustrated in Figure 3.1-1.

Wavelength: The distance in the line of advance of a wave from any one point to the next point at which, at the same instant, the phase is the same.

White: (1) An achromatic color of maximum lightness, representing one limit of a series of grays. (2) The visual sensation typically evoked by radiant energy with the spectral distribution approximating normal daylight. (Note – Spectral distributions of radiant energy that appear white when viewed singly can appear to have a distinct hue when viewed in a side-by-side situation. Similarly, a surface that appears to have a low saturation hue when first seen may appear white after a period of continuous viewing.)

White noise: In electronics, unwanted variations in signal strength (noise) which have equal power for each frequency over a specified range of frequencies. Also called flat noise.

Working distance: 1. In the use of microscopes and other optical devices, the distance from the objective lens to the object viewed; 2. The distance at which a display operator desires or is required to read or perform other essential functions.

Writing speed (CRT): Lineal scanning rate of the beam across the phosphor surface of a CRT.

Zoom (magnification): Continuously variable magnification, as opposed to magnification variable only in discrete steps.

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