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DESIGN PROBLEMS IN VISUAL DISPLAYS

Part I. Classical Factors in the Legibility of Numerals and Capital Letters

JUNE 1966

D. Shurtleff

Prepared for

DEPUTY FOR ENGINEERING AND TECHNOLOGY

DECISION SCIENCES LABORATORY

ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

Project 7030

Prepared by

THE MITRE CORPORATION
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ABSTRACT

The effects of classical factors, such as symbol geometry, symbol brightness, and brightness contrast, upon the legibility of numerals and capital letters are discussed. The literature of the last few decades is evaluated, and selected studies are reviewed in detail and referenced. Conclusions are drawn, and recommendations are made for display design and application.

<u>REVIEW AND APPROVAL</u>

This Technical Report has been reviewed and is approved.

JAMES D. BAKER
703 Project Officer
Decision Sciences Laboratory

ROY MORGAN
Colonel, USAF
Director, Decision Sciences Laboratory

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GLOSSARY

Accuracy of Identification. The number of correct symbol identifications divided by the total number of symbol identifications times 100.

Advanced Display Console. A modified IBM console with an internal memory and a Stromberg-Carlson, new, bright charactron.

Ambient Illumination. The light incident upon the display and surrounding areas. The light density in these areas is typically measured in foot-candles.

Blur. In the Howell and Kraft study, the width of the transition gradient from figure to ground divided by the stroke-width of the symbol. Different widths of the transition gradient were obtained by defocussing the symbol.

Brightness. A photometric term describing a human judgment of the intensity of a light source. There are many units in which the brightness is measured, but they may be divided into two classes: (a) luminance, which is measured in candles per unit area (mm., cm., etc.) and (b) luminance emittance, which is measured in lambert units or any combination of lambert units. For a detailed discussion of brightness and other photometric terms see Reference 1, page 96.

Brightness Contrast. A measure of the relative difference between the brightness of a symbol and the brightness of the symbol's background. There are several different equations for determining brightness contrast. The one used in this paper was suggested by R. T. Mitchell. It is: brightness contrast equals the brightness of the symbol minus the brightness of the background all divided by the brighter of the two. Brightness contrast can vary from minus 1.00 to plus 1.00. Negative values of contrast indicate that the symbol is darker than the background, and positive values of contrast indicate that the symbol is lighter than the background.

Charactron. A shaped-beam direct-view cathode-ray tube.

Confusion Matrix. A table showing the number of times each of "n" symbols is presented and the frequency with which a symbol is identified either correctly or as any one of the "n-1" other symbols. The matrix is useful for such things as indicating particular symbol pairs which are commonly confused, particular symbols which are generally confused with many other symbols, identification preferences of the subjects, etc.

Foot-Candle. The illumination falling on a surface which is located at a distance of one foot from a point source of one international candle.

Foot-Lambert (ft.-l). A measure of luminous emittance (see brightness)

Lebensohn Test. A test chart for determining visual acuity at reading distances (one foot). It employs the principle of the Grow chart in which blocks of letters can be masked into columns or rows as a means of decreasing the possibility of the subject's memorizing letter sequences.

Legible. Traditionally, capable of being read or deciphered, and was used to refer to both text and single symbols. It has no standard meaning. It is used by some investigators to refer to a property of letters and numerals, and by other investigators to refer to a property of text. In this report, legibility refers to a property of letters and numerals which is measured in objective performance units of identification accuracy, rate, speed, and threshold.

GLOSSARY (Cont'd)

Multitest Visual Devices. Multitest screening instruments (the Bausch and Lomb Ortho-Rater and the Keystone Telebinocular) which are, essentially, compact and portable stereoscopes. By a suitable optical system, the standard distance for determining far acuity (20 feet) is simulated optically while the test for near acuity (1 foot) is made either at the actual distance or at its optical equivalent. The testing devices also provide for a measure of phoria and color vision.

Normal Line-of-Sight. The line connecting the fovea to the point of fixation (visual axis) perpendicular to the display surface. In practice, the two eyes are regarded as coincident, in which case the normal line of sight is considered as a single, straight line. The studies in this report refer to the zero degree viewing angle when the visual axis is perpendicular to the display surface; to other investigators, however, this represents a 90-degree viewing angle.

Self-Paced. A symbol identification procedure in which the rate of symbol presentation is partly, or wholly, dependent upon the rate at which the subject is able to identify symbols.

Serif. A fine line or embellishment appearing chiefly at the ends of symbol strokes.

Snellen Test. A visual acuity test chart made up of letters designed by Snellen. The chart consists of rows of letters in decreasing sizes, and it is normally used as a test for far vision (20 feet). An acuity score is obtained for each eye and for both eyes and represents the distance at which the testee is able to identify letters correctly, expressed as a ratio to the distance at which subjects with "normal" vision are able to read the same letters.

Spacing. A measure of the distance between vertical tangents erected at the outer limits of adjacent symbols.

Speed of Identification. The rapidity with which a symbol is identified by the subject. In experimental psychology, it is a measure of reaction time and is the interval between the presentation of a stimulus (symbol) and the subject's response (identification). Estimates of identification speed are often unknowingly biased by the measurement technique. If care is not taken to eliminate from speed scores artifacts arising from apparatus delays in symbol presentation and response recording, then speed scores will not mean the same thing in different studies.

Symbol Set. The 26 letters of the alphabet, the 10 numerals, or all alphanumerics, consisting of the 26 letters of the alphabet and the 10 numerals.

Tachistoscope. An experimental device for controlling the exposure of stimulus material, e.g., symbols.

Threshold of Identification. The distance from the eye of the subject to the symbols when the number of identifications by the subject are either 50 percent correct (50 percent threshold) or 100 percent correct (100 percent threshold). The distances are typically determined by initially placing the symbol sufficiently far away from the subject so that he is able to make only a few correct identifications and subsequently moving the symbols closer to the subject, in small steps, until he is able to identify correctly 50 or 100 percent of the symbols presented.

Transilluminated. A method of symbol illumination in which the light source is either viewed directly by the subject or is viewed on a translucent screen of some type. The word is used to differentiate this type of illumination from that of reflected light. In transilluminated displays, the transmission properties of the screen determine, in part, the light characteristics of the symbol. In reflected displays, the light characteristics of the symbol are determined, in part, by the reflectant properties of the material used to construct the symbol, e.g., ink, pencil, tape, print, etc.

Visual Acuity. The ability of the eye to distinguish fine detail. Near acuity is a measure of resolving power of the eye at a distance of approximately 1 foot. Far acuity is a measure of the resolving power of the eye at a distance of approximately 20 feet. In experimental studies, acuity is commonly reported as the reciprocal of the smallest detail, measured in minutes of arc, which the eye is capable of resolving.

In the Snellen test at a rating of 20/20, the subject is said to be able to resolve detail subtending one minute of arc at the eye. However, other tests of acuity indicate that the eye is capable of resolving much finer detail. For example, under ideal conditions, the eye is capable of resolving a length of wire across a bright field when the width of the wire subtends approximately one-half second of visual angle.

Visual Angle. The angle subtended at the eye by a visual object. For example, the visual angle, $\theta = 2 \tan x$, where $x = h/2d$, h = the height of the symbol, and d = the distance from the symbol to the eye of the subject. See Appendix I for calculation of visual angles of subtense for several distances of viewing and heights of symbol.

SECTION I

INTRODUCTION

LEGIBILITY SPECIFICATIONS

This report defines the classical factors in the legibility of numerals and capital letters for the development of legibility specifications for procuring visual display devices. Two of the more important objectives of legibility specifications are: (a) to insure that display symbols can be quickly and accurately identified by the user and (b) to provide objective criteria which the manufacturer and procurer of display equipment can use as a basis for agreement about the acceptability of a given display device.

Specification of Physical Factors and Performance Criteria

These objectives can be met in two ways. One way is to specify for each relevant physical factor the exact value required for acceptable operator performance. Examples of these factors are symbol geometry, blur, jitter, refresh rate, etc. A great deal of technical information showing the effects of each factor and their interactions on legibility would have to be available before appropriate values could be specified for a particular application.

A second way of achieving the same objectives is to specify acceptable operator performance criteria which must be met by a given display device. When performance specifications are used, it is necessary to show, in an operational or simulated operational setting, that the display symbols can be identified by the operator with a degree of accuracy and speed which is agreeable to both parties concerned.

Inadequate Physical Factors Data

Initially an attempt was made to write legibility specifications by designating appropriate values of each physical factor involved. This approach seemed more in keeping with tradition and did not entail time consuming operator performance testing. However, it became apparent, after a review of the technical literature on legibility, that the existing data on the physical factors were inadequate and could not satisfy the first objective of legibility specifications stated above.

Performance Criteria

The second approach, namely the specification of operator performance criteria, was adopted as the one most feasible at this time. It was recognized that the choice of operator performance specifications resulted from a process of elimination rather than from a consideration of the relative merits of the two approaches: it is generally agreed that the specification of optimal values for the factors involved is more desirable in the long run.

Review of Legibility Literature Needed

It was felt that a first step in providing the necessary data for the specification of physical factors should consist of a review and organization of the material already available. In this way, the usefulness and limitations of the existing literature for writing legibility specifications could be determined. Accordingly, an extensive review of the literature was begun three years ago. Documents and papers were collected, regardless of date of publication, and critically reviewed. Nearly three hundred studies were examined. The extensive literature on legibility necessitated dividing it in some way in order to reduce the review to manageable proportions. One possibility is the division of the physical factors related to legibility. The physical factors can be categorized into classical factors versus those introduced by modern display equipment. The former factors are those which were investigated early in the history of legibility (e.g., brightness, stroke-width, spacing) while the latter are those factors introduced relatively recently by the evolution of modern display equipment (e. g., refresh rate, blur (by optical defocussing), TV linear scanning). This arbitrary division of the physical factors in no way reflects upon their importance in legibility nor does it rule out the necessity for determining interactions among factors in the two categories. The effects on legibility of factors introduced by optical, mechanical, and electrical components of modern display equipment as well as the interaction of these factors with classical factors will be reported in a second paper. Of those concerned with classical factors, thirty-one were found satisfactory for reference and detailed review in this paper. This literature reports only the effects of classical factors on the legibility of capital letters and numerals.

A Guide to Design Legibility

In presenting the literature on the legibility of capital letters and numerals, an effort was made to organize the data into a guide, in a way most useful to people who write and/or evaluate legibility specifications for visual displays. However, even in the relatively narrow area of legibility as the one summarized here, the data are not complete enough, nor described in sufficient detail, for one to be able to specify unequivocally what the values of each relevant factor should be for a given display situation.

Purposes

The major purposes of the guide at the present time are: to indicate those values of each factor which provide some assurance that the symbols will pass a typical operator performance specification; to indicate where the source of trouble may be if a display fails to pass a performance specification; and to indicate the areas in which more research is needed to provide adequate data for specifications of optimal values of relevant factors.

Features

The legibility literature is classified according to the particular factor(s) investigated and the measure of the subject's performance. The experimental findings for each of these categories are summarized, and the best estimates of the effects on performance of each factor are presented. Recommendations are made of the conditions most likely to yield maximum performance within each category.

The reasons for separate treatment and presentation of literature based upon different measures of performance are as follows. First, the intercorrelations among the various performance measures are not known with any precision. At the present time there are no equations which will enable one to determine, for example, what the precise values of speed or rate of symbol identifications will be, given the accuracy of symbol identification. Second, the performance requirements for all display situations are not the same. In some situations, speed or rate of symbol identification is not critical and only a high degree of identification accuracy is required. In other situations, both rate and accuracy of symbol identification are important, and in still other situations, it may be important to determine the minimal symbol size required for identification. Therefore, those sections should be consulted which are most relevant to the particular display situation of interest.

Tabulations of Experimental Findings

In some cases, where most of the details of an experiment are reported, the findings are summarized in tables. The tables indicate the effects of a number of different factors on performance, and they suggest, in addition, how "trade offs" may be made among the factors by showing how they interact with one another. Each table also includes a detailed description of the situation in which the measurement was made. A comparison of the situations described in the tables with the display situation of interest will give a rough approximation of the extent to which one can generalize the findings from the experimental situation to the applied situation.

Limitations of the Guide

There are numerous reasons why the guide is not a definitive reference source on symbol legibility:

(a) The studies reported have not been designed to develop general principles of symbol legibility; their intent has been to answer specific questions raised by a particular application.

(b) Even at the applied level, researchers have not attempted to study legibility as affected by all relevant factors.

(c) The factors which have been investigated have not been explored systematically throughout their entire ranges; only selected values determined by a particular application have been studied.

(d) Studies which have explored a given factor have often used different experimental techniques: one cannot relate the findings of one study to those of another because the respective results are determined, partly by different experimental procedures, and partly by different values of the factors investigated.

(e) The effects on symbol legibility attributed to variations within a single factor are dependent upon the situation in which the measurement was made. That is to say, there are interactions among the factors which affect symbol legibility. For example, the effect that a given value of stroke-width has on symbol legibility depends upon the particular values of brightness,

brightness contrast, etc., used; therefore, statements about the effects of stroke-width must be qualified accordingly.

(f) Many of the factors affecting legibility have not received enough experimental investigation for their effects to be understood.

(g) A number of experiments that should be included in this reference could not be obtained because they were out of print or were otherwise not attainable.

(h) Many studies were excluded from detailed consideration because of their failure to specify the exact situation in which the measurement was made: incompleteness in the description of the situation in which performance was measured makes it impossible to determine the situations for which the finding is valid and the situation for which it is invalid; therefore, such findings are of little practical significance and such material is reported only when there are no better data available.

The legibility data are limited further to short-term performance: the experimental sessions lasted from about 15 to 60 minutes. It would be expected that the data summarized here are not applicable to situations in which the operator is required to perform for long periods of time. Some correction of the performance data would be required to take into account such effects as fatigue, boredom, eye strain, and so on. It might be expected that the latter factors would have a more deleterious effect on performance in marginal display situations than in good display situations. In any event, the corrections needed to extend these data to long-term performance are not known at the present time.

SECTION II

SUMMARY OF THE EFFECTS OF CLASSICAL FACTORS ON LEGIBILITY

SYMBOL BRIGHTNESS AND BRIGHTNESS CONTRAST

Accuracy of Identification

The Howell and Kraft Study

Howell and Kraft[2] report the effects on identification accuracy of several values of brightness contrast, visual angle, and symbol blur in a simulated radar-type display situation. Each of 12 subjects was asked to identify singly presented alphanumerics (see Figure 1) in 64 different experimental conditions: the 64 conditions represented all possible combinations of 4 values of brightness contrast, visual angle, and blur. The subjects were instructed to work for both speed and accuracy in a self-paced situation. The data from this study, presented in Table I, show only the results for the two extreme values of brightness contrast used, namely, +0.97 and +0.92. Table I indicates that for blur values of 0.00 and 0.55, and angles of subtense from 16.4 to 36.8 minutes of arc, brightness contrast has little effect on identification accuracy. For the latter conditions, symbol brightness can be reduced approximately 2/3 (from a contrast value of +0.97 to a contrast value of +0.92) without a decrease in identification accuracy.

The Crook, Hanson and Weisz Study

Crook, Hanson and Weisz[4] report the effects on identification accuracy of several values of brightness contrast, visual angle, symbol spacing, and symbol stroke-width. The study was the third in a series of experiments on the legibility of symbols used on aeronautical charts. Twelve subjects identified letters (see Figure 2) in 54 different experimental conditions

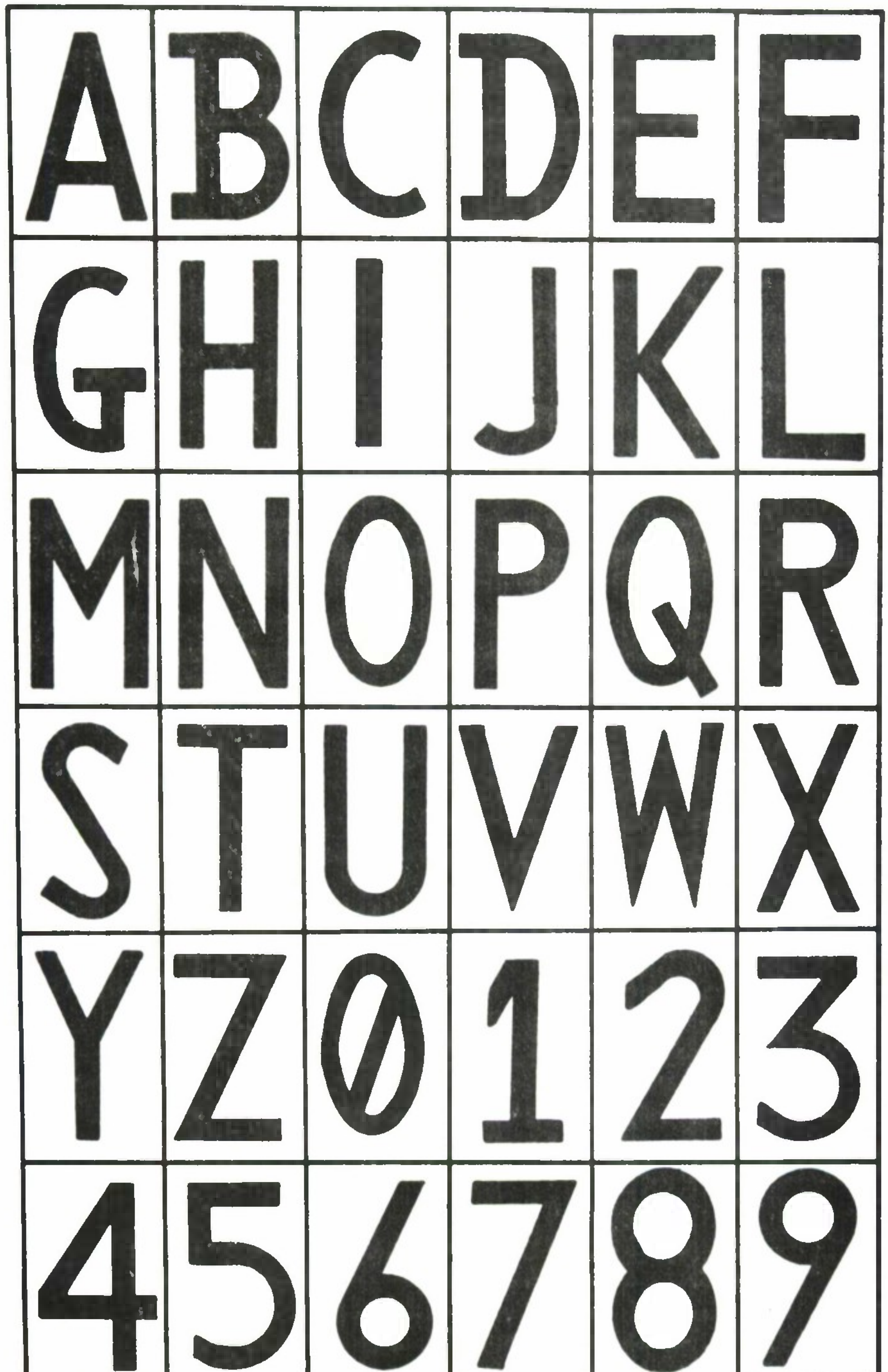

Figure 1. Letters and Numerals Used by Howell and Kraft

Table I

Accuracy of Identification

Visual Angle In Minutes of Arc	Blur	Brightness Contrast	Percentage Correct
36.8	2.82	+.97	95.4
		+.92	88.8
	1.66	+.97	96.9
		+.92	94.7
	0.55	+.97	97.3
		+.92	96.7
	0.00	+.97	98.0
		+.92	97.9
26.8	2.82	+.97	96.4
		+.92	93.6
	1.66	+.97	97.7
		+.92	96.4
	0.55	+.97	97.9
		+.92	97.3
	0.00	+.97	98.3
		+.92	97.3
16.4	2.82	+.97	94.2
		+.92	87.4
	1.66	+.97	96.9
		+.92	93.0
	0.55	+.97	96.8
		+.92	96.3
	0.00	+.97	97.6
		+.92	96.3
6.0	2.82	+.97	47.0
		+.92	23.2
	1.66	+.97	48.3
		+.92	30.0
	0.55	+.97	57.7
		+.92	48.3
	0.00	+.97	65.3
		+.92	50.8

(Table I Continued)

Table I Continued

Description of Experimental Conditions

Symbol Brightness: 46 and 134 foot-lamberts

Background Brightness: 3.5 foot-lamberts

Ambient Illumination: 3.5 foot-lamberts

Properties of Light Source: Not stated

Symbol-Background Relation: Light on dark

Symbol Style: Mackworth Style with modified zero and one (see Figure 1)

Symbol Stroke-Width: 13 percent of height

Horizontal Spacing: Not relevant

Symbol Width: 53 percent of height

Symbol Exposure Time: Not relevant

Number of Symbols: 26 letters and 10 numerals (Complete set of alphanumerics)

Number of Subjects: 12

Visual Characteristics of Subjects: Experimentally corrected to 20/20

Viewing Distance: Not stated

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consisting of all combinations of three values of brightness contrast, two values of symbol spacing, three values of visual angle and three values of stroke-width. The letters were arranged in 12 horizontal lines with 30 letters to the line on test sheets 3 5/8 inches high and 4 1/4 inches wide. The sheets were stacked face down in front of the subject who turned them over into a reading position during the experiment. The subjects were instructed to work for both speed and accuracy when identifying letters. The results of this study are presented in Table II and indicate, for visual angles of 22 and 16 minutes of arc and for a stroke-width of 20.1 percent of height, that background brightness can be reduced approximately 40 percent

News Gothic	ABCDEFGHIJKLMNOPQRS	1234567890
New Gothic Condensed	ABCDEFGHIJKLMNOPQRSTUVWXYZ	1234567890

Figure 2. Letters Similar to Those Used by Crook, Hanson and Weisz

(corresponding to a brightness contrast of -0.90) without decreasing accuracy of identification. There was a decrease in accuracy corresponding to each decrease in brightness contrast when the angle of subtense was 11.0 minutes of arc.

Conclusions and Recommendations

These results show that in some display situations brightness contrast as small as 0.90 can be used without impairing accuracy of identification. Tables I and II indicate the conditions for which a contrast of 0.90 will be satisfactory and how brightness can be traded off with other factors without loss in identification accuracy. For example, Table II shows that contrast in excess of 0.90 will be needed if symbols in the smallest stroke-width are used.

Table II

Accuracy of Identification

Visual Angle in Minutes of Arc	Brightness Contrast	Stroke-Width in Percent of Symbol Height	Spacing in Percent of Symbol Height	Percentage Correct
22.0	-.94	9.8	35.6	99.7
			63.2	99.6
		20.1	35.6	99.8
			63.2	99.6
		30.0	35.6	98.8
			63.2	99.0
	-.90	9.8	35.6	99.2
			63.2	99.0
		20.1	35.6	99.4
			63.2	99.8
		30.0	35.6	99.1
			63.2	98.8
	-.81	9.8	35.6	94.7
			63.2	95.9
		20.1	35.6	99.1
			63.2	98.5
		30.0	35.6	95.8
			63.2	95.6
16.0	-.94	9.8	35.6	98.8
			63.2	98.9
		20.1	35.6	99.4
			63.2	99.7
		30.0	35.6	97.3
			63.2	97.9
	-.90	9.8	35.6	97.3
			63.2	97.0
		20.1	35.6	99.1
			63.2	98.8
		30.0	35.6	96.7
			63.2	96.1

(Table II Continued)

Table II Continued

Visual Angle in Minutes of Arc	Brightness Contrast	Stroke-Width in Percent of Symbol Height	Spacing in Percent of Symbol Height	Percentage Correct
16.0 (cont'd)	-.81	9.8	35.6	80.6
			63.2	78.2
		20.1	35.6	95.3
			63.2	95.3
		30.0	35.6	88.8
			63.2	87.5
11.0	-.94	9.8	35.6	94.0
			63.2	91.8
		20.1	35.6	96.7
			63.2	94.9
		30.0	35.6	89.8
			63.2	90.2
	-.90	9.8	35.6	81.1
			63.2	78.0
		20.1	35.6	93.7
			63.2	89.4
		30.0	35.6	86.8
			63.2	84.3
	-.81	9.8	35.6	62.7
			63.2	53.9
		20.1	35.6	75.9
			63.2	68.0
		30.0	35.6	65.8
			63.2	58.3

Description of Experimental Conditions

Symbol Brightness: 0.004 foot-lamberts

Background Brightness: 0.021, 0.041 and 0.071 foot-lamberts

Ambient Illumination: Not stated (Probably negligible since experiment conducted in light tight booth)

Table II Continued

Properties of Light Source: Westinghouse spotlight #4345 operated at 6.4 volts covered with Corning red glass #2403

Symbol-Background Relation: Dark on light

Symbol Style: Gothic (Similar to News Gothic shown in Figure 2)

Symbol Width: 86.3 percent of height

Symbol Exposure Time: Not relevant

Number of Symbols: 26 letters (Complete alphabet)

Number of Subjects: 12

Visual Characteristics of Subjects: 20/20 near and far vision on Bausch and Lomb Ortho-Rater and normal color vision. Dark adapted 10 minutes prior to experimental session.

Viewing Distance: 10 to 20 inches

Rate and Speed of Symbol Identification

The studies described above also measured the rate at which subjects were able to make symbol identifications. In addition, a study reported by Schapiro [3] shows speed of symbol identification to be affected by a decrease in symbol brightness from 1.0 to 0.01 foot-lamberts.

The Howell and Kraft Study

The data from the Howell and Kraft study [2], presented in Table III, shows that brightness contrast can be reduced from +0.97 to +0.92 without decreasing the rate of symbol identification provided that the visual angle of subtense is 16 minutes of arc or greater and that symbol blur is 0.00. When the visual angle is 6 minutes of arc, the rate of identification drops off markedly for both values of contrast, particularly for a contrast of +0.92.

Table III

Rate of Identification

Visual Angle in Minutes of Arc	Blur	Brightness Contrast	Symbols Per Second
36.8	2.82	+.97	1.26
		+.92	1.20
	1.66	+.97	1.31
		+.92	1.24
	0.55	+.97	1.36
		+.92	1.29
	0.00	+.97	1.34
		+.92	1.30
26.8	2.82	+.97	1.27
		+.92	1.21
	1.66	+.97	1.34
		+.92	1.22
	0.55	+.97	1.36
		+.92	1.31
	0.00	+.97	1.34
		+.92	1.32
16.4	2.82	+.97	1.16
		+.92	1.03
	1.66	+.97	1.30
		+.92	1.10
	0.55	+.97	1.28
		+.92	1.21
	0.00	+.97	1.29
		+.92	1.26
6.0	2.82	+.97	.70
		+.92	.66
	1.66	+.97	.72
		+.92	.66
	0.55	+.97	.82
		+.92	.66
	0.00	+.97	.78
		+.92	.65

(Table III Continued)

Table III Continued

Description of Experimental Conditions

Symbol Brightness: 46 and 134 foot-lamberts

Background Brightness: 3.5 foot-lamberts

Ambient Illumination: 3.5 foot-lamberts

Properties of Light Source: Not stated

Symbol-Background Relation: Light on dark

Symbol Style: Mackworth with modified zero and one (see Figure 1)

Symbol Stroke-Width: 13 percent of height

Horizontal Spacing: Not relevant

Symbol Width: 53 percent of height

Symbol Exposure Time: Not relevant

Number of Symbols: 26 letters and 10 numerals (Complete set of alphanumerics)

Number of Subjects: 12

Visual Characteristics of Subjects: Experimentally corrected to 20/20

Viewing Distance: Not stated

The Crook Hanson and Weisz Study

Crook, Hanson, and Weisz [4] also report rates of symbol identification and these data are presented in Table IV. For each value of visual angle and stroke-width, a consistent, although in some cases slight, decrease in rate of identification is noted when brightness contrast was reduced from -0.94 to -0.81. The decrease in rate caused by a reduction in brightness contrast can be offset to some degree by use of an optimal symbol stroke-width, in this case about 20 percent of symbol height.

Table IV

Rate of Identification

Visual Angle in Minutes of Arc	Brightness Contrast	Stroke-Width in Percent of Symbol Height	Spacing in Percent of Symbol Height	Symbols per Second
22.0	-.94	9.8	35.6	3.2
			63.2	3.1
		20.1	35.6	3.2
			63.2	3.3
		30.0	35.6	3.1
			63.2	3.2
	-.90	9.8	35.6	2.8
			63.2	2.7
		20.1	35.6	3.1
			63.2	3.1
		30.0	35.6	3.0
			63.2	2.9
	-.81	9.8	35.6	1.7
			63.2	1.7
		20.1	35.6	2.8
			63.2	2.7
		30.0	35.6	2.3
			63.2	2.2
16.0	-.94	9.8	35.6	2.7
			63.2	2.8
		20.1	35.6	3.1
			63.2	3.1
		30.0	35.6	2.7
			63.2	2.7
	-.90	9.8	35.6	2.2
			63.2	2.3
		20.1	35.6	2.8
			63.2	2.7
		30.0	35.6	2.6
			63.2	2.4
	-.81	9.8	35.6	0.8
			63.2	0.9
		20.1	35.6	2.1
			63.2	2.1
		30.0	35.6	1.8
			63.2	1.6

(Table IV Continued)

Table IV Continued

Visual Angle in Minutes of Arc	Brightness Contrast	Stroke-Width in Precent of Symbol Height	Spacing in Percent of Symbol Height	Symbols per Second
11.0	-.94	9.8	35.6	1.7
			63.2	1.7
		20.1	35.6	2.3
			63.2	2.3
		30.0	35.6	1.9
			63.2	1.8
	-.90	9.8	35.6	0.9
			63.2	1.1
		20.1	35.6	1.8
			63.2	1.7
		30.0	35.6	1.6
			63.2	1.4
	-.81	9.8	35.6	0.2
			63.2	0.3
		20.1	35.6	0.8
			63.2	0.9
		30.0	35.6	0.8
			63.2	0.8

Description of Experimental Conditions

Symbol Brightness: 0.004 foot-lamberts

Background Brightness: 0.021, 0.041, 0.071 foot-lamberts

Ambient Illumination: Not stated (Probably negligible since experiment conducted in light tight booth)

Properties of Light Source: Westinghouse spotlight #4345 operated at 6.4 volts covered with Corning red glass #2403

Symbol-Background Relation: Dark on light

Symbol Style: Gothic (Similar to News Gothic shown in Figure 2)

Symbol Width: 86.3 percent of height

(Table IV Continued)

Table IV Continued

Symbol Exposure Time: Not relevant

Number of Symbols: 26 letters (Complete alphabet)

Number of Subjects: 12

Visual Characteristics of Subjects: 20/20 near and far acuity on Bausch and Lomb Ortho-Rater and normal color vision. Dark adapted for 10 minutes prior to experimental session

Viewing Distance: 10 to 20 inches

The Schapiro Study

Schapiro[3] had 12 subjects identify numerals in each of 4 symbol styles, 4 stroke-widths and 4 brightnesses (see Figure 3). A factorial design (in which each subject identified numerals for each combination of the experimental conditions) was used. The results of the study are presented in Table V and show that speed of identification decreased progressively as symbol brightness was reduced from 1.0 to 0.01 foot-lamberts. However, the only statistically significant differences in speed were between a symbol brightness of 0.01 foot-lamberts and each of the other values of symbol brightness.

Conclusions and Recommendations

For display situations described in Tables III and IV brightness contrast can vary from 0.97 to 0.90 without impairment of the rate of symbol identification provided that the visual angle of subtense is larger than 16 minutes of arc and that stroke-width is approximately 20 percent of symbol height. However, the reason for the difference in rates of symbol identification for the two studies is not clear, the difference being almost two to one in favor of the Crook study.

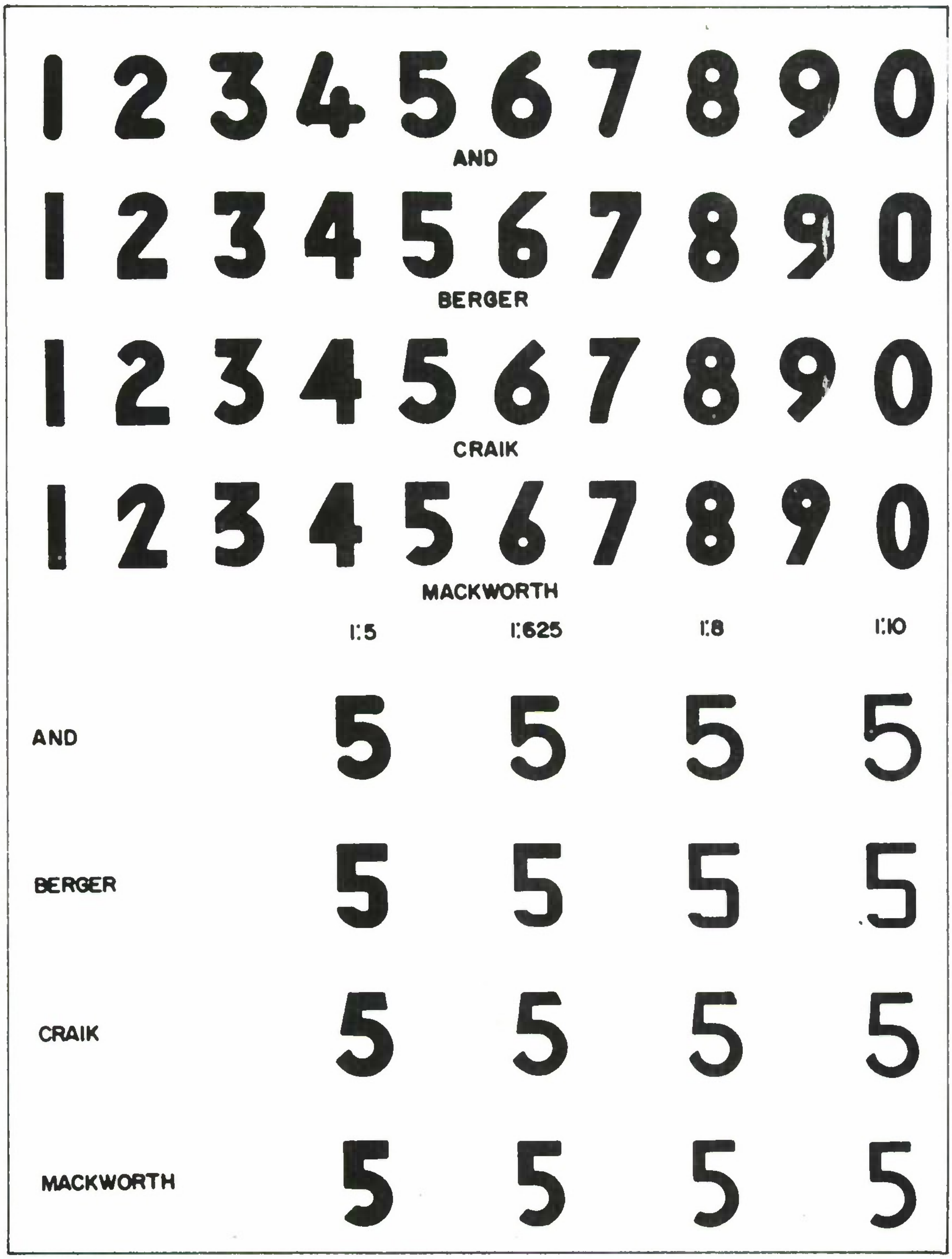

Figure 3. Numerals Used by Schapiro

Table V

Speed of Identification

Symbol Brightness in Foot-Lamberts	Stroke-Width in Percent of Symbol Height	Speed in Seconds
1.0	10.0	.47
	12.5	.47
	16.0	.47
	20.0	.47
0.15	10.0	.50
	12.5	.50
	16.0	.50
	20.0	.49
0.04	10.0	.55
	12.5	.54
	16.0	.53
	20.0	.53
0.01	10.0	.98
	12.5	.87
	16.0	.81
	20.0	.77

Description of Experimental Conditions

Background Brightness: About 0.2, 0.03, 0.008 and 0.002 foot-lamberts for symbol brightnesses of 1.0, 0.14, 0.04 and 0.01 foot-lamberts respectively

Ambient Illumination: Not stated (Probably negligible since experiment conducted in light tight booth)

Properties of Light Source: 300 watts, 120 volts standard slide projection lamp operated at 60 volts

Symbol-Background Relation: Light on dark

Symbol Style: AND10400, Berger, Craik, Mackworth

Horizontal Spacing: Not relevant

Symbol Width: 65, 52, 61 and 50 percent of height for the AND, Berger, Craik and Mackworth, respectively

(Table V Continued)

Table V Continued

Angle of Subtense: 32 minutes of arc

Symbol Exposure Time: 0.95 seconds

Number of Symbols: 10 numerals in each style

Number of Subjects: 12

Visual Characteristics of Subjects: "Normal" near and far acuity, depth perception, lateral and vertical phoria as measured by Bausch and Lomb Ortho-Rater

Viewing Distance: 28 inches

One of the reasons for the difference may be the way in which the symbols were presented for identification. In the Crook, et al study, no apparatus delays were involved in the presentation of successive symbols since the subject merely identified a series of printed symbols. In the Howell and Kraft study, a voice key was used to pulse a relay which in turn advanced a film strip projector a single frame. It is possible that part of the difference in rates of symbol identification was due to lag time in the projection of successive symbols.

Another factor which may account, in part, for the rate differences reported in the two studies is the type of format used to display symbols. In the Howell and Kraft study, the symbols were presented one at a time. In the Crook, et al study, many symbols were presented at once. Schapiro's data suggest that when symbols are presented one at a time for identification, as in the Howell and Kraft study, the maximum rate should be approximately 2.0 to 2.1 symbols per second which, like that reported by Crook, is faster than those reported by Howell and Kraft. Therefore, the low rates of identification reported by Howell and Kraft are probably a joint product of the lag time in the projection of successive symbols (which probably accounts for the differences between the estimated rate of identification from the Schapiro data and that reported by Howell and Kraft) and the manner of symbol presentation (which probably accounts for the difference between the estimated rate of identification from the Schapiro data and that reported by Crook, et al.).

If the preceding analysis is correct, then it appears that subjects are able, under appropriate conditions (see Table V), to identify symbols at a rate of 3.0 to 3.3 per second when the display consists of symbol arrays, and at a rate of 2.0 to 2.1 per second when the display consists of symbols presented one at a time.

Threshold of Identification

The effects of symbol or background brightness on identification thresholds have been reported in two independent studies: Shurtleff, et al.[5] and Kuntz and Sleight.[6] Only the former study will be reported in detail since Kuntz and Sleight failed to report the height of the symbols used so that it is impossible to calculate the visual angle subtended by the symbols at threshold.

The Shurtleff, Botha and Young Studies[5]

Shurtleff, Botha and Young, in two exploratory studies, investigated the effects of symbol or background brightness, letter spacing and surround brightnesses on the 50-percent threshold of identification. The letters were arranged in matrices with each matrix containing 4 rows and 5 columns. The data from this study, presented in Table VI, indicate that an increase in symbol or background brightness from 20 to 40 foot-lamberts did not improve the threshold while, in most cases, the threshold was impaired when symbol or background brightness was decreased from 20 to 1 foot-lambert. It was

Table VI

Threshold of Identification*

Symbol or Background Brightness in Foot Lambert's	Symbol Background Relation	Symbol Spacing in Percent of Height	Reciprocals of Visual Angle
1	D/L	25	.30
		200	.32
	L/D	25	.30
		200	.31
20	D/L	25	.40
		200	.44
	L/D	25	.32
		200	.40
40	D/L	25	.40
		200	.44
	L/D	25	.32
		200	.41

*In the table, identification thresholds have been converted to acuity scores.

Description of Experimental Conditions

Brightness Contrast: ± 0.94

Ambient Illumination: Brightness throughout most of the visual field was controlled and was 1, 20 and 40 foot-lamberts for background brightness of 1, 20 and 40 foot-lamberts respectively. For symbol brightness of 1, 20 and 40 foot-lamberts the ambient was 0.06, 1.2 and 2.4, respectively

Properties of Light Source: Cool White Fluorescent

Symbol Style: Futura Medium (Figure 6)

Symbol Stroke-Width: 16 percent of symbol height

(Table Continued)

Table VI Continued

Symbol Width: 77 percent of symbol height

Symbol Exposure Time: Not relevant

Number of Symbols: 26 letters (Complete alphabet)

Number of Subjects: 2

Visual Characteristics of Subjects: 20/20 near and far acuity on Bausch and Lomb Ortho-Rater and normal color vision

Viewing Distance: Was varied to obtain visual thresholds

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estimated subsequently from these data that the visual angles required for a 100-percent threshold of identification were approximately 6 to 8 minutes of arc for a brightness of 40 foot-lamberts and about 8 minutes of arc for a symbol or background brightness of 1 foot-lambert. The Kuntz and Sleight study showed that a progressively larger angle of subtense was required when symbol or background brightness was decreased from 31 to 3 foot-lamberts.

Conclusions and Recommendations

These data are insufficient to support any general recommendations about visual angles required for different values of symbol or background brightness. However, in the absence of more reliable data, they may be used as a provisional guide for selection of visual angles, especially when they are considered along with data from the section on accuracy of identification. The threshold data above and the data of Crook, shown in Table II, suggest that the visual angle subtended by the height of the symbols should be increased from 6 minutes of arc to 16 minutes of arc when brightness is reduced from 20 foot-lamberts to 0.07 foot-lambert. The exact relation between visual angle and brightness for the range of values involved is not known, but it is reasonable to assume a linear relationship for this small range of angles and brightnesses. Also, the estimates of visual angles apply only when appropriate values of other factors such as contrast and stroke-width (Table II) are used. In addition, the symbols used in these studies were either high quality print or photographic reproductions which were viewed directly, so the recommended visual angles will probably not be sufficiently large for symbols constructed and displayed in other ways.

For example, the data of Table I indicate that accuracy of identification for a visual angle of 6 minutes of arc was only approximately 50 percent even for the best conditions of the study. The Shurtleff, et al., data suggested that at least 99 percent identification accuracy should be attained with visual angles of 6 to 8 minutes of arc for the values of brightness and brightness contrast used in the Howell and Kraft study.

However, the symbols in the latter study were not viewed directly on the film but were projected through a series of optical lenses and displayed to the subjects on a ground glass screen. It is possible that the fidelity of the symbols was altered in the projection process and caused the poor performance with symbols subtending angles of 6 minutes of arc.

Until more is known about how the components of projection systems affect legibility a minimum visual angle of 16 minutes of arc is recommended for projection devices* even when symbol brightness is 20 foot-lamberts or greater. In situations involving direct viewing of high quality printed or photographed symbols, visual angles as small as 6 minutes of arc may be satisfactory.

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*This recommendation may apply equally to most modern display devices, including CRTs and television, in which electrical and optical components may cause some degradation of symbol construction.

AMBIENT ILLUMINATION

In many situations, the display (e.g., CRT, television, printed pages, and the like) occupies only a small part of the operator's total field of view. The amount of ambient illumination and the reflectance of objects around the display determine what the brightness of the surrounding area will be. The question is often raised about the value or values of brightness which are appropriate for use in this area. Unfortunately, the question cannot be answered by reference to experimental data since there is only a single experiment, of limited scope, which shows how legibility is affected by different values of surround brightness.

Even in the case of visual acuity, where there has been a considerable amount of experimental work with the brightness of the surround, Chapanis [7] has indicated that the results are not consistent enough for one to draw valid conslusions about the effects of surround brightness on acuity.

Light Letters on A Dark Background

In a study by Shurtleff, Botha and Young (details of the study can be found above, and in Table VI) the effects of different surround brightnesses on the legibility of light letters on a dark background were investigated. The width of the symbol background subtended 15 degrees at the eye, and the width of the surround subtended 60 degrees at the eye.* Two values of symbol brightness were used, namely, 1 and 40 foot-lamberts. One value of surround

*The width of the task background and task surround areas was determined arbitrarily. Chapanis, [7] in a review of the acuity literature, indicates that investigations of the effects of surround brightness on visual acuity have not used standard widths for these areas. The widths used in the Shurtleff, et al., study are, however, within the range of those used in acuity studies.

brightness was the same as that of the task background, while a second brightness of the surround was equal to that of the symbol. The results showed that when the symbol brightness was 1 foot-lambert, the brightness of the surround area did not affect the threshold. When symbol brightness was 40 foot-lamberts, the threshold was better when the brightness of the surround matched that of the symbol than when the brightness of the surround matched that of the symbol background.

Conclusions and Recommendations

If acuity data [7] are considered along with those of the Shurtleff, et al., study, then the following recommendations may be used as a tentative guide for selection of surround brightnesses until more reliable data are available.

For dark symbols on a light background with background brightness of 1 foot-lambert or less, a surround brightness equal to or dimmer than the background is recommended.

When the background brightness is greater than 10 foot-lamberts, a surround brightness equal to the background brightness is recommended.

For light symbols on a dark background, the recommendations are the same as the preceding with the exception that the relationships are restated to refer to the brightness of the symbol rather than the brightness of the background.

For symbol brightnesses of 1 foot-lambert or less, the surround brightness should be equal to or dimmer than the symbol brightness.

For symbol brightnesses of 10 foot-lamberts or more, the surround brightnesses should be equal to the symbol brightness.

The magnitude of the differences between surround brightness and symbol or background brightness which can be tolerated without loss of legibility is not known; recommendations based upon other kinds of performance measures can be found elsewhere, [7] along with a discussion of the validity of the data.

SYMBOL EXPOSURE TIME

Most of the studies of legibility have used only a single value of symbol exposure time: there has been little interest shown, to date, in determining the effects of systematic variations in exposure time on legibility. The intent of many of the studies has been to use exposure time merely as a means of degrading the experimental situation so that the effects of other factors on legibility are demonstrated more clearly.

Aeronautical Medical Research Laboratory Studies

Five studies [8, 9, 10, 11, 12] were undertaken at the Aeronautical Medical Research Laboratory to determine legibility requirements for letters, numerals, and markings to be used on transilluminated control panels in military aircraft. Two sets of legibility tests were conducted in each of the studies: one set attempted to simulate values of illumination encountered during night flying and the other, simulated values of illumination encountered during day flights.

The simulated night tests are of interest here because accuracy of symbol identification was determined for two different values of symbol exposure time, namely, 0.20 and 0.04 seconds. These data are described briefly because they represent the only experimental data available which indicates the nature of the interactions between symbol exposure time and symbol brightness, symbol exposure time and stroke-width, symbol exposure time and symbol width and symbol exposure time and symbol height.

The First Study

In the first study, [10] the simulated night tests included an investigation of the effects on accuracy of identification of the two values of exposure time (0.20 and 0.04 seconds), five values of symbol brightness, and five values of symbol stroke-width. The five values of symbol brightness were 0.32, 0.79, 1.62, 2.62 and 3.34 foot-lamberts.* The letters were constructed in five different stroke-widths of 7, 10, 13, 17, and 20 percent of symbol height. Groups of three symbols, made up of the letters A, C, D, E, F, H, L, N, O, P, T, X, Y, Z, were presented for identification. The symbols were capital block letters the heights of which subtended angles of approximately 20 minutes of arc. The horizontal length of a group of three letters subtended an angle of 1 degree, 36 minutes at the eye.

The subjects were screened for 20/30 vision or better on the Snellen test and were dark adapted for 5 minutes before the experiment. The results showed that the effect of symbol brightness on identification accuracy depended in part on the length of symbol exposure time. For the 0.20 second exposure identification accuracy was similar for brightnesses of 0.79, 1.62, 2.62 and 3.34 foot-lamberts with a decrease in accuracy of 6 to 7 percent for a symbol brightness of 0.32 foot-lambert.

When symbol exposure was shortened to 0.04 seconds, there was a decrease in accuracy for every reduction in brightness from 3.34 to 0.32 foot-lamberts. The effects of stroke-width on accuracy of identification also depended upon the length of symbol exposure. For an exposure of 0.20 second, accuracy was similar for values of stroke-width from 7 to 17 percent

*The author of this report estimated brightness contrast to be about +0.93. The actual brightness contrast used in the studies was not reported.

with a 2-percent decrease in accuracy when stroke-width was increased to 20-percent.

Accuracy of identification for a symbol exposure of 0.04 second decreased for every reduction in stroke-width from 20 to 7 percent of symbol height. There was a decrease in accuracy (averaged for all conditions) of 30 percent when symbol exposure time was reduced from 0.20 second to 0.04 second.

<u>The Third Study</u>

In the third study, [12] numerals were used instead of letters. Two different styles, the AND10400 and Berger (see Figure 4), were viewed at the same values of brightness as in the first study described above. The

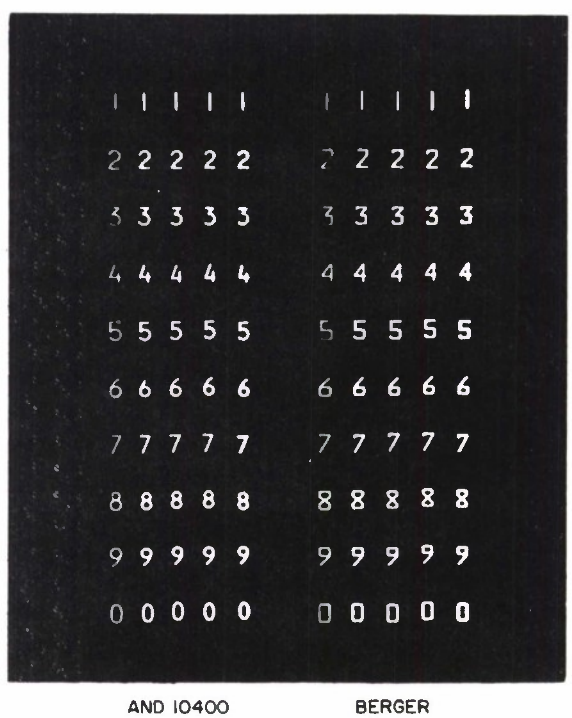

Figure 4. Numerals Used by Brown, Lowery and Willis

values of stroke-width were changed slightly to those of 6.6, 11.6, 12.5, 14.2, and 16.6 percent of symbol height. The width of the numerals was 60 percent of symbol height with the exception of the number "1" which had a width equal to the stroke-width of the symbols. The angle subtended by the horizontal length of the three numerals when placed side-by-side was 58 minutes of arc.

Other features of the experiment are similar to those described above for the first study of the series. The interaction between exposure time and symbol brightness was the same as that found in the first study.

For a symbol exposure of 0.20 second, accuracy of identification was similar for symbol brightnesses of 3.34, 2.62, 1.62 and 0.79 foot-lamberts with a decrease in accuracy at a symbol brightness of 0.32 foot-lambert. When symbol exposure time was shortened to 0.04 second, there was a decrease in accuracy for each reduction in symbol brightness from 3.34 to 0.32 foot-lamberts.

However, there did not appear to be an interaction between symbol exposure time and stroke-width as was found in the first study. In the present study, for both values of exposure time, accuracy was best for a stroke-width of 12.5 percent of symbol height with a gradual decrease in accuracy when stroke-width was either increased or decreased. Accuracy of identification decreased about 17 percent (average for all conditions) when symbol exposure time was reduced from 0.20 to 0.04 seconds.

<u>The Fourth Study</u>

The fourth study was concerned again with the legibility of capital letters (see Figure 5), as a function of five values of symbol brightness, four values of symbol width, six values of symbol height and the same two

ACDEFGHLMNOPRSTUXYZ

GARAMOND BOLD

A C D E F G H L M N O P R S T U X Y Z

H/W RATIO 1.81

A C D E F G H L M N O P R S T U X Y Z

H/W RATIO 1.43

ACDEFGHLMNOPRSTUXYZ

H/W RATIO 1.17

ACDEFGHLMNOPRSTUXYZ

H/W RATIO 1.00

Figure 5. Letters Used by Brown

values of exposure time as used in the first and third studies. The five values of symbol brightness were changed slightly to those of 0.30, 0.80, 1.60, 2.60 and 3.30 foot-lamberts. The four values of symbol width were 55, 70, 85, and 100 percent of symbol height. The six values of symbol height subtended visual angles from 14 to 22 minutes of arc.

In the tests of the effects on legibility of different values of letter height, the horizontal extent of the three letters placed side-by-side subtended angles from 1 degree, 12 minutes to 1 degree, 50 minutes. The visual angle subtended by the three letters for the tests of letter widths ranged from 52 minutes to 1 degree, 22 minutes of arc.

The letters B, I, J, K, Q, V, and W were not included in the study because of their infrequent use on control panels. Most of the other details of the experiment were similar to those described above for the first and third experiments of the series. The results showed the same interaction between exposure time and symbol brightness as noted in the other two studies reported above.

There did not appear to be any interaction between symbol exposure time and symbol width. For both values of exposure time, there was a loss in accuracy of identification for each decrease in symbol width from 100 to 55 percent of symbol height. Symbol exposure time and symbol height did not appear to interact. There was a loss in accuracy for each decrease in visual angle of subtense from 22 to 14 minutes of arc for both values of symbol exposure time.

<u>Botha and Shurtleff Study</u>

In a study by Botha and Shurtleff, [13] subjects viewed tachistoscopically presented Futura Medium and Bold letters (Figure 6) at exposure times of

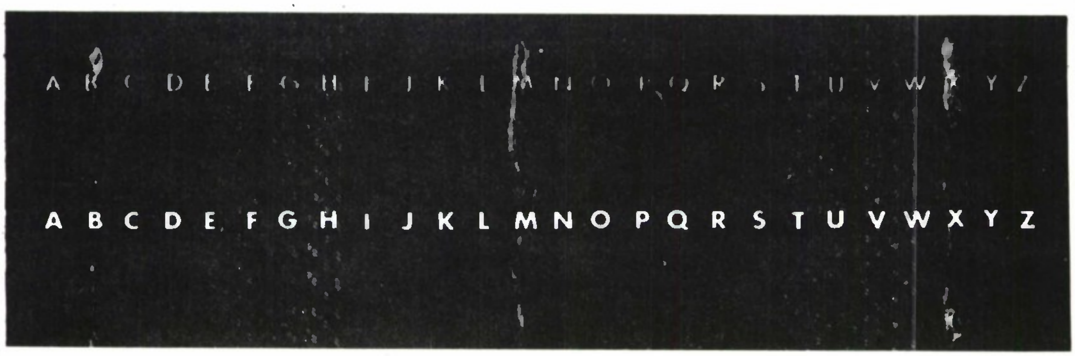

Figure 6. Letters Used by Shurtleff, Botha and Young

0.03 and 0.003 seconds. The letters were light on a dark background with a symbol brightness of 28 foot-lamberts and a brightness contrast of +0.96. The symbols were presented one at a time and subtended an angle of 14 minutes of arc. The subjects were screened for 20/20 vision on the Snellen test. The results indicated that both accuracy of identification and speed of identification did not differ significantly for these two values of exposure time. Identification accuracy, averaged for the two values of exposure time, was approximately 98 percent. Speed of identification, averaged for the two values of exposure time, was approximately 0.44 seconds.

<u>The Sanders Study</u>

Sanders, in an unpublished study,[14] investigated the effects on speed and accuracy of symbol identification of different values of symbol exposure time and intensity. The study will not be presented in detail because it was exploratory in nature and involved only a few subjects for whom different values of exposure time and intensity were used. The purpose of the study was to identify those values of exposure and intensity most promising for use in a more detailed study of performance in a situation in which symbol exposure time and symbol intensity are varied simultaneously, but the product of the two is held constant.

Symbol exposure time ranged from 0.004 to 0.030 seconds, symbol intensity from 20 to 69 foot-lamberts and symbol background intensity from 5 to 14 foot-lamberts. In one case, speed and accuracy of symbol identification were determined when symbol background intensity was held constant without regard to the particular values of symbol intensity used. In a second case, the ratio of symbol intensity to background intensity was maintained for the different values of symbol intensity used.

The results suggested that accuracy of symbol identification is independent of particular values of symbol exposure time and intensity provided the product of the two remains constant, but only when the ratio between symbol intensity and background intensity is also held constant. When background intensity was maintained without regard to the values of symbol intensity, performance was not independent of the particular values of intensity and exposure time used. Both speed and accuracy improved for each increase in the duration of exposure time. These findings are only suggestive and need to be verified by a larger sample of subjects.

Conclusions and Recommendations

These data are not complete enough to warrant recommendations of specific values of exposure time for display applications. There are some suggestions from the data that may be of some help in the selection of symbol exposure time.

The results of the studies from the Aeronautical Medical Research Laboratory showed an interaction between symbol exposure time and symbol intensity, but not between symbol exposure time and height or width. The findings of an interaction between symbol exposure time and stroke-width were equivocal: one study showed it while a second study did not. Taken together, the findings indicate that recommendations of symbol exposure time cannot be made independently of recommendations of symbol intensity; both must be considered, particularly when either factor is at an extreme value.

Sanders' data suggest that in some display situations trade offs can be made between duration of exposure time and intensity provided that the product of the two remains the same.

In the display situation described by Botha and Shurtleff, [13] exposure times as brief as 0.003 second did not affect speed or accuracy of identification. The finding occurred when the subject was aware of the exact position in the visual field in which the symbol was to be displayed. Obviously, much longer exposure times will be required for similar performance when such information is not provided to the subject.

SYMBOL SPACING

Spacing is a factor to be taken into account whenever there is need for displaying more than one symbol at a time. It is important to determine the minimal spacing required for good symbol legibility since the capacity of the display may be unnecessarily restricted by the use of more spacing than is needed. The experimental work on this factor has been concerned only with the effects of different values of horizontal spacing on legibility and in most cases the minimal spacing requirements have not been established. The effects of spacing in other directions, e.g., vertically and obliquely, have yet to be determined experimentally.

Accuracy of Identification

Two studies by Crook and co-workers [4, 15] report the effects on identification accuracy of different values of horizontal spacing. In the first study, [15] eighteen male subjects identified letters for all combinations of two values of illumination, two values of symbol width, three values of stroke-width and three values of spacing. The symbols were printed in 12 lines on sheets 3 5/8 inches by 4 1/4 inches. The sheets were stacked face down in front of the subject who turned them over to a reading position during the experiment. The subject was instructed to identify the letters as rapidly and as accurately as possible.

The data from this study are presented in Table VII. Part A of the table shows that accuracy of identification is similar for all values of spacing for both values of background brightness. The only major decrease in accuracy of identification occurred for the lowest value of illumination, the narrowest value of stroke-width and the closest value of spacing.

Part B of the table indicates that for the higher background brightness, horizontal spacing has no consistent effect on accuracy of identification. There appears to be a slight reduction in accuracy for all values of spacing under the dimmer background illumination. There is also an appreciable reduction in accuracy of identification when horizontal spacing is decreased from 25 percent of symbol height to 4.8 percent of symbol height. In another study by Crook, et al., previously described, no differences were found for spacings of 35 and 63 percent of symbol height.

Table VII

Accuracy of Identification

Part	Symbol Width in Percent of Height	Spacing in Percent of Symbol Height	Stroke-Width in Percent of Symbol Height	Background Illumination in Foot-Lamberts	Percent Correct
A	86.3	8.1	9.8	11.8	99.4
				.07	94.5
			21.1	11.8	99.8
				.07	98.8
			30.0	11.8	99.6
				.07	98.6
		35.6	9.8	11.8	99.7
				.07	98.9
			21.1	11.8	99.8
				.07	99.3
			30.0	11.8	99.9
				.07	97.6
		63.2	9.8	11.8	100.0
				.07	98.6
			21.1	11.8	99.8
				.07	99.2
			30.0	11.8	99.7
				.07	98.2
B	59.8	4.8	8.8	11.8	98.2
				.07	89.5
			15.5	11.8	99.1
				.07	95.6
			20.3	11.8	99.6
				.07	94.7
		25.4	8.8	11.8	99.7
				.07	97.3
			15.5	11.8	99.7
				.07	97.6
			20.3	11.8	99.3
				.07	95.8
		46.1	8.8	11.8	99.2
				.07	96.8
			15.5	11.8	99.7
				.07	97.7
			20.3	11.8	99.8
				.07	95.5

(Table VII Continued)

Table VII Continued

Description of the Experimental Conditions

Symbol Brightness*: 0.07 and 0.004 foot-lamberts for background brightnesses of 11.8 and 0.07 foot-lamberts, respectively

Brightness Contrast*: -0.94

Ambient Illumination: Not stated (Probably negligible since experiment conducted in light tight booth)

Properties of Light Source: For 0.07 foot-lamberts used Westinghouse spotlight #4345 covered by Corning red glass #2403. For 11.8 foot-lamberts, 40-watt frosted bulb was used.

Symbol-Background Relation: Dark on light

Symbol Style: Monotype Gothic (Similar to News Gothic used on maps and charts shown in Figure 2)

Angle of Subtense: 16 minutes of arc

Symbol Exposure Time: Not relevant

Number of Symbols: Complete alphabet (26 letters)

Number of Subjects: 18

Visual Characteristics of Subjects: 20/20 near and far acuity determined by Bausch and Lomb Ortho-Rater. Normal color vision. Were dark adapted prior to sessions for 0.07 foot-lambert.

Viewing Distance: 14 inches

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*These figures are based upon the assumption that the reflectance of symbol and background were the same as those used in a previous experiment. Since both studies were part of the same research program, it is a fairly reasonable assumption to make. However, the reflectances were not reported in the study for which the data is summarized above.

Conclusions and Recommendations

These results show for the conditions described in Table II and Part A of Table VII that horizontal spacing has little effect on identification accuracy. However, Part B of Table VII suggests that for the lower value of brightness spacing less than 25 percent of symbol height should be avoided.

Rate and Speed of Symbol Identification

Crook, Hanson and Weisz Studies [15]

Two studies by Crook, Hanson and Weisz, previously described, report the rate of letter identification as a function of different values of horizontal spacing. The data from one of these studies (Table VIII, A and B) show that the slowest rates of identification occur consistently for the smallest value of horizontal spacing. Part B of Table VIII indicates that horizontal spacing can be decreased to 25 percent of letter height before the rate of symbol identification is reduced appreciably.

The statistical significance of the differences due to different values of horizontal spacing was not reported. The data from a second study, in Table IV, also show that spacings of 35 and 63 percent of letter height do not affect the rate at which the subjects make letter identifications.

Crook and Baxter Study

Crook and Baxter[16] looked at the effects of spacings of 5.4 and 16.2 percent of symbol height on speed of identification. The general purpose of the study was to examine the legibility of dial type numerals when viewed at low levels of illumination.

The study used four male subjects with near acuity of 20/25 or better on the Lebensohn Acuity Test. The subjects identified AND numerals

Table VIII

Rate of Symbol Idenfification

Part	Symbol Width in Percent of Height	Spacing in Percent of Symbol Height	Stroke-Width in Percent of Symbol Height	Background Illumination in Foot-Lamberts	Symbols per Second
A	86.3	8.1	9.8	11.8	2.9
				.07	2.1
			21.1	11.8	3.1
				.07	2.7
			30.0	11.8	3.2
				.07	2.6
		35.6	9.8	11.8	3.3
				.07	2.7
			21.1	11.8	3.2
				.07	3.0
			30.0	11.8	3.1
				.07	2.7
		63.2	9.8	11.8	3.3
				.07	2.8
			21.1	11.8	3.2
				.07	3.0
			30.0	11.8	3.4
				.07	2.8
B	59.8	4.8	8.8	11.8	2.5
				.07	1.5
			15.5	11.8	2.8
				.07	1.9
			20.3	11.8	2.8
				.07	1.8
		25.4	8.8	11.8	3.0
				.07	2.2
			15.5	11.8	3.1
				.07	2.6
			20.3	11.8	3.2
				.07	2.3
		46.1	8.8	11.8	3.3
				.07	2.2
			15.5	11.8	3.1
				.07	2.5
			20.3	11.8	3.2
				.07	2.3

(Table VIII Continued)

Table VIII Continued

Description of Experimental Conditions

Symbol Brightness*: 0.07 and 0.004 foot-lamberts for background illumination of 11.8 and 0.07 foot-lamberts respectively

Brightness Contrast*: -0.94

Ambient Illumination: Not stated (Probably negligible since experiment conducted in light tight booth)

Properties of Light Source: For 0.04 foot-lamberts used Westinghouse spotlight #4345 covered by red Corning glass #2403. For 11.8 foot-lamberts, 40-watt frosted bulb was used

Symbol-Background Relation: Dark on light

Symbol Style: Monotype Gothic (Similar to News Gothic used on maps and charts shown in Figure 2)

Angle of Subtense: 16 minutes of arc

Symbol Exposure Time: Not relevant

Number of Symbols: Complete alphabet (26 letters)

Number of Subjects: 18

Visual Characteristics of Subjects: 20/20 near and far acuity determined by Bausch and Lomb Ortho-Rater. Normal color vision and were dark adapted prior to sessions for 0.07 foot-lambert

Viewing Distance: 14 inches

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*See footnote on Table VII.

(Figure 7), and each numeral was presented as the middle digit in a three-digit group. The 0 and 5 were used as the flanking digits. The numerals were projected from the rear onto a translucent screen and had a brightness of about 0.01 foot-lambert with a background brightness of about 5.0×10^{-5} foot-lamberts. The subjects were dark adapted prior to the experiment and viewed the numerals from a distance of 28 inches. The height of the numeral was adjusted for each subject during preliminary trials to produce identification times longer than those obtained in an ideal viewing situation, but shorter than ten seconds.

The results indicated that speed of identification for seven of the ten numerals was faster for the wider spacing than for the narrower spacing.

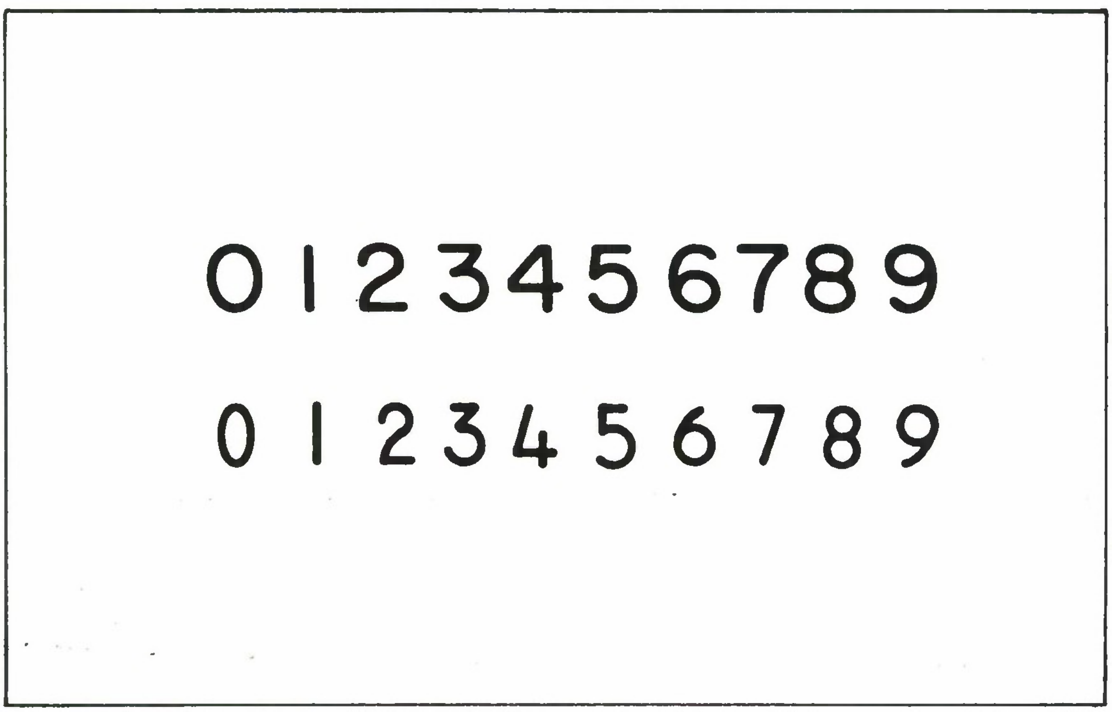

Figure 7. Numerals used by Kuntz and Sleight (top), by Crook and Baxter (bottom).

However, tests indicated no statistically significant differences between speeds of identification for the two values of spacing.

Conclusions and Recommendations

For the situation described in Table VIII, spacing between symbols can be as close as 25 percent of symbol height without decreasing the rate of symbol identification. The values of horizontal spacing between zero and 25 percent of symbol height need to be investigated in order to determine the lower limit of horizontal spacing. Until such data are available, horizontal spacings less than 25 percent of symbol height should be avoided.

Threshold of Identification

Shurtleff, Botha, and Young Study [5]

Horizontal spacings of 25 and 200 percent of symbol height were compared in a study by Shurtleff, Botha, and Young previously described. The data from this study are shown in Table VI and indicate that spacing interacts with other factors to produce a somewhat complicated set of relationships.

For a symbol or background brightness of 1 foot-lambert threshholds were approximately the same for the two values of spacing. For brightness values of 20 and 40 foot-lamberts, the threshold was better, i.e., a smaller visual angle was required for 50 percent accuracy of identification for the wider spacing than for the narrower spacing. The superiority of the wide spacing was more pronounced for light letters on a dark background than for dark letters on a light background.

Tinker Study

In a study by Tinker,[17] the legibility of old style versus modern numerals* was investigated for two different values of horizontal spacing. The wider spacing was about 1000 percent of numeral height while the narrower spacing, although not reported by the author, was probably about 25 percent of numeral height. Black numerals printed on white cardboard were identified under 31 foot-candles. Tinker reports that the identification threshold was best for numerals printed in the wider spacing than for those printed in the narrower spacing.

Lauer Study

A study by Lauer,[18] in which a different psychophysical procedure was employed** showed that, in a spacing range from 25 to 125 percent of symbol height, values between 50 and 100 percent of height tended to produce the best thresholds. However, the differences attributed to symbol spacing were slight and the author did not report the statistical significance of his results.

Conclusions and Recommendations

These data indicate that horizontal spacing significantly affects identification thresholds when symbol or background brightness is 20 foot-lamberts or greater. It is not possible at this time to recommend what the

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*The distinction Tinker makes between old style and modern numerals is that the former vary in height and vertical position while the latter are uniform in height and vertical position (see Figure 18).

**The thresholds were obtained by gradually increasing the amount of illumination until the subject reported that he could correctly identify the symbol.

optimal value of spacing should be when symbol or background brightness is greater than 20 foot-lamberts. Horizontal spacing between symbols does not appear to affect the threshold when the higher brightness (symbol or background) is 1 foot-lambert or less.

SYMBOL SIZE

When the threshold of identification is used as a measure of legibility, symbol size is made progressively larger, by decreasing the distance between the subject and the symbols, until the subject is able to identify correctly 50 percent or 100 percent of the symbols presented. Symbol size is varied continuously for the purpose of deriving a threshold of identification. The studies reported in this section also vary symbol size but they differ from the threshold studies in that only selected values of symbol size are used and there is no attempt to derive a 50- or 100-percent threshold of identification.

Accuracy of Identification

Howell and Kraft Study

In a study by Howell and Kraft,[2] the accuracy of identification was determined for four different symbol sizes. The angles subtended by the height of the symbols were 36.8, 26.8, 16.4, and 6.0 minutes of arc. The data from this study, presented in Table I, indicated for the 0.00 blur condition a reduction of approximately 32 percent in accuracy of identification for the higher value of contrast and approximately 46 percent for the lower value of contrast when the visual angle was decreased from 16.4 to 6.0 minutes of arc. There was little additional gain in accuracy of identification when the angle of subtense was increased from 16.4 to 36.8 minutes of arc for either value of contrast.

Crook, Hanson and Weisz Study [4]

Accuracy of identification for symbols whose height subtended 22.0, 16.0, and 11.0 minutes of arc is shown in Table II. These data, from a study by Crook, Hanson and Weisz, show a decrease in accuracy of identification for all values of stroke-width, brightness contrast, and spacing when the angle of subtense was reduced from 16.0 to 11.0 minutes of arc. Also, changes in stroke-width and brightness contrast had a greater effect on accuracy when the angle of subtense was 16 minutes of arc than when it was 22 minutes of arc.

The Brown Study

The effects on identification accuracy of changes in symbol width have been reported by Brown. [9] Four different widths were investigated: 55, 70, 85, and 100 percent of symbol height. In the simulated night tests, for symbol brightnesses between 0.30 and 3.30 foot-lamberts and symbol exposures of 0.20 and 0.04 seconds, Brown found a consistent increase in accuracy as symbol width was extended from 55 to 100 percent of symbol height. In the simulated day tests, with symbol brightnesses of about 23 and 46 foot-lamberts* and a symbol exposure of 0.007 second, there was an increase in accuracy of 33 to 50 percent when symbol width was extended from 55 to 70 percent of height. There was little further increase in accuracy when symbol width was extended from 70 percent to 85 or 100 percent of symbol height.

The Soar Study

The study above (Brown) showed an increase in accuracy of identification, at least up to a point, with increases in symbol width. Soar [19] points out that

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*These brightness values were estimated by the author of this report.

changes in the width (or height) of the symbols does two things. First, it increases the area of the symbol. Second, it changes the ratio of the symbol height to the symbol width.

Soar reasoned that one might expect an increase in symbol area to aid identification accuracy, but questioned whether or not changes in the ratio of symbol height to symbol width would also affect accuracy. Soar, therefore, investigated the effects of four height-to-width ratios of 10:3, 10:4.5, 10:6, and 10:7.5 on accuracy of identification when symbol area was the same for each of the four ratios. Symbols in each of the four ratios were constructed with three different stroke-widths.

Six subjects were assigned to each of the twelve different conditions. All subjects scored 95 percent or better for near visual acuity on the Keystone Telebinocular Test.* Ten numerals in the AMEL style (Figure 8) were presented tachistoscopically for an exposure of 0.04 second. The numerals were dark on a light background and were illuminated by one foot-candle. The author did not report symbol brightness or brightness contrast.

The results indicated that identification accuracy, for most numerals, was best for the 10:7.5 height-to-width ratio. The data suggested that, for some of the numerals, accuracy would continue to increase as the ratio approached unity.

Conclusions and Recommendations

Symbol heights which subtend less than 16 minutes of arc should be avoided in display situations described in Tables I and II. For most of the conditions described in the two tables, there is no need for angles of sub-

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*For a description of this test see Glossary under "Multi-Test Visual Devices."

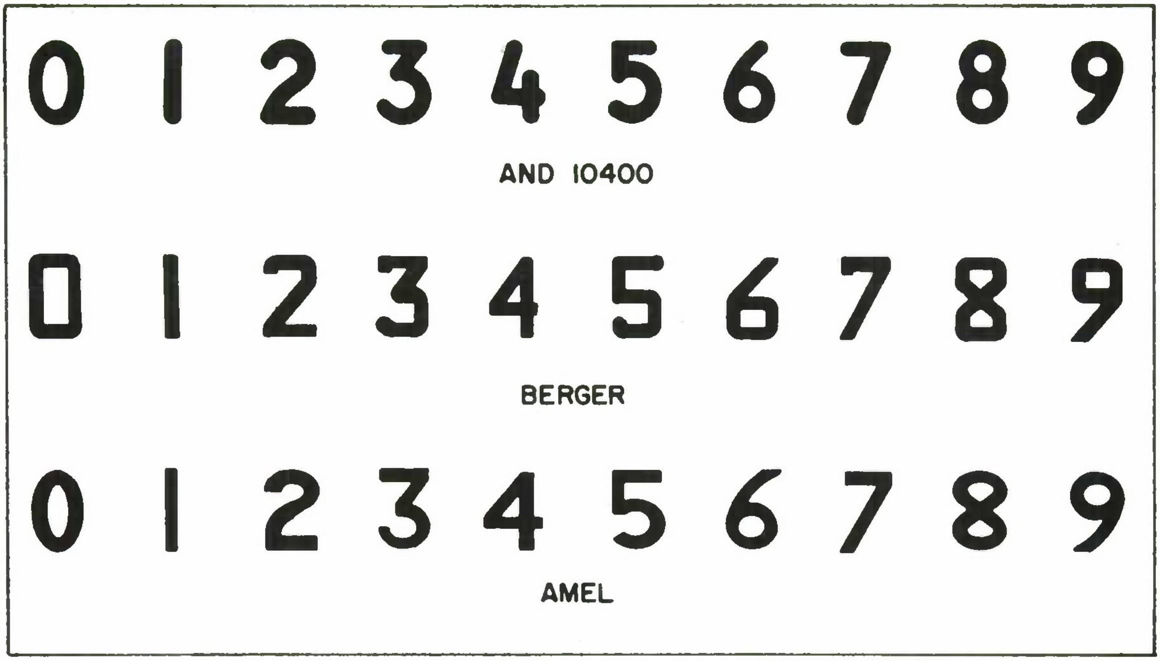

Figure 8. Numeral Styles Evaluated by Atkinson, Crumley and Willis

tense greater than 16 minutes of arc, although, as Table II indicates, there are several conditions for which a larger angle of subtense might be desirable.

The Brown study showed that a symbol width equal to symbol height is best for intermediate and low levels of symbol illumination, and for brief symbol exposure times. When the symbols were brighter than 23 foot-lamberts, there was little improvement in accuracy of identification for symbol widths greater than 70 percent of symbol height.

The Soar study suggested that changes in the ratio of symbol height to width should be accounted for in studies of either the height or width of symbols. It may be, for example, that accuracy might have been better in the Brown study if the area represented by a symbol height equal to symbol width had been in the ratio of 4:3, which was the height-to-width ratio found to be best by Soar.

Rate and Speed of Symbol Identification

Howell and Kraft Study [2]

The data in Table III, from a study by Howell and Kraft, show that rates of identification are similar for symbol heights which subtend angles of 36.8 and 26.8 minutes of arc for the no blur condition. When the angle of subtense was reduced from 26.8 to 16.4 minutes of arc, there was a 4- to 4.5-percent decrease in the rate of symbol identification. When the visual angle of subtense was reduced from 16.4 to 6.0 minutes of arc, the decrease in rate was 39 percent for a brightness contrast of +0.97 and 48 percent for a brightness contrast of +0.92.

Crook, Hanson and Weisz Study [4]

Table IV shows the rate of symbol identification (from a study by Crook, Hanson and Weisz) for three values of visual angle subtended by symbol height. The average decrease in rate of identification when the visual angle was reduced from 22 to 16 minutes of arc was about 17 percent. The average of 17 percent is based upon a decrease of 12, 14 and 27 percent for brightness contrasts of -0.94, -0.90 and -0.81 respectively.

When stroke-width is considered, the average of 17 percent is based upon a decrease of 20, 13, and 17 percent for stroke-widths of 9.8, 20, and 30. The average loss in rate of identification when the visual angle was reduced from 22 to 11 minutes was about 54 percent.

The 54 percent is based upon a decrease in rate of identification of 40, 50, and 73 percent for brightness contrasts of -0.94, -0.90 and -0.81. The average percentage decrease in the rate of symbol identification for stroke-width was 60, 47, and 50 percent for the values of 9.8, 20, and 30.

Crook and Baxter Study [16]

A study by Crook and Baxter reported the effects of several height-to-width ratios on the speed of symbol identification. Symbol area was held constant and the effects of height-to-width ratios of 10:5, 10:5.7, 10:6.7 and 10:8 on speed of identification were investigated.

The results showed that no single ratio produced the fastest speed of identification for all numerals. However, the authors point out that if a single ratio had to be selected for all numerals, the 10:5.7 would be best. The latter finding conflicts with that of Soar who found a height-to-width ratio of 10:7.5 to be best for most of the numerals used in this study.

Conclusions and Recommendations

Symbol height should subtend between 22 and 26 minutes of arc whenever it is desirable to achieve the fastest possible rates of symbol identification for situations similar to those outlined in Tables III and IV. Symbol heights subtending less than 16 minutes at the eye should be avoided since both Tables III and IV indicate a marked drop in rate of symbol identification when the angle of subtense is smaller than 16 minutes of arc. When the visual angle is smaller than 22 minutes of arc, selected values of symbol stroke-width and brightness contrast must be used if maximal rates of identification are to be maintained.

There are little data available which show how rate or speed of identification is affected by changes in symbol width or height-to-width ratio. Crook showed that symbol identifications tended to be faster when the height-to-width ratio was 10:5.7. Since this finding has been demonstrated only for one display situation, its generality is limited.

Threshold of Identification

Crook and Baxter Study [16]

In an experiment reported by Crook and Baxter, the threshold technique was used to evaluate differences in symbol width. What Crook and Baxter did was to find the height of the symbol required for identifications of symbols with widths of 60, 67, and 74 percent of the height of the symbol.

The procedure included presenting, one at a time, four of the ten numerals in three different widths. The height of the numeral was increased gradually at a fixed distance from the subject until he was able to identify the symbol correctly. The question of interest was, if a symbol is made progressively wider, can the height of the symbol be made progressively smaller without changing the accuracy of identification?

The results showed no proportionate decrease in symbol height when symbol width was increased. In fact, the same symbol height was required for widths of 60 and 67 percent of symbol height. The implication of these data is that symbol area is not the sole factor affecting the threshold since the area for a symbol width 67 percent of height was greater than that for 60 percent of height. It appears that the ratio of symbol height to width may also be a factor affecting the threshold of identification.

The Berger Study

Berger,[20, 21] in a series of experiments intended to improve the legibility of numerals (see Figure 9) used on automobile license plates, investigated the effects of different symbol widths on the threshold of identification. His data are of little value for applied situations because his study was not described in sufficient detail, but they are mentioned here because they suggest that the threshold of identification will not necessarily improve for all numerals when the width of the numeral is increased.

The data Berger presents on this point were collected for light numerals on a dark background. The numerals were viewed out-of-doors under daylight illumination and had a stroke-width to height ratio of 1:13.

The numerals 9, 2, 5, 6, and 7 showed an improvement in the threshold of identification when width was extended to about 50 percent of numeral height, and possibly would have continued to show further improvement if widths greater than 50 percent had been included. The identification thresholds for the numerals 3 and 4, however, indicated that they had reached a maximum at 50 percent of symbol height, and that additional increases in numeral width would not improve the thresholds.

The results indicate that a maximally legible set of numerals could be attained only by using symbols with different widths. When a single width or height-to-width ratio is specified for a set of numerals, it represents a value which will be best for the majority of the numerals.

STROKE-WIDTH

Of the factors related to legibility, stroke-width has received the most experimental attention and is, therefore, the best understood of the classical factors. The reason for the popularity of stroke-width is probably the ease with which it is manipulated.

Accuracy of Identification

Crook, Hanson and Weisz Study [15]

The effects of three values of stroke-width on accuracy of identification for several values of brightness contrast and visual angle are shown in

Table II. These data, from a study by Crook, Hanson and Weisz, show that when the visual angle subtended by the symbol is 22 minutes of arc and the brightness contrast is greater than -0.90, stroke-widths from 10 to 30 percent of symbol height do not affect accuracy of identification. A stroke-width of 20 percent of symbol height is best for the rest of the conditions described in Table II. In another study by Crook, et al., the effects of stroke-width on accuracy of identification were determined for both medium and low levels of illumination.

Part A of Table VII indicates that for the higher background brightness, accuracy is not affected by changes in stroke-width from 10 to 30 percent of symbol height. At the lower background illumination, there is a tendency for accuracy of identification to be best for a stroke-width 20 percent of symbol height. In general, the differences among stroke-widths are not large, and their statistical significance was not reported.

The effects on accuracy of stroke-width values from 9 to 20 percent of height are shown in Part B of Table VIII. Again, stroke-width had little effect on accuracy at the higher background illumination. At the lower background illumination, there is a tendency for accuracy to be better for the intermediate value of stroke-width than for either one of the extreme values. In all cases, the differences in accuracy due to stroke-width are minor and their statistical significance was not reported.

Brown and Lowery Study

In the first of a series of studies designed to evaluate the legibility of symbols used on aircraft control panels, Brown and Lowery [10] investigated the effects of stroke-width values ranging from 7 to 20 percent of symbol height on accuracy of identification (the general procedure and conditions used in all studies have been described on pages 10-11.

The experimental variables included, in addition to values of stroke-widths of 7, 10, 13, 17 and 20 percent of symbol height, seven values of symbol brightness and three values of symbol exposure time. In the present experiment, groups of three letters (only the fourteen letters: A, C, D, E, F, H, L, N, O, P, T, X, Y, Z were used) were exposed for 0.20 and 0.04 seconds for symbol brightnesses ranging from 0.32 to 3.34 foot-lamberts and for 0.007 second for symbol brightnesses of 23.2 and 46.4 foot-lamberts. Letter height subtended an angle of 19 minutes of arc at the eye, and the width of three letters together subtended an angle of 1 degree, 36 minutes at the eye. All subjects had a rating of 20/30 or better on the Snellen test.

The results indicated that stroke-width values from 7 to 20 percent of symbol height did not affect accuracy of identification for a symbol exposure of 0.04 second and symbol brightnesses of 1.62, 2.62, and 3.34 foot-lamberts. For symbol brightnesses of 0.32 and 0.79 foot-lamberts and a symbol exposure of 0.04 second, accuracy for stroke-width values of 7 and 10 percent of symbol height was significantly less than that for stroke-width values of 13, 17, or 20 percent of symbol height. Stroke-width did not significantly affect accuracy for symbol brightnesses of 0.32, 0.79, 1.62, and 2.62 for a symbol exposure of 0.20 second.

At a symbol brightness of 3.34 foot-lamberts, accuracy of identification was significantly better for the narrowest stroke-width (7 percent of symbol height) than at any other value of stroke-width except that of 17 percent of symbol height. When symbol brightness was 23 foot-lamberts and symbol exposure time was 0.007 second, accuracy was significantly less for stroke-widths of 7 and 10 percent of symbol height than it was for stroke-widths of 13, 17, or 20 percent of symbol height.

For a symbol brightness of 46.4 foot-lamberts, and a symbol exposure of 0.007 second, accuracy was significantly worse for a stroke-width of 7 percent of symbol height than it was for each of the other values of stroke-width.

The authors concluded that a stroke-width 17 percent of symbol height would be best for most of the conditions investigated. However, in most cases, accuracy of identification was similar for stroke-widths of 17 and 20 percent of symbol height.

Brown, Lowery and Willis Study

In another study by Brown, Lowery, and Willis,[12] the effects of stroke-width and style on accuracy of identification were investigated. The numeral styles and stroke-widths used are shown in Figure 4. Details of the experiment have been described in this report.

For symbol brightnesses between 0.32 and 3.34 foot-lamberts and symbol exposures of 0.20 and 0.04 seconds, stroke-widths of 6.6, 11.6, 12.5, 14.3, and 16.6 percent of symbol height were investigated.

For symbol brightnesses of 23.2 and 46.4 foot-lamberts and a symbol exposure of 0.007 second, numeral stroke-widths of 6.6, 11.6, and 16.6 percent of symbol height were investigated.

The width of the numerals was about 60 percent of symbol height, and the numerals were light on a dark background. Groups of four numerals were shown when symbol brightnesses were 23.2 and 46.4 foot-lamberts.

The groups of four symbols subtended an angle of 1 degree, 21 minutes of arc at the eye.*

The results indicated that accuracy of identification, for numerals in both styles, was not altered significantly by stroke-width for brightnesses from 0.32 to 3.34 foot-lamberts and symbol exposure times of 0.20 and 0.04 seconds. The only exception to this was that accuracy of identification for a symbol exposure of 0.04 second and a symbol brightness of 0.32 foot-lambert was significantly worse for Berger numerals in stroke-width values of 6.6 and 11.6 percent of symbol height than it was for stroke-width values of 12.5, 14.3, and 16.6 percent of symbol height.

For symbol brightnesses of 23.2 and 46.4 foot-lamberts and a symbol exposure of 0.007 second, accuracy was significantly worse for a stroke-width 6.6 percent of height than it was for stroke-widths of 11.6 and 16.6 percent of symbol height.

The authors concluded that a stroke-width of 12.5 percent of height is optimal for the conditions investigated in their study. However, if the choice of stroke-width is based upon statistically demonstrated differences in accuracy, then stroke-widths of 12.5, 14.3, or 16.6 percent of symbol height would be suitable for the conditions investigated in this study.

<u>The Soar Study</u>

Soar[22] investigated the effects on accuracy of identification of variations of stroke-width within individual symbols. Identification accuracy for sets of ten numerals in different styles was compared in one case when they

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*Angle of subtense of the group was somewhat smaller when the numeral "1" was included in the group since the width of the "1" was equal to the stroke-width of the numerals, and the other numerals were moved more closely together.

were constructed with a constant stroke-width and in a second case when they were constructed with a variable stroke-width.

An attempt was made to de-emphasize elements common to several numerals by use of a thin stroke (about 5 percent of symbol height) and to emphasize elements unique to numerals by use of the thicker stroke (about 20 percent of symbol height). It was not clear how the author determined which elements were common or unique among the ten numerals.*

The numerals were dark on a light background with a width equal to 75 percent of height. The numerals were exposed for 0.04 second in a Gerbrands tachistoscope and were illuminated by 1 foot-candle. Numeral brightness and brightness contrast were not reported. The height of the numerals was 0.1 inch and probably subtended an angle of approximately 10 minutes of arc, although the exact angle of subtense was not reported by the author.

One hundred subjects, screened for normal acuity (exact test not reported), were used in the experiment. The results showed that accuracy of identification of the numerals 3, 4, 7, and 9 was as good for a constant stroke-width as for a variable stroke-width. Variation of stroke-width within the numerals 5, 6, and 8 improved accuracy of identification.

Conclusions and Recommendations

For the display situations described above, stroke-widths from 12 to 20 percent of symbol height, corresponding to stroke-width-to-height ratio of 1/8 to 1/5, are recommended for best accuracy of identification.

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*It is not uncommon to encounter similar statements about similarities or differences among symbols, or symbol elements, or symbol patterns. Data are seldom, if ever, collected to ascertain whether such concepts are related to reading or recognition performance.

The Soar study showed that accuracy can be improved by varying stroke-width within some of the numerals. The validity of his finding for other display situations has not been demonstrated, and recommendations of the use of a variable stroke-width in symbol construction is not warranted at this time, particularly since many display situations do not have the capabilities to construct symbols with variable stroke-widths.

Rate and Speed of Symbol Identification

The Crook Studies [4,15]

The effects of different values of stroke-width on rate of symbol identification are shown in Tables IV and VIII. Both sets of data are from studies by Crook and co-workers, and additional details of these experiments can be found in this report. Table IV shows that stroke-width has little effect on rate of identification when the angle subtended by the symbol is 22 minutes of arc and the brightness contrast is -0.94. For other values of brightness contrast and visual angle, identification rate is fastest for a stroke-width equal to 20 percent of symbol height.

In Table VIII the effects of stroke-width on rate of identification are shown for two values of illumination, three values of symbol spacing and two values of symbol width. Stroke-width does not affect rate of identification for the higher value of illumination with the exception of a slight reduction in rate of identification for the narrowest stroke-width and closest spacing. At the lower value of illumination the intermediate value of stroke-width gives the highest rates of identification for each of the three values of spacing. However, in all cases the differences between rate of identification for stroke-widths are small and their statistical significance was not reported.

The Schapiro Study [3]

Table V shows the effects on speed of identification of values of stroke-width between 10 and 20 percent of symbol height for each of four values of illumination. These data are from a study by Schapiro, which is described in this report. The only significant differences attributed to stroke-width occurred for a symbol brightness of 0.01 foot-lambert where speed of identification for stroke-widths of 16 and 20 percent of symbol height was significantly faster than for stroke-widths of 12.5 and 10 percent of symbol height. Also, speed of identification for a stroke-width 10 percent of symbol height was significantly slower than for a stroke-width 12.5 percent of symbol height.

Conclusions and Recommendations

For the display situations described in Tables IV, V and VIII, stroke-widths from 15 to 20 percent of symbol height give the fastest rate and speed of symbol identification. Stroke-widths in the lower part of this range are indicated for conditions described in Part B of Table VIII and in the upper part of this range for conditions described in Part A of Table VIII and Table V.

Threshold of Identification

Each of the studies of the effect of stroke-width on the threshold of identification has failed to give a complete description of the situation in which the measure was obtained. Therefore, the findings are of little practical use and comparisons among the studies are not possible. The studies are presented since they represent the only experimental data available in this category.

Kuntz and Sleight Study

Kuntz and Sleight [6] reported the effects on the threshold of identification of stroke-width values from 22 to 13 percent of symbol height. Standard Leroy numerals (Figure 7) were arranged on cards in two rows of 15 numerals each. Two sets of cards were used. One set contained light symbols on a dark background; the other set contained dark symbols on a light background. The lighter part of the card (symbol or background) was illuminated to 3, 10, or 31 foot-lamberts. The brightness contrast of numerals was not reported, although it was probably in the range of ±0.90 to ±0.95.

The measure of legibility was the distance at which the subject was able to make 100 percent correct numeral identifications. Fourteen subjects, screened for normal acuity (exact test not reported), identified numerals for all combinations of three values of brightness, two values of symbol-background relation, and seven values of stroke-width.

The analysis of results showed significant interactions between stroke-width and numerals, stroke-width and subjects, and stroke-width and brightness, but not between stroke-width and symbol-background relation. The significant interaction between stroke-width and brightness indicates that the effects of stroke-width on the threshold of identification depend upon brightness.

Their graph* showed that (a) at 31 foot-lamberts, stroke-widths from 17 to 13 percent of symbol height were better than those from 18 to 22 percent of symbol height, (b) at 10 foot-lamberts, stroke-widths from 20 to 14 percent of symbol height were better than a stroke-width of 22 or 13 percent of symbol height, and (c) at 3 foot-lamberts, stroke-widths from 22 to 15 percent of symbol height were better than those of 14 or 13 percent of symbol height.

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*See Reference 2, page 572.

The Berger Studies [20,21]

The Berger studies, described in this report, show the effects on the threshold of identification of variations in stroke-width for both high and low values of illumination. All of the experiments were conducted out-of-doors either during the day or at night. One set of experiments was conducted during the morning hours. Although the author did not report the actual brightnesses involved, they were probably in excess of 1,000 foot-lamberts.

Only the Berger numerals 8, 5, and 2 (see Figure 8) were used, and they were shown as dark on a light background and as light on a dark background. The brightness contrast was high and probably within the range of ±0.90 to ±0.95. Two subjects with normal far acuity (test not stated) served in these experiments. Berger used a method for deriving thresholds in which a single numeral was moved toward the subject until he could read it and then moved away from the subject until the subject said he could not read it.*

Numeral stroke-width was varied from 2.5 to 20 percent of symbol height. For light numerals on a dark background, the best thresholds occurred for a stroke-width of 7.5 percent of height. For dark numerals on a light background, the best threshold was obtained for a stroke-width of 12.5 percent of height.

In another set of experiments conducted at night, stroke-width was investigated for both transilluminated numerals and numerals illuminated by reflected light. The author failed to report the values of brightness

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*This method differs in a number of respects from the one described in the glossary and probably yeilds smaller angles of subtense at threshold since the threshold is based in part on measurements taken when the symbol is moved away from the subject.

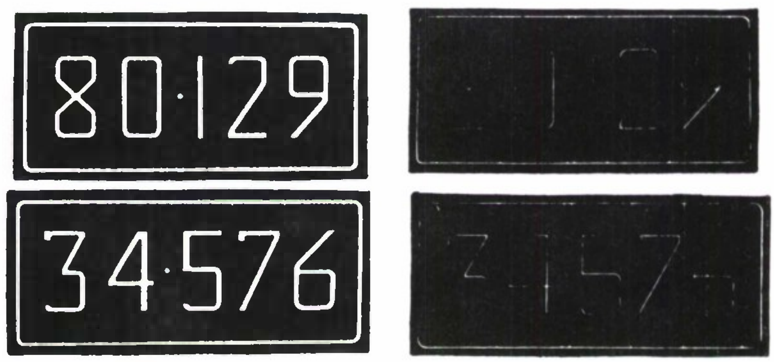
contrast; but for the transilluminated numerals, it was probably in excess of +0.95, and for numerals illuminated by reflected light, it was probably in a range from -0.90 to -0.95. The subjects were dark adapted for the night tests.

Other features of the experiment were identical to those of tests conducted during the day. Stroke-widths from 1 to 6 percent of numeral height were investigated for the transilluminated numerals. The results showed that thresholds were best for a stroke-width 2.5 percent of numeral height. For the numerals illuminated by reflected light, and probably with reduced contrast (0.90 to 0.95), a stroke-width of 7.5 percent of numeral height gave the best threshold of identification.

The Soar Study

The studies above have shown interactions between symbol stroke-width and illuminations, and between symbol stroke-width and symbol-to-background relation. Soar [23] reports a study of AND numerals (Figure 9) which also showed interactions between stroke-width and symbol illumination and between stroke-width and symbol-background relation. The experimental design included two values of stroke-width (25 and 6.2 percent of symbol height), two values of illumination (500 and 0.5 foot-candles), and two background relations (light symbols on dark background and dark symbols on light background). The symbol and background brightnesses were not reported, nor was brightness contrast.

Forty subjects with normal vision (type of acuity test was not reported) were used. Five subjects were assigned to each combination of experimental conditions. The measure of legibility was the distance at which the subjects could identify correctly 50 percent of the numerals presented.



For Daytime Use For Night Use

Figure 9. Automobile License Plate Numerals

The analysis of the results revealed statistically significant interactions between stroke-width and illumination, and between stroke-width and symbol-to-background relation. At 500 foot-candles, for dark numerals on a light background, thresholds were better for a stroke-width 25 percent of symbol height than for a stroke-width 6 percent of symbol height.

For light numerals on a dark background at 500 foot-candles, the threshold was better for the narrower stroke-width than for the wider stroke-width. At an illumination of 0.5 foot-candle, the threshold was better for both symbol-to-background relations when the stroke-width was 25 percent of symbol height than when it was 6 percent of symbol height.

Conclusions and Recommendations

Because of the limitations of the data noted above, reliable recommendations regarding stroke-width cannot be made at the present time. There are, however, some tentative recommendations which may be used as a guide for selection of stroke-widths.

For light symbols on a dark background, with a symbol brightness in excess of 100 foot-lamberts and a brightness contrast in the range of +0.90 to +0.95, a stroke-width 6 to 7 percent of symbol height seems to yield the best threshold of identification.

For the same conditions of brightness and brightness contrast as above, but for dark symbols on a light background, a thicker stroke of around 12 percent of symbol height is indicated.

For medium brightnesses and the same range of brightness contrast as stated above (+0.90 - +0.95), there are two tendencies noted in the data: (a) stroke-width has a similar effect on the threshold of identification for both values of symbol to background relation, and (b) as brightness (symbol or background) is decreased from 31 to 3 foot-lamberts, the best thresholds are obtained if there is an increase in stroke-width from 13 percent of symbol height for a brightness value of 31 foot-lamberts to 20 percent of symbol height for a brightness value of 3 foot-lamberts.

At values of illumination lower than 3 foot-lamberts, the Soar data suggests that the threshold will be best for both symbol-to-background relations if stroke-width is increased from 20 to 25 percent of symbol height.

A final recommendation is that extremely narrow stroke-widths may be appropriate, even those as narrow as 2 to 3 percent of symbol height when (a) the subject is dark adapted, (b) the brightness contrast is higher than +0.95, (c) the symbols are light on a dark background and (d) medium to high values of symbol brightness are used.

SYMBOL STYLE OR GEOMETRY

Symbol style is not easy to specify in quantifiable terms which apply equally well to all symbols in a set. One of the reasons for this is that symbol style, or geometry, involves many factors rather than a single factor.

For example, an experimental comparison of the relative legibility of Berger and AND numerals might be made for the purpose of evaluating the relative effects on legibility of angular versus curved symbol construction (see Figures 7 and 8). Although, as one can see, the Berger numerals have angular construction of their inner dimension while the AND have curved construction, the two sets of numerals also differ in the proportionality of upper to the lower parts of some numerals, the inclusion of short legs on some of the Berger numerals, etc. Therefore, reported differences in the legibility of existing styles cannot be attributed to a single factor.

Despite these difficulties in the interpretation of results, there has been a good deal of experimental work on symbol style. Two distinct trends are evident in the literature. Some studies were designed to compare entire sets of symbols and to make statements about the relative legibility of the symbol sets. Other studies have tried to reduce intersymbol confusions within a single set of symbols.

Accuracy of Identification

Aeronautical Medical Laboratory Studies

The effect on identification accuracy of different styles of alphabetic and numeric symbols has been investigated in three of the five studies conducted at the Aeronautical Medical Equipment Laboratory. The purpose of the studies was to derive legibility specifications for symbols on aircraft instrument and control panels.

In the fourth study of the series, described in this report, the legibility of Garamond Bold letters and the NAMEL letters (shown in Figure 5) was investigated. The intent of the study was to compare the legibility of an alphabet constructed with a uniform stroke-width and without serifs (NAMEL) with one constructed with a variable stroke-width and with serifs (Garamond Bold).

Only 19 of the 26 letters were shown for identification. The B, I, J, K, Q, V, and W were excluded because of their infrequent use on instrument and control panels. The widest part of the stroke-width of Garamond Bold letters was equal to 17 percent of letter height. The NAMEL letters had a stroke-width equal to 17 percent of letter height. The Garamond Bold letters had an average letter width of 83 percent* of letter height, with the serifs excluded from the width measurements, and were compared with NAMEL letters in a width equal to 85 percent of letter height.

The results indicated, for letters exposed for 0.20 second and with brightnesses of 0.30 and 0.80 foot-lambert, that, on the average, 11 percent more errors of identification occurred with the Garamond Bold letters than with the NAMEL letters. For letter brightnesses of 1.60, 2.60, and 3.30 foot-lamberts and a symbol exposure time of 0.20 second, there were only 2 percent more errors, on the average, made in the identification of Garamond Bold letters than in the identification of NAMEL letters.

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*Estimated by the author of this report.

When symbol exposure time was shortened to 0.04 second, there was an average of 15 percent more errors in the identification of the Garamond Bold letters than in the identification of NAMEL letters for all 5 symbol brightnesses combined.

For the simulated daylight situation, an average of 50 percent more errors was made in the identification of Garamond Bold letters than NAMEL letters. The statistical significance of differences in accuracy of identification was not reported for any of the conditions studied.

Brown, Lowery and Willis Study [12]

Brown, Lowery and Willis, in the third paper of the series, compared accuracy of identification for AND10400 and Berger numerals (see Figure 4). Both sets of numerals were prepared in the same height, width, and height-to-width ratio, although in the latter two respects the Berger numerals differ from those recommended by Berger for use on automobile license plates (see Figure 8). The width of the numerals in both styles was 60 percent of symbol height with the exception of the "1" which had a width equal to the stroke-width of the numerals. Other features of the experiment are described in this report.

In the simulated day tests, numerals were presented in groups of four rather than groups of three. Separate Chi Square tests were performed on the error scores for each individual numeral. The results of these tests indicated only two significant differences in accuracy of identification between the two styles; the Berger number "4" was significantly better than the AND "4" for both the simulated day and night situations. For the simulated daylight situation, accuracy of identification of the AND "9" was significantly better than that of the Berger "9".

Atkinson, Crumley and Willis Study [8]

Atkinson, Crumley and Willis, in the fifth report of the series from the Aeronautical Medical Laboratory, evaluated a new numeral style which was suggested, in part, by the Brown, et al., study described above. The new numerals (AMEL) were compared with the Berger and AND10400 numerals. The three styles used in the study are shown in Figure 8.

The conditions used in the Atkinson, et al., study were changed slightly from those of the first four studies in the series. Only a single exposure of 0.20 second was used in the simulated night situation, but the brightness values were the same as those described earlier. In the simulated day situation, exposure time was shortened from 7 to 5 milliseconds, and illuminations of 11, 24, and 34 foot-candles were used.

The viewing distance at which the numerals were identified was increased to 30 inches, thus decreasing the visual angle of subtense to approximately 18 minutes of arc. The numerals in all three styles were prepared in a width 60 percent of numeral height except that the AMEL "4" was one stroke-width wider than the other numerals, and the numeral "1" was one stroke-width wide in each of the three styles.

Accuracy of identification was significantly better for numerals in the AMEL style than for numerals in either the Berger or AND style. The study should be referred to if information is desired about differences among individual numerals in each of the three styles.

The Lansdell Study

There have been several attempts to improve numeral legibility by making radical changes in geometry. In a study reported by Lansdell, [24] a new numeral style was compared with the Mackworth numerals. The numeral styles are shown in Figure 10.

The basic idea in the design of the new numerals was to use triangular and rectangular components (because of the purported ease with which these shapes are discriminated from other shapes) in the construction of the ten numerals. Dark numerals on a light background were shown one at a time for 0.6 second exposure with a background brightness of 10 foot-lamberts. The numerals subtended an angle of 5 minutes of arc at the eye. The subjects were given practice in identification of the new numerals before the experiment. The author reports that accuracy of identification of the new numerals was significantly better than the accuracy of identification of the Mackworth numerals.

A second study, by Foley,[25] reported the legibility of a revision of the Lansdell numerals. The numeral styles compared in the study are shown in Figure 11. Foley carried out several different experiments with the two styles. In one experiment, the revised Lansdell numerals were compared with Mackworth numerals at illuminations of 10, 30, and 50 foot-candles, and at exposure times of 0.3, 0.8, and 1.3 seconds.

The Mackworth numerals had a width equal to 50 percent of numeral height and a stroke-width equal to 12.5 percent of numeral height, with the exception of the numeral "1" which was one stroke-width wide. The revised Lansdell numerals had a width 50 percent of numeral height and a variable stroke-width with the exception of the numeral "1" which had a constant stroke-width equal to 13.3 percent of numeral height.

Dark numerals on a light background subtended an angle of about 5 minutes of arc at the eye. Six subjects with 20/20 far acuity, as measured by the U. S. Armed Forces vision tester, were used in the study. The

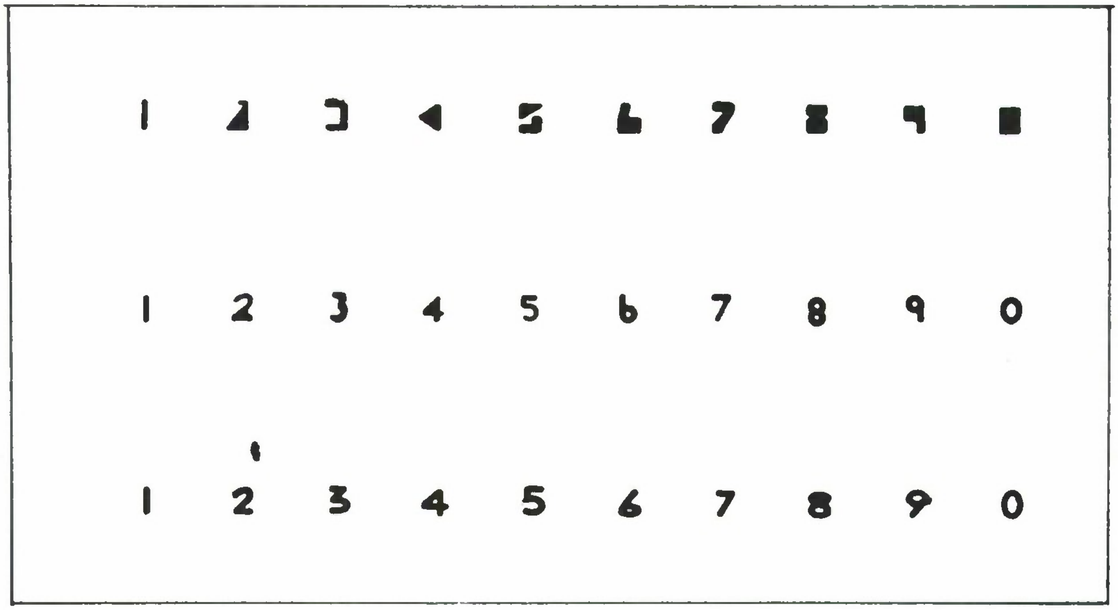

Figure 10. Numeral Styles Evaluated by Lansdell

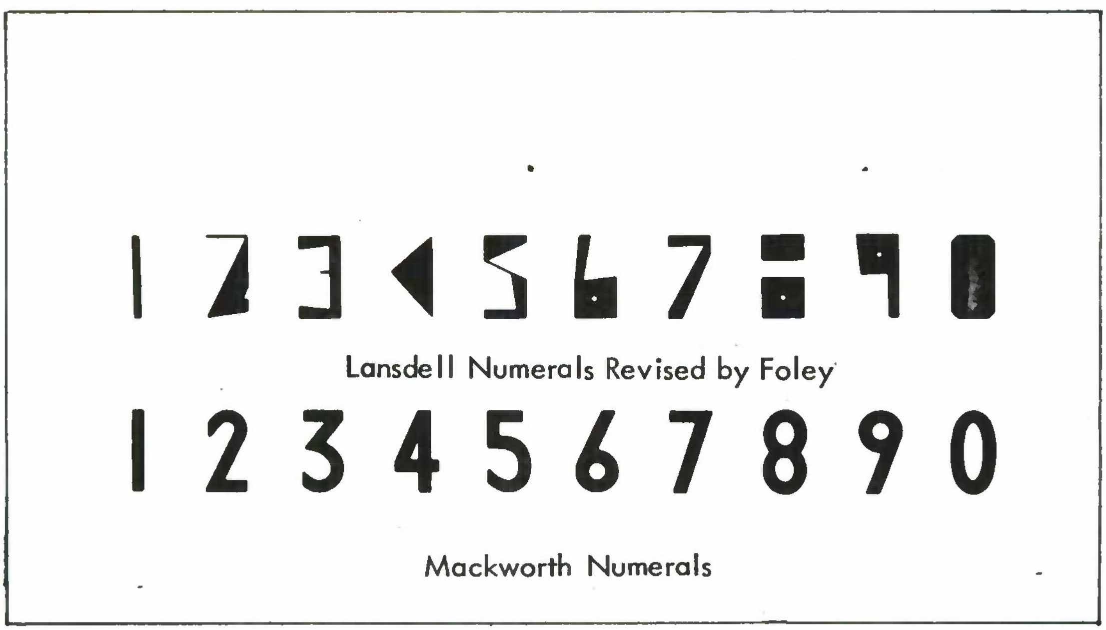

Figure 11. Numerals Used by Foley

subjects were given practice so they could learn the identity of the new numerals before the experiment began.

The results indicated that accuracy of identification was significantly better for the experimental numerals than for the Mackworth numerals. In a second experiment, the two numeral styles were compared at different angles of viewing. Accuracy of identification of the experimental digits was significantly better than the identification of Mackworth numerals for viewing angles 45 degrees right and left of normal line of sight.

The Mackworth Study

One of the few attempts to improve the legibility of an entire set of alphanumerics was undertaken by Mackworth [26] during World War II. The symbols Mackworth redesigned were those used on air raid sector maps, and they had a letter style similar to that of the AND10400 and a numeral style similar to the Leroy. The set of alphanumerics used on the maps and the new set designed by Mackworth are both shown in Figure 12.

Mackworth ran symbol identification tests on the two sets of alphanumerics at viewing distances of 25, 30, 35, and 40 feet. The angles subtended by the height of the symbols ranged from 9 minutes of arc at 25 feet to 6 minutes of arc at 40 feet. The symbols were presented one at a time for one and one half seconds and were illuminated by 10 foot-candles. The symbols in the old design were shown as dark on an orange background while the symbols in the new design were shown as dark on a yellow background.

Crook and Baxter [16] have pointed out that the use of different colored background probably gave the symbols in the new design a higher value of brightness contrast than the symbols in the old design, and

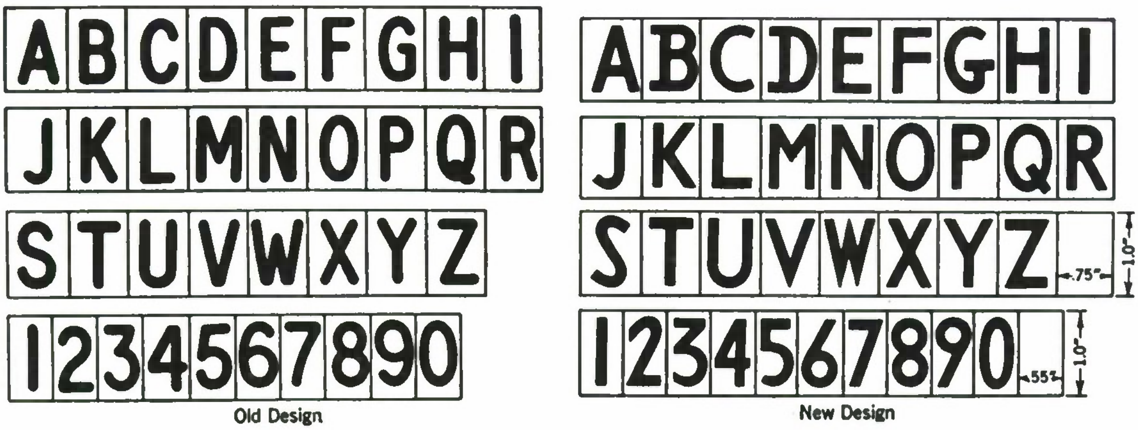

Figure 12. Letters and Numerals Used By Mackworth

consequently, the new symbols had an advantage over the old symbols in the legibility test. Therefore, Mackworth's finding that the accuracy of identification of symbols in the new design was better than that for symbols in the old design cannot be considered as conclusive evidence for the superiority of the new design.

It still might be argued, on the basis of the geometry of the symbols alone, that the new set of symbols is better than the old, since commonly confused symbols were redesigned to increase their geometric distinctivencss. Some examples of these changes are the lengthening of the bars on the "Q" and "G," the addition of overhangs to the "B," the enlargement of the gap in the "C," etc.

The Mackworth alphanumerics were used, with some modifications, by MIT's Lincoln Laboratory on the Sage Charactron display. Some of the modifications of the Mackworth alphanumerics have been reported in a study by Harris, Green, Wilson and Liaudansky.[27] The first experiment was designed, in part, to evaluate the legibility of the Mackworth numerals and, in part, to determine the effects on legibility of symbol overprinting. The results of this study indicated that the most prominent sources of error in numeral identification were "6" called "4," "3" called "5," "5" called "3," "7" called "2," "2" called "7," and "9" called "7." An effort was made to reduce these confusions by redesigning the Mackworth numerals. The revised set of numerals is shown in Figure 13.

A second experiment included an identification test of the new numerals, the Mackworth letters* and some special symbols. Several identification tests of all these symbols (60 in all) were carried out in situations which included varying amounts and colors of ambient illumination and symbol brightness. The preceding evaluations, as well as several additional identification tests, formed the basis for the final design of the set of alphanumerics (shown in Figure 13) used on the Sage Charactron.

Several additional design improvements** of the Mackworth alphanumerics were attempted by Lincoln Laboratory and these are shown in

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*Some modifications were made of the original Mackworth letters in that horizontal serifs were added to the "I," the central point of the "M" was raised, a central horizontal bar was added to the "Z," the horizontal strokes of the "E" were lengthened, and the tail of the "Q" was extended inward toward the center of the letter.

**These improvements in the alphanumerics were attempted after the production deadline for the Sage Charactron matrix so that successful changes in some of the letters could not be included in the Mod X design.

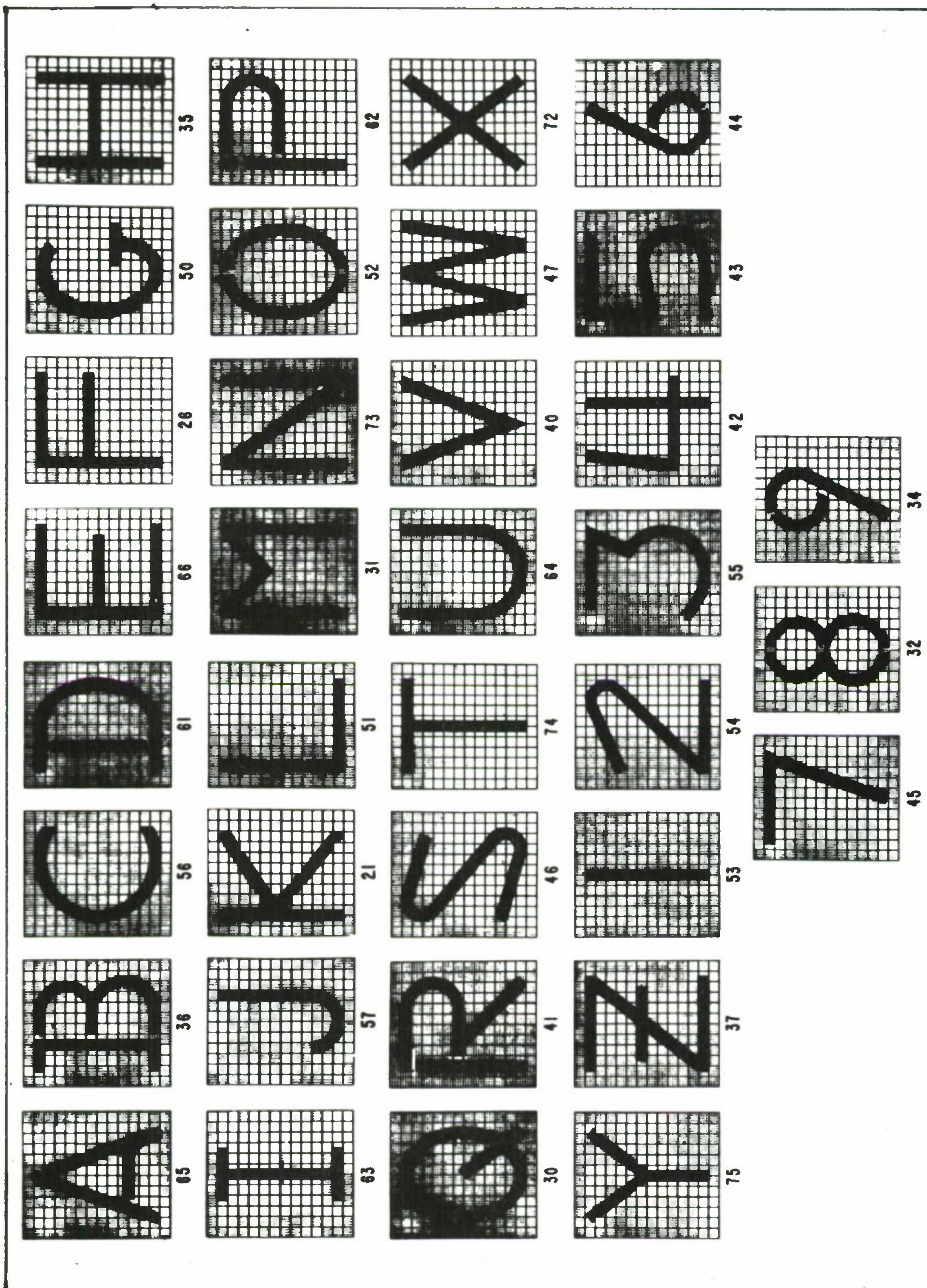

Figure 13. Mod $\overline{X}$ Symbols for use on SAGE Consoles

Figure 14. An experimental evaluation of the new symbols showed the following: (a) the new design of the letter "I" was successful and eliminated the "I" called "1" confusion, (b) the new design of the "Q," "Z," and "8" did not lead to any noticeable improvement since the "Q" was missed often, the "Z" was still called "2," and the "8" continued to be confused with many other symbols.

On the basis of the poor showing of the "Q," "Z," and "8," some additional changes in the geometry of these letters were suggested by Lincoln Laboratory to improve their legibility (see Figure 15). Sanders, in a study previously described in this report, experimentally evaluated the new design of the "Q" and "Z" which are shown in Figure 15.

The set of alphanumerics used by Sanders was the one selected for the Advanced Display Console (ADC) and is similar in design to that of the Mod X alphanumerics shown in Figure 13. The major difference between the ADC and Mod X alphanumerics, aside from the new design of the "Q" and "Z," is that the ADC also has the improved letter "I" shown in Figure 14. Sanders' data showed that the new design of the letter "Z" eliminated the "Z called 2" confusion, but in so doing introduced new confusions between the "1" and the "Z," and between the "I" and the "Z."

Conclusions and Recommendations

The Brown study indicated that accuracy of identification for most of the conditions investigated was better for letters constructed with uniform stroke-width and without serif (NAMEL) than it was for letters constructed with a variable stroke-width and serifs. Therefore, it is recommended that letter styles featuring variable stroke-widths and serifs be avoided in display situations, particularly when factors such as symbol brightness and exposure times are at marginal values.

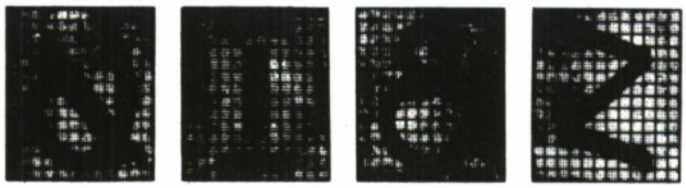

Figure 14. Revisions to Mod $\overline{X}$ Symbols

Figure 15. Further Revisions to Mod $\overline{X}$

The results of the Mackworth study suggest that alphanumerics of his design were superior to a style similar to the AND10400 and the Leroy. The demonstrated superiority of the new symbols was questioned because of a confounding of experimental variables. Despite the lack of conclusive evidence about the most legible set of alphanumerics, the modified Mackworth font designed by Lincoln Laboratory seem to be the best choice at this time. The Mod X and ADC alphanumerics have one advantage that other sets of alphanumerics do not have, namely, an extensive experimental evaluation which led to a reduction of major confusions among symbols.

If only numerals are used, the studies by the Aeronautical Medical Laboratory suggested that AMEL numerals would be better than the AND10400 and Berger. Unfortunately there are no studies as yet which compare the legibility of the AMEL, Mackworth or Mod X numerals. Several laboratory studies have shown that numerals constructed of triangles and rectangles are more legible than Mackworth numerals, but their superiority in an operational display situation has yet to be demonstrated.

Rate and Speed of Symbol Identification

The Schapiro Study[3]

A study by Schapiro, described in this report, showed speed of symbol identification as a function of the four different numeral styles shown in Figure 3. The interpretation of the results of the Schapiro study is complicated by the fact that symbols in the different styles were not equated in width or in height-to-width ratio.

Crook and Baxter[16] have indicated that the average widths of numerals in the various styles were 65, 61, 52, and 50 percent of symbol height for the AND, Craik, Berger, and Mackworth. The results of the study, shown in Table IX, indicate that speed of identification was similar for the four styles at symbol brightnesses between 0.04 and 1.0 foot-lamberts.

Table IX

Speed of Identification

Symbol Brightness in Foot-Lamberts	Symbol Size	Speed in Seconds
1.0	AND	.48
	BERGER	.47
	CRAIK	.47
	MACKWORTH	.47
0.15	AND	.50
	BERGER	.50
	CRAIK	.50
	MACKWORTH	.49
0.04	AND	.54
	BERGER	.53
	CRAIK	.55
	MACKWORTH	.54
0.01	AND	.83
	BERGER	.85
	CRAIK	.91
	MACKWORTH	.84

Description of Experimental Conditions

Background Brightness: About 0.2, 0.03, 0.008 and 0.002 foot-lamberts for symbol brightnesses of 1.0, 0.14, 0.04 and 0.01 foot-lamberts, respectively

Brightness Contrast: +0.80

Ambient Illumination: Not stated (Probably negligible since experiment conducted in light tight booth)

Properties of Light Source: 300 watt, 120 volt standard projection lamp operated at 60 volt.

Symbol-Background Relation: Light on Dark

(Table IX Continued)

Table IX Continued

Symbol Stroke-Width: Stroke-widths were 10, 12.5, 16 and 20 percent of symbol height

Horizontal Spacing: Not relevant

Symbol Width: 65, 52, 61 and 50 percent of height for the AND, Berger, Craik and Mackworth, respectively

Angle of Subtense: 32 minutes of arc

Symbol Exposure Time: 0.95 seconds

Number of Symbols: 10 numerals in each style

Number of Subjects: 12

Visual Characteristics of Subjects: "Normal" near and far acuity, depth perception, lateral and vertical phoria as measured by the Bausch and Lomb Ortho-Rater

Viewing Distance: 28 inches

At a symbol brightness of 0.01 foot-lambert, there was a marked decrease in speed of identification for all styles, and the greater decrease in speed of identification occurred for numerals in the Craik style.

Speed of identification of the Craik numerals was significantly slower than that for numerals in the other three styles. There were no significant differences in speed of identification for numerals in the AND, Berger, and Mackworth styles. Since the Mackworth numerals were the narrowest of all, it is possible that any advantage of the Mackworth style was obscured by the disadvantage in width.

Conclusions and Recommendations

Although there were no significant differences among the AND, Berger, and Mackworth numerals, the effects of style may have been obscured by associated differences in numeral width and/or height-to-width ratios. It might be expected on the basis of the Brown data in this report, that numeral width would affect speed of identification, especially at low values of illumination. It could be that the Mackworth style numerals had some special merit which counterbalanced their disadvantage in symbol width. It seems reasonable, therefore, to recommend the Mackworth numerals over numerals in the other three styles when a display situation approximates that described in Table IX.

Threshold of Identification

The Reinwald Study

The legibility of AND10400, Mackworth, Reinwald, and Berger symbols (see Figures 8, 12, 16 and 17) was compared at several horizontal and vertical angles of viewing by Reinwald.[28, 29, 30] Light symbols on a dark background were presented singly for identification. The measure of legibility was the 100 percent threshold of identification. Symbol brightness was 1.28 foot-lamberts and background brightness was 0.125 foot-lambert; brightness contrast was +0.90. The ambient illumination ranged from 0.25 to 0.33 foot-candles and the subjects were adapted to these ambient lighting conditions 10-15 minutes prior to the experiment.

In the first experiment[29] AND10400, Mackworth, and Berger symbols were compared. Ten subjects screened for normal vision by the Telebinocular test identified symbols in each of the three styles for straight-on viewing (symbols displayed normal to the line of sight) and for five angles of viewing of 15, 30, 45, 60, and 75 degrees from the normal line of sight. The stroke-width of the AND10400 and Mackworth symbols was approximately 12.5 percent of symbol height while that for the Berger numerals was approximately 7.6 percent of height.

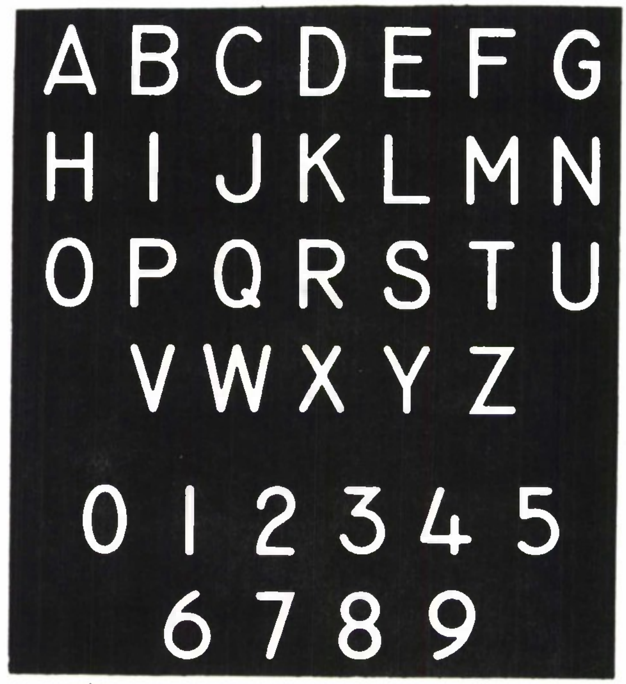

Figure 16. Alphanumerics Specified by MIL Standard MS-33558 Nearly Identical to AND10400

It is not clear what width of symbol was used. The author reports only that the width of most of the symbols was 66 percent of symbol height. However, if he used symbol widths recommended by the designers of the fonts, then the Mackworth and Berger numerals were probably less wide (average width about 50 percent of height) than the AND10400 numerals while the AND10400 and Mackworth letters were probably of similar width.

The data indicated little difference between symbols in the AND10400 and in the Mackworth style. The numerals in each style required a larger angle of subtense for identification than did the letters. The Berger numerals required a larger angle of subtense at all angles of viewing than either the AND10400 or the Mackworth numerals.

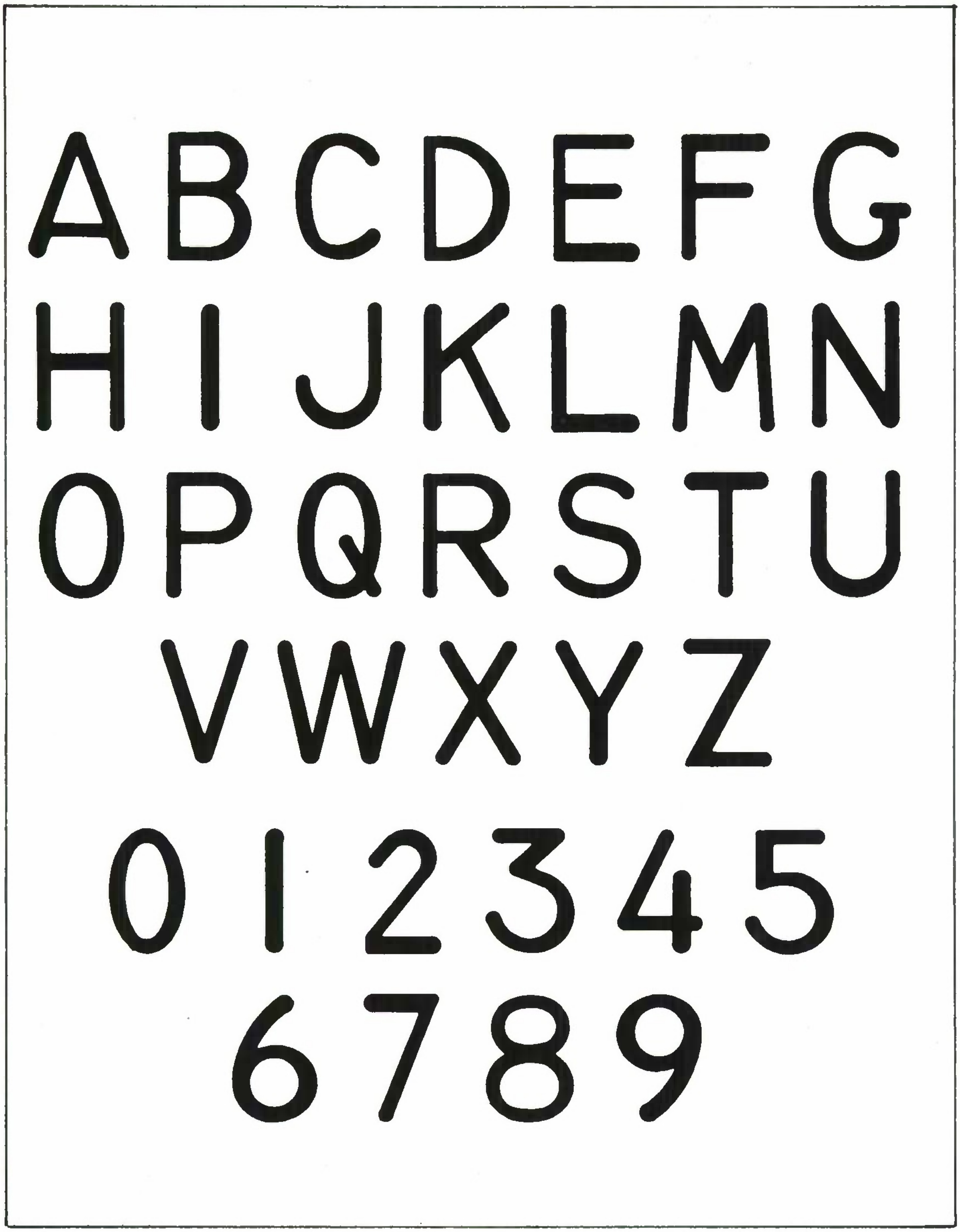

Figure 17. Alphanumerics Designed by Reinwald

The statistical analysis of the data consisted of a series of t tests between individual symbols in each of the three styles at each angle of viewing. The results of the t tests indicated that in the majority of cases there were no statistically significant differences between symbols. In those instances in which statistically significant differences occurred, the AND10400 had a greater proportion of more legible symbols than either the Mackworth or Berger symbols.

The data from the study are not presented in tables because the reported angles at which correct identification occurred seem smaller than one would expect for the conditions under which the identifications were made. For example, the average angle of subtense at which AND10400 symbols were correctly identified for straight-on viewing was only 3 minutes and 39 seconds of arc and that for the Mackworth symbols was 3 minutes and 41 seconds of arc. With a stroke-width of 12 percent of height, the width of the stroke subtended approximately 27 seconds of arc when correct identification occurred.

The perception of such fine detail would be expected only under ideal conditions and with a different visual task such as resolving a length of wire laid across a bright field. In the Snellen test, which also involves the identification of symbols, normal acuity is defined as the ability to resolve letters which subtend 5 minutes of arc (stroke-width subtends one minute of arc) and for higher brightnesses than were used in the Reinwald study. Furthermore, because of differences in stroke-width and width among symbols in the three styles the results of the study cannot be attributed solely to geometric differences. It is likely, for example, that the Berger numerals required a larger angle of subtense for correct identification than numerals in the other styles because of their smaller stroke-width.

In the second study by Reinwald,[30] a new set of letters and numerals (Figure 17) was compared with the AND10400 (Figure 16). The conditions of the study were similar to those reported above for the first study. The results showed that while the new font consistently yielded smaller angles of subtense for correct identification than the AND10400, in only a few cases were the new symbols significantly more legible. For the straight-on viewing condition only the new numeral "4" was significantly more legible than the AND10400 numeral "4"; there were no statistically significant differences between any of the other 35 symbol pairs.

Berger Studies

The Berger studies [20,21] represent a systematic attempt to determine the effects on legibility of changes in symbol geometry. Some of the details of these experiments are described in this report. Berger's work included an examination of the geometry of the numerals 2 through 9. All the experiments Berger performed will not be described here because they are too lengthy and their values as a guide to numeral design is questionable since the situation in which the investigations were undertaken was not described in detail.

However, several of his manipulations of symbol geometry are described in order to illustrate the kind of experiments that are possible with symbol style. The numeral "4", for example, was varied in several ways. First, the distance from the base of the numeral to the middle horizontal line was manipulated to determine its effect on the threshold of identification. Second, the effect on the threshold of different inclinations of the line extending upward from the left side of the horizontal bar was determined.

Berger reports the best threshold of identification occurred when the horizontal bar crossed about 1/3 of the way up the vertical stroke. Also, a line connecting the left side of the horizontal bar and the top of the vertical line was found to be best.

In another case, Berger investigated the effect on the identification threshold of different angles between the horizontal bar and the vertical leg of the numeral seven. He reports that the threshold was best for an angle equal to about 27 degrees. Additional findings of effects on the threshold of identification of manipulation of the geometric features of other numerals can be found in Reference 20, pages 222 to 224.

The Tinker Study [17]

In a study by Tinker described in this report, the effects on the threshold of identification of old style and modern numerals was investigated (see Figure 18). The only details provided by the author concerning the geometrics of the two sets of numerals was that the old style numerals varied in height and vertical position while the modern style of digits were uniform in height and vertical position. Both styles have been used in printing mathematical tables. Tinker found that the threshold was better for old style numerals than for modern style numerals when the numerals were presented singly and in groups. The differences in thresholds were statistically significant in both cases, but the greatest relative difference between the two styles occurred when the numerals were presented in groups.

Conclusions and Recommendations

The Reinwald data are inconclusive with regard to the most legible style of numerals. The AND10400 and the Mackworth numerals were

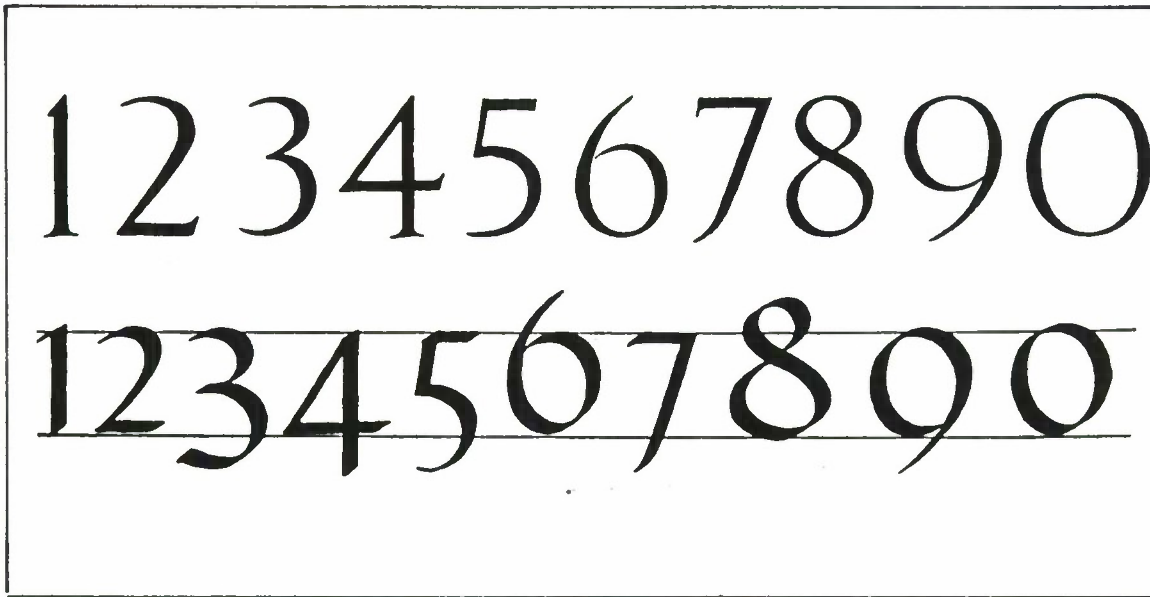

Figure 18. Modern (above), and "Old Style" (below) Numerals

identified at smaller angles of subtense than the Berger numerals but the latter had a disadvantage of a smaller stroke-width. As far as letter numeral sets are concerned the AND10400, Mackworth, and Reinwald required similar angles of subtense for identification. The AND10400 and Mackworth are preferred over the Reinwald because the small improvement in legibility for the Reinwald is more than offset by the greater difficulty in construction of Reinwald symbols. When tables of numerals are displayed, Tinker's data indicate that some advantage might be gained by the use of old style numerals.

VIEWING ANGLE

When a display is shared simultaneously by several observers, each of them must view the display from a different angle. It is important to determine the way in which legibility is affected by angle of viewing so that the usable viewing area for a display can be plotted. There are a few studies which have investigated this factor each of which has used the threshold of identification as the measure of legibility.

Foley and Scott Study

Foley and Scott [31] investigated the legibility of Leroy digits at several distances of viewing, angles of viewing, and intensities of illumination. The data from this study are presented in Table X and represent the angle in minutes subtended by symbol height when all subjects were able to make identifications without error. The median angle subtended by the symbols is smallest for the normal line of sight (straight-on viewing), next smallest for 45 degress left of the normal line of sight and largest for 45 degrees right of the normal line of sight. However, the angle required for 45 degrees left of the normal line of sight is approximately the same as that required for straight-on viewing while the angle required for 45 degrees right is 2 to 3 minutes of arc larger than that for straight-on viewing.

Reinwald Studies

Several studies by Reinwald [28, 29, 30] report symbol legibility for angles of viewing of 0, 15, 30, 45, 60, and 75 degrees, both horizontally and vertically. Zero degrees is the normal line of sight, while each of the other angles is an angular displacement from the normal line of sight. The horizontal displacements were made to the right of the normal line of sight, and the vertical displacements were made upward from the normal line of sight. The measure of legibility was the 100 percent threshold.

Table X

Threshold of Identification

Viewing Angle in Degrees	Intensity in Foot-Candles	Distance in Inches	Threshold in Minutes of Arc	Median Threshold in Minutes of Arc for All Distances
0	1	12 48 96 129	11 10 9 7	9.5
	10	12 48 96 129	9 7 8 7	7.5
	50	12 48 96 129	9 7 6 6	6.5
45 left	1	12 48 96 129	11 10 10 --	10.0
	10	12 48 96 129	9 7 8 7	7.5
	50	12 48 96 129	9 7 7 7	7.0
45 right	1	12 48 96 129	14 13 13 --	13.0
	10	12 48 96 129	9 8 10 9	9.0
	50	12 48 96 129	9 9 9 9	9.0

(Table X Continued)

Table X Continued

Description of Experimental Conditions

Symbol Brightness: 0.05, 0.5, 2.5 foot-lamberts*

Background Brightness: 0.75, 7.5, 37.5 foot-lamberts*

Brightness Contrast: -0.92

Ambient Illumination: Not stated

Properties of Light Source: 40 watt lumi-line bulbs, Variac controlled for different brightnesses

Symbol-Background Relation: Dark on light

Symbol Style: Leroy

Symbol Stroke-Width: Ranged from 10 to 17** percent of height with a median width of 13.4 percent

Symbol Spacing: Not relevant

Symbol Width: 70 percent of symbol height

Symbol Exposure Time: Not relevant

Number of Symbols: 10 numerals (complete set)

Number of Subjects: 20 for 0 degrees (normal viewing) and 5 each for angles of viewing

Visual Characteristics of Subjects: 20/20 binocular acuity as measured by the U.S. Armed Forces Vision Tester

Viewing Distance: Was varied to obtain visual thresholds

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*Estimated by the present author; assumes a reflectance of 75 percent for the background and 5 percent for the symbol.

**The reason for the variation in stroke-width is that the authors of the study used pen sizes recommended by the manufacturer for templates of different sizes--the same pen sizes are recommended for several different heights of symbols.

The results showed for AND10400, Mackworth and Berger symbols that a slight increase in visual angle of subtense was required for viewing angles of 15, 30, and 45 degrees over that found for zero degrees. Substantially larger angles of subtense were needed for viewing angles of 60 and 75 degrees.

The author reports that the data were fitted quite well by a function in which legibility (angle of subtense) decreased according to an exponential cosine of the angle of displacement. The same exponent adequately described in the data for each of the three fonts but the angle of subtense required for identification at the various angles differed for the three fonts.

The maximum distances from the display at which observers can be positioned for various angles of viewing can be determined, according to the author, by use of the following formula: $D_{ft} = b\ (\text{cosine}\ \theta)^{2/3}$ for the horizontal angles and, $D_{ft} = b\ (\text{cosine}\ \theta)^{1/2}$ for the vertical angles, where b represents the distance in feet required to correctly identify symbols displayed normal to the line of sight, and θ represents the angle in degrees between the position of interest and the normal line of sight. The constant b will differ for various conditions of viewing, e.g., brightness, contrast, stroke-width, fonts, etc.

In applied situations, then, the distance required for identification of symbols displayed normal to the line of sight would have to be determined by use of the threshold procedure before distances required for different angles of viewing could be calculated.

Conclusions and Recommendations

The distances from observers to the display required to maintain legibility at different angles of viewing can be estimated by use of the exponential cosine function suggested by Reinwald. However, it should be recognized that this is only an estimate; there is no guarantee that the function will hold for viewing conditions other than those of the Reinwald study. Whether one uses the formula or not, it appears that, for all practical purposes, observers sharing a common display can be placed at angles up to 45 degrees from the normal line of sight at about the same distance as that required for the normal line of sight. The Reinwald data indicate that substantial increases are required in the angle of subtense (moving the observer closer to the display) for angles of viewing greater than 45 degrees.

APPENDIX I

Visual Angles in Minutes of Arc

The visual angles in minutes of arc subtended by symbols of different size are tabulated below for various viewing distances.

Viewing Distance in Inches	Symbol Height in Thousandths of Inches								
	50	75	100	125	150	175	200	225	250
12	14.3	21.5	28.6	35.8	43.0	50.1	57.3	64.5	71.6
14	12.3	18.4	24.6	30.7	36.8	43.0	49.1	55.2	61.4
16	10.7	16.1	21.5	26.9	32.2	37.6	43.0	48.3	53.7
18	9.6	14.3	19.1	23.9	28.6	33.4	38.2	43.0	47.8
20	8.6	12.9	17.2	21.5	25.8	30.1	34.4	38.7	43.0
22	7.8	11.7	15.6	19.5	23.4	27.4	31.2	35.2	39.1
24	7.2	10.7	14.3	17.9	21.5	25.1	28.6	32.2	35.8
30	5.7	8.6	11.5	14.3	17.2	20.0	22.9	25.8	28.6
36	4.8	7.2	9.6	11.9	14.3	16.7	19.1	21.5	23.9
42	4.1	6.1	8.2	10.2	12.3	14.3	16.4	18.4	20.5
48	3.6	5.4	7.2	9.0	10.7	12.5	14.3	16.1	17.9
54	3.2	4.8	6.4	8.0	9.6	11.1	12.7	14.3	15.9
60	2.9	4.3	5.7	7.2	8.6	10.0	11.5	12.9	14.3

APPENDIX I - PART II

Viewing Distance in Inches	Symbol Height in Thousandths of Inches							
	250	500	750	1000	1250	1500	1750	2000
60	14.3	28.6	43.0	57.3	71.6	85.9	100.3	114.6
72	11.9	23.9	35.8	47.8	59.7	71.6	83.6	95.5
84	10.2	20.5	30.7	40.9	51.2	61.4	71.6	81.8
96	9.0	17.9	26.9	35.8	44.8	53.7	62.7	71.6
108	8.0	15.9	23.9	31.8	39.8	47.8	55.7	63.7
120	7.2	14.3	21.5	28.6	35.8	43.0	50.1	57.3
132	6.5	13.0	19.5	26.0	32.6	39.1	45.6	52.1
144	6.0	11.9	17.9	23.9	29.8	35.8	41.8	47.8
156	5.5	11.0	16.5	22.0	27.6	33.1	38.6	44.1
168	5.1	10.2	15.4	20.5	25.6	30.7	35.8	40.9
180	4.8	9.6	14.3	19.1	23.9	28.6	33.4	38.2
192	4.5	9.0	13.4	17.9	22.4	26.9	31.3	35.8
204	4.2	8.4	12.6	16.8	21.1	25.3	29.5	33.7
216	4.0	8.0	11.9	15.9	19.9	23.9	27.8	31.8
228	3.8	7.5	11.3	15.1	18.8	22.6	26.4	30.2
240	3.6	7.2	10.7	14.3	17.9	21.5	25.1	28.6

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Symbols						
Display Design						
Psychology						
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13. ABSTRACT

The effects of classical factors, such as symbol geometry, symbol brightness, and brightness contrast, upon the legibility of numerals and capital letters are discussed. The literature of the last few decades is evaluated, and selected studies are reviewed in detail and referenced. Conclusions are drawn, and recommendations are made for display design and application.

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