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AN EVALUATION OF THE EFFECT OF SPOT WOBBLE UPON OBSERVER PERFORMANCE WITH RASTER SCAN DISPLAYS

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A television image is formed by a series of parallel luminous lines called a raster. The visual prominence of the raster structure has been shown to interfere with the extraction of information from the image. However, the raster may be suppressed experimentally by a deflection process called spot wobble.

Experiments were conducted to determine the effects of raster structure suppression on visual sine-wave contrast sensitivity thresholds, dynamic target

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) acquisition performance using noise-free and noise-degraded imagery, and alphanumeric recognition performance using noisy and noise-free static displays.

Results of the dynamic experiment indicate raster structure suppression and improvements in sine-wave threshold sensitivity are correlated and that a suppressed raster significantly improves target acquisition performance for noise-free conditions.

Results of the static experiment were inconclusive, as no spot wobble effect was obtained, although display noise had a significant effect upon search time. Significant correlations with the modulation transfer function area (MTFA) image quality metric were obtained, although the correlations were neither large nor consistent enough to be strongly advocated for detailed design evaluations.

PREFACE

This study was initiated by the Visual Display Systems Branch, Human Engineering Division of the Air Force Aerospace Medical Research Laboratory. The research was conducted by the Department of Industrial Engineering and Operations Research, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, under Air Force Contract No. F33615-76-C-5022. Dr. Harry L. Snyder was the Principal Investigator for Virginia Polytechnic Institute and State University. Mr. Wayne L. Martin and Dr. H. Lee Task were the Technical Monitors for the Air Force Aerospace Medical Research Laboratory. The report covers research performed between October 1975 and June 1977 under Task II: Spot Wobble.

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INTRODUCTION

Television or raster-scan systems have been used for about four decades in a wide variety of commercial, scientific, and military settings. While the basic principles of television operation have not changed, there have been many improvements in sensor system technology in recent years. These improvements have generated an apparent need for raster-scan displays with greater bandwidth, smaller spot size, higher line rates, and greater dynamic range. Unfortunately, many of these seemingly realistic requirements interact: for example, higher line rates lead to reduced dynamic range because of increased spot velocity, and a smaller spot size yields larger dark areas between raster lines if the raster line pitch is not reduced. In an effort to understand the effects of these and other design variables upon the performance of the operator viewing the display, numerous laboratory and analytical investigations have been conducted during the past 15 years. Much of this research has been oriented toward the development of a unitary metric of image quality (Rosell and Willson, 1973; Snyder, 1973; Task, 1979). Other studies have addressed the effects of specific display and system variables upon operator performance.

One of the variables that appears to have a significant effect upon operator performance, yet has been researched very little, is that of raster line visibility on the display and the benefits of reducing the visibility of the raster. A convenient experimental technique by which the visibility of the raster can be manipulated is termed spot wobble.

SPOT WOBBLE

Spot wobble allows an experimenter to easily control raster modulation from a minimum of ≤ 0.04 to whatever maximum the monitor may produce. Modulation is defined by:

$$M = (L_{max} - L_{min})/(L_{max} + L_{min}), \quad (1)$$

where

M = modulation ($0 < M < 1$),

L_{max} = the scanning line luminance, and

L_{min} = the luminance of the space between the scanning (raster) lines.

Spot wobble describes the path of the scanning spot on the display when it is subjected to an additional micro-deflection process. By use of auxiliary deflection plates within the CRT, or an additional deflection yoke ahead of the main yoke, the scanning spot is subjected to a small high frequency (> 3 X video bandwidth) vertical deflection. This causes the scanning spot to generate a sinusoidal path as it wobbles across the normal scanning line. The wobble preserves the spot shape along the axis of the scanning line and thus the horizontal resolution is unchanged. In the vertical direction, however, the effect is to stretch the spot such that adjacent raster lines overlap. This overlap covers the darker interline spaces and reduces the modulation of the raster structure. At extreme spot wobble amplitudes, raster lines may spread over several adjacent lines, and smearing of details becomes noticeable with the resulting decrease in the vertical modulation transfer function (MTF) (Beamon and Snyder, 1975).

Raster modulation may be measured by a scanning microphotometer having a magnifying objective lens and a narrow slit oriented parallel to the raster line to integrate phosphor grain noise (Snyder, 1973). The output of the photometer may be plotted on an X-Y plotter to illustrate the raster modulation, or it may be subjected to Fourier analysis to calculate the exact modulation and spatial frequency of the fundamental and the other spatial frequency components. Both methods have been used successfully, but Fourier techniques are more accurate, especially when the raster pattern is significantly different from a sine wave.

Figure 1 illustrates a typical plot of raster modulation as a function of spot wobble amplitude. As indicated, the normal raster structure may be quite prominent (e.g., 60% modulation). As the spot wobble amplitude is increased, the scanning spot spreads in the dimension perpendicular to the raster, line overlap increases, and raster modulation is reduced. At some point a minimum is reached and further spot wobble produces an increase in raster modulation. An additional null may be reached at a higher wobble amplitude, which corresponds to a line overlap of alternate raster lines. At this level, noticeable vertical smearing of small details is apparent, but since both fields as well as the frame of raster lines are structure free, flicker due to the field or frame rate is very diminished.

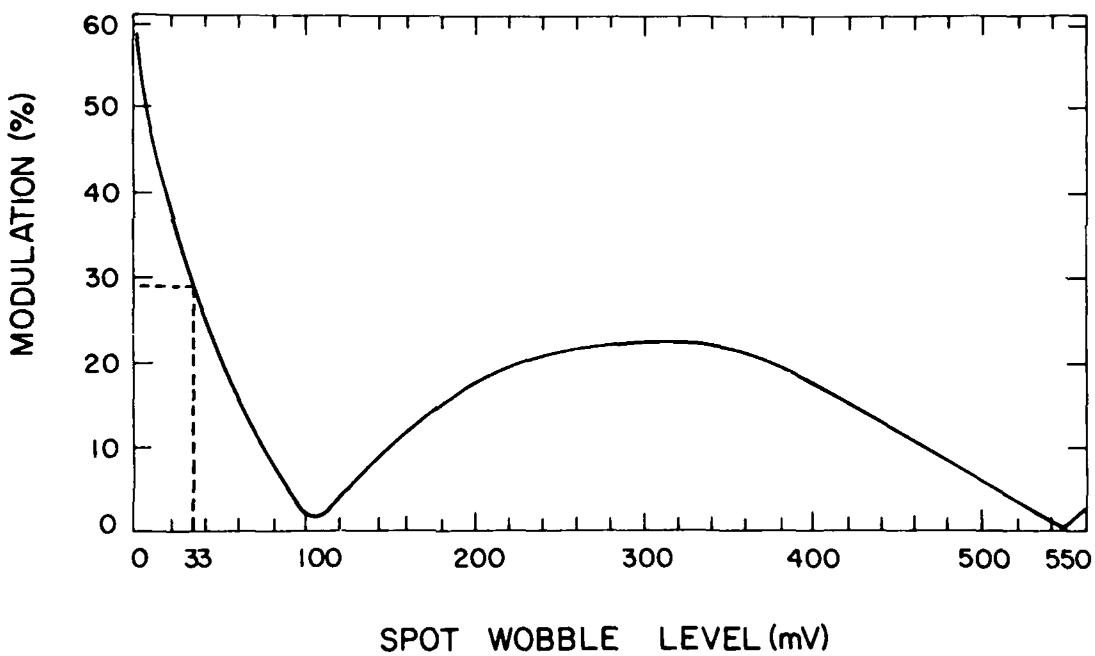

Figure 1: Raster Modulation as a Function of Spot Wobble Level.

Spot wobble originated in the United Kingdom (Schade, 1973) and was implemented on a few receivers to improve the image quality of the British Broadcasting Corporation's 405-line system which was in use from 1953 until the early 1960s. Spot wobble did reduce raster visibility, but it did not enjoy wide use primarily because it utilized an additional deflection yoke and oscillator which added expense and required radio frequency interference shielding. Early sets were tube type, and thermal changes upset vertical linearity and interlace accuracy, which in turn reduced the effectiveness of spot wobble.

The early British Broadcasing Corporation format was phased out in the 1960s in favor of the Independent Television's 625-line, 50 field-per-second format which became the standard in the United Kingdom. The 625-line format on entertainment receivers normally does not require spot wobble since raster visibility is diminished.

In 1957, F. T. Thompson at Westinghouse Research Laboratories investigated the use of spot wobble as a means of improving the image quality of large screen (> 61 cm) monochrome receivers. His surveys had indicated that observers chose a 17 deg horizontal field of view for motion pictures and an 8 deg field for television; thus, proposed large screen sets would require an inordinately large room for comfortable viewing. His first experiment was to determine preferred viewing angles for a 53 cm display with and without spot wobble. Fifty observers viewed the blank screen at a luminance of 68.5 cd/m^2. They were then asked to move away from the set until they could no longer resolve the raster lines. These distances were recorded. The same procedure was employed when the spot wobble was turned on. The results showed a marked reduction in average viewing distances, 1.86 m with spot wobble as compared to 3.23 m without spot wobble.

The next test was to use broadcast video with and without spot wobble. Subjects were asked to choose a comfortable or "preferred" viewing distance. Again, subjects chose to sit closer to the display when the raster structure was made to be less prominent. Although Thompson (1975) made no mention was made of the effect on subjective image quality when spot wobble was employed, it was shown that the spot wobble could facilitate the use of large screen sets in a home environment (figure 2).

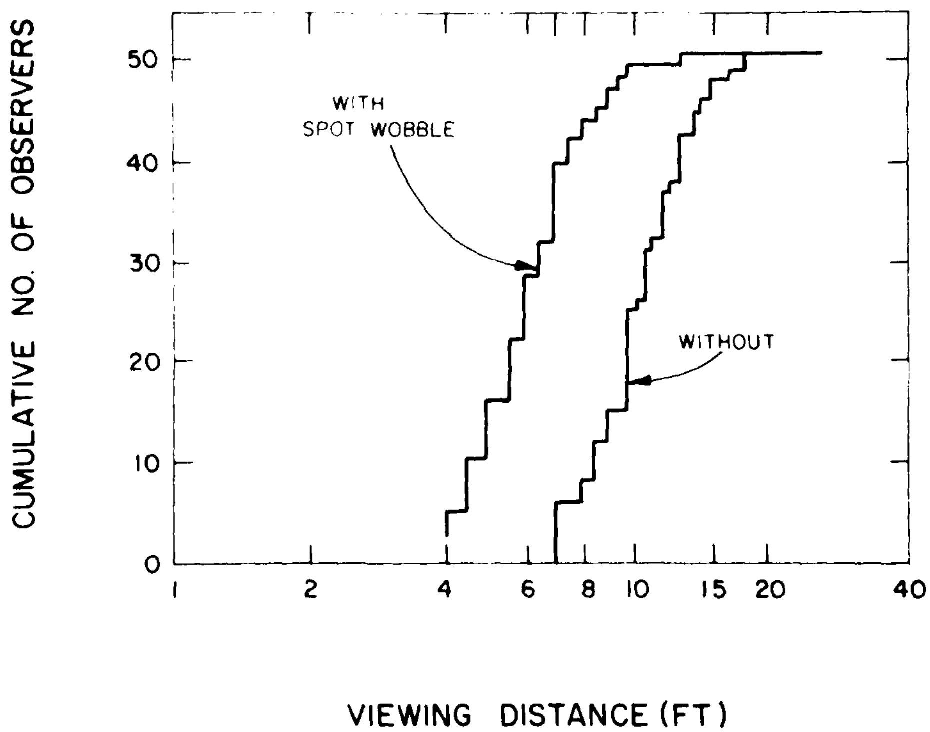

Figure 2: Results of Thompson (1957).

Beamon and Snyder (1975) conducted an experiment to assess spot wobbled displays for a simulated air-to-ground target acquisition task. Four experimental levels of spot wobble amplitude were chosen on the basis of the resulting raster modulation which had generated two "flat field" or raster structure-free conditions. These were factorially combined with viewing distances of two, four, and six times the picture height, or 45.7, 91.4, and 137 cm, respectively.

Six volunteer subjects, four male and two female, were randomly assigned to each of the 12 factorial conditions. Each was presented a 30 min TV image of terrain containing 14 prebriefed targets, only one of which was present in the field of view at any one time. Targets ranged from a cluster of small buildings to a large airfield and were randomly interspersed throughout the clip. Subjects, having been briefed, observed the TV display and pushed a button when the proper target was acquired, which recorded the input film frame number and provided a means by which the simulated ground range could be calculated. The ground range at target acquisitions for correct responses was the primary dependent variable. In addition, preferred viewing distances and raster fusion distances were obtained to compare against Thompson's (1957) results. The video chain was operated at 525 lines/8 MHz.

Results were mixed. Neither spot wobble levels nor viewing distance conditions produced reliably different numbers of targets correctly identified. An analysis of variance on the range data revealed a significant spot wobble effect and a spot wobble by viewing distance interaction. Of particular interest is the fact that the 550 mV level produced the or longest target acquisition range. This mean range was reliably better than the other three, which were similar (figure 3). Theory would have predicted the 100 mV level to be best, since the flat-field condition occurred without the loss of vertical high frequency detail on the display. The 550 mV level also produced a flat-field raster, but with noticeable smearing of scene detail. It was thought that field flicker, of 60 Hz, provided some visual interference, since it was not apparent at the 550 mV level o. alternate line overlap. Clearly additional study was needed.

Beamon and Snyder (1975) also obtained preferred viewing distances after the target detection task had been completed, and the results showed that subjects preferred viewing distances similar to those used in the test.

Raster fusion distances were found to be reduced by spot wobble, though not to the degree that one might expect from contrast threshold function data (e.g., DePalma and Lowry, 1962). The 550 mV level again produced significantly shorter distances for raster fusion (figure 4).

Preferred spot wobble levels were inconsistent. Some subjects preferred a highly visible raster structure, stating that, "The lines are sharper." Others said the "softer" screen was less

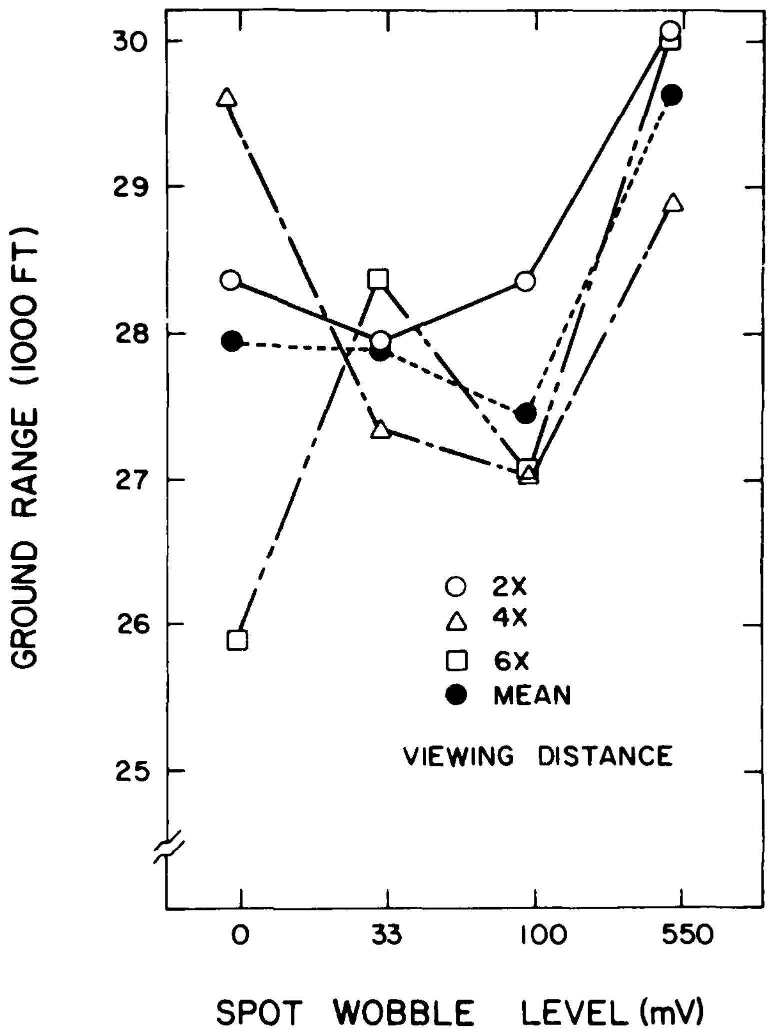

Figure 3: Correct Response Simulated Ground Range Produced by Four Spot Wobble Levels at Three Viewing Distances

fatiguing to watch. These data differ from Thompson's (1957) results since naive subjects set their own criteria.

The square-wave transfer functions for the system at each spot wobble level were obtained and reflect the loss of vertical high frequency response with increased line overlap at the 550-mV level. No observer threshold data were obtained for the system;

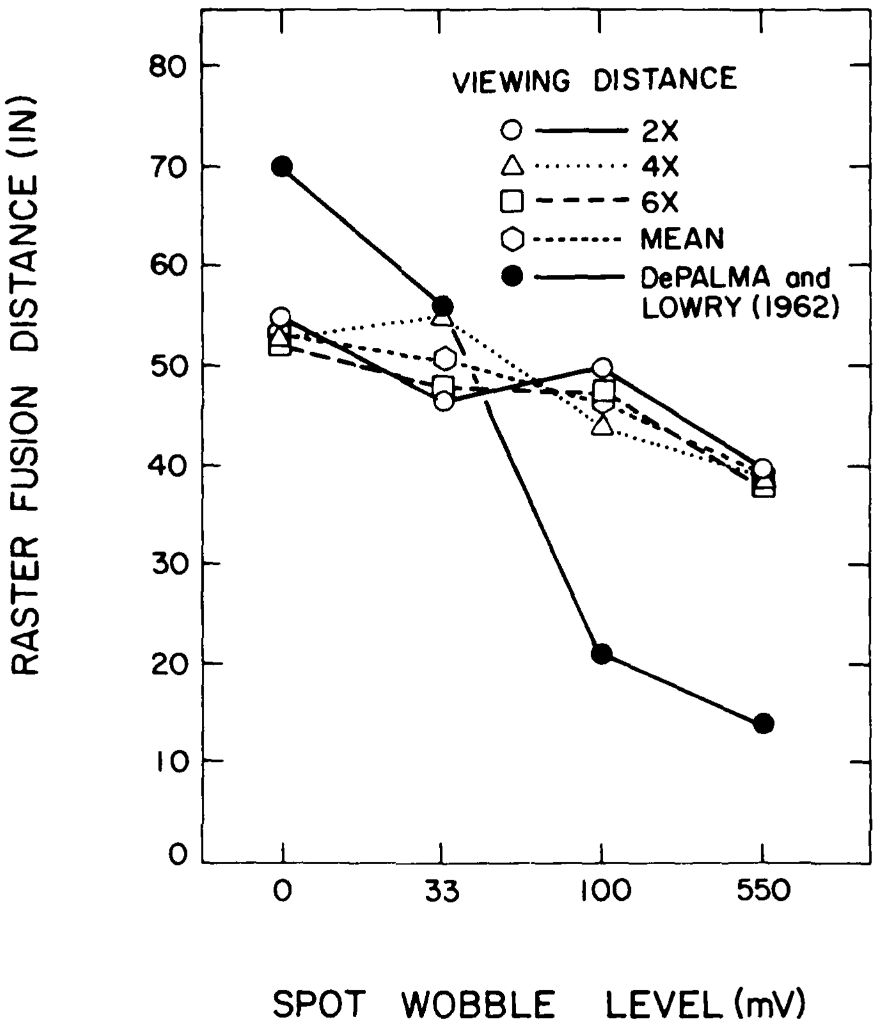

Figure 4: Distance at Which Raster Fusion Was Perceived at Four Spot Wobble Levels

thus, MTF areas (MTFA, Snyder, 1973) and observer performance could not be correlated.

While not conclusive, the data did indicate that reduced raster visibility could produce significantly improved observer performance.

OTHER RASTER SUPPRESSION TECHNIQUES

Other techniques exist which may be used to reduce the prominence of the raster structure. The main difference between the spot wobble process and other techniques is that spot wobble provides a means of easily and accurately changing the width of the spot and its effects on the raster pattern. Other processes, primarily the use of lenticular lenses (Schade, 1971) or asymmetrical electron gun aperture geometry (Kogo, Nakatsukasa, and Kawese, 1960), provide only a fixed amount of raster line overlap, and are not as useful for experimental purposes. To be effective, each technique requires accurate interlace, stable raster dimensions, and linearity (Schade, 1973). However, once the appropriate level of spot wobble has been determined, other "spot stretch" techniques will allow the economic implementation of displays having a reduced raster structure prominence, as no extra deflection circuits or shielding would be required.

RESEARCH PURPOSE

In the research reported here, two additional experiments were conducted to evaluate the efficacy of display spot wobble as a means to improve observer performance. One experiment used the same air-to-ground target acquisition task as in the former spot wobble study, while the other experiment employed a static television display of randomly positioned alphanumeric characters. Noisy and noise-free displays were evaluated in each experiment for several levels of display spot wobble.

In addition, to place the results in the overall context of display image quality metrics, the modulation transfer function area (MTFA) measure was calculated for each experimental condition and related to observer performance. This measure has been shown previously (Snyder, 1973; Snyder, 1976; Snyder, Keesee, Beamon, and Aschenbach, 1974; Task, 1979) to correlate highly with target acquisition performance.

METHOD: DYNAMIC TARGET ACQUISITION EXPERIMENT

This experiment was organized as a series of tasks that were performed in sequence, as diagrammed in figure 5. The first step was to implement spot wobble and photometrically analyze the resulting raster modulation. Next, the target acquisition experiment with combinations of noise and spot wobble levels was performed and the results were analyzed.. Observer sine-wave grating thresholds and system MTFs were measured so that MTFAs could be calculated. The dependent variables in the target acquisition task, range and number of correct responses, were then correlated with MTFAs, threshold functions, and raster modulation levels to evaluate the utility of spot wobble and the MTFA image quality metric.

The remainder of this section will address each of the tasks in turn and present the experimental design, apparatus, and procedures required.

APPARATUS

Video System

The video chain consisted of a Cohu 6000 series high-resolution multi-line-rate camera fitted with an RCA 8601 vidicon. The camera control unit (CCU) was designed for the

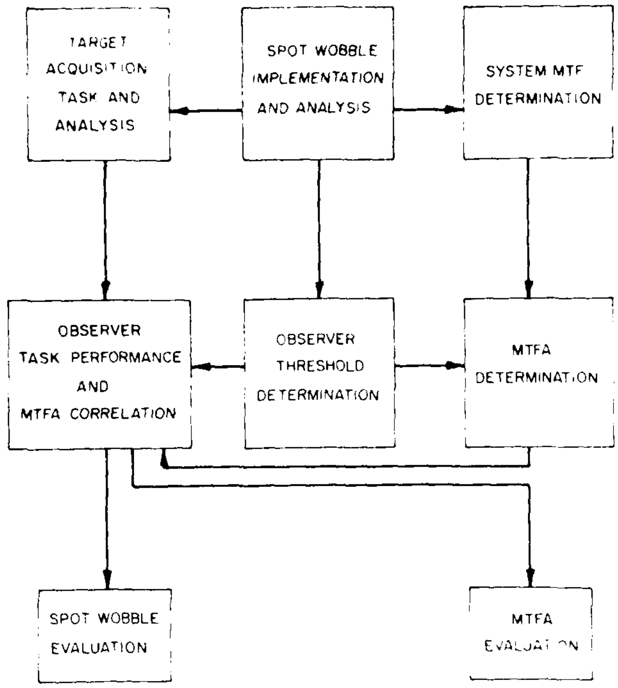

Figure 5: Research Strategy

6000 series camera and was set for 525-line, 8-MHz operation with composite video output. Using an illuminated standard broadcast test chart, linearity and focus were adjusted and video levels were initially set to the standard +1 V video, -0.4 V synchronization levels. The 75 ohm video output was fed to a Conrac multi-line rate, high resolution RQB-15 monitor which provided accurate interlace, good vertical linearity, and a stable raster pattern.

The display tube in the monitor was changed to a special kinescope obtained from Thomas Electronics, Inc. This tube, type 15EM11P4M, measured 38.1 cm diagonally, used a P4 (white) phosphor, and was fitted with two pairs of carefully aligned deflection plates ahead of the main electron gun. One set of these plates provided the additional deflection capability required for inducing spot wobble. These plates were biased to float at the second anode potential of 16 kV, which was supplied by the high voltage section via automotive ignition cable. The electron gun of the new CRT was pin-for-pin compatible with the one originally supplied with the monitor.

A one-transistor, common emitter, tuned amplifier was transformer coupled to the deflection plates and sinusoidally driven by a Hewlett-Packard 8601A signal generator set at 45 MHz. Transformer coupling provided an element of safety, and no high voltage terminals were exposed. Spot wobble amplitude was indirectly measured by detecting the radio frequency voltage in the collector circuit of the amplifier. This was measured by a digital voltmeter so that repeatable voltage levels could easily be obtained. Spot wobble amplitude was adjusted by setting the output of the signal generator. A Heathkit low voltage DC supply was set for -34 V for the deflection amplifier. A Cohu dot/bar generator was used to adjust the focus of the scanning spot to provide a sharply defined symmetrical spot. The interlace was also adjusted so that no "line pairing" was evident. With these equipments, the spot wobble circuits did indeed reduce the visibility of the raster structure. At the highest output, vertical smear exceeded six raster lines. The spot wobble display block diagram is shown in figure 6.

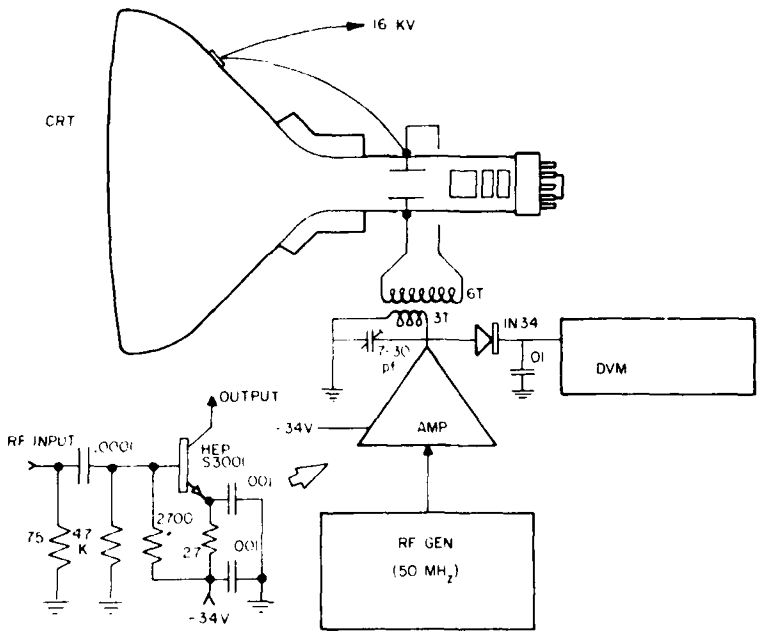

Figure 6: Spot Wobble Apparatus Arrangement

The TV camera was hard mounted on a platform attached to a modified Norelco 35 mm motion picture projector, such that the image of the 35 mm motion picture film in the projector film gate was imaged directly on the vidicon photocathode. The flywheel position of the projector was sensed to provide synch for the TV chain and for a Strobex lamp mounted behind the film gate on the projector. Each film frame was thus illuminated (twice) while the frame was stationary in the film gate, thereby avoiding blur or frame misregistration on the TV display. Details of this apparatus are provided in Snyder et al. (1974).

A laboratory designed wideband (20 Hz - 40 MHz) video mixer was inserted between the camera control unit and the monitor's video input. One input to the mixer was the video signal from the camera control unit, while the other was the output of a variable amplitude white noise generator (General Radio Model 1383), having a 20 Hz - 20 MHz Gaussian amplitude density function. Its output level was adjustable and monitored by a Ballantine True RMS voltmeter.

Photometric Apparatus and Procedures

Photometric measurements of the raster on the CRT were necessary to determine the relationship between spot wobble voltage and raster modulation. The photometer was a Gamma Scientific Model 2400 digital unit with a 4X objective lens and a 25 x 2500 micron sampling slit eyepiece. The 4X objective was used to magnify the raster pattern such that each raster line was approximately 10 times as wide as the effective slit height (6.25 microns) for adequate resolution. The long axis of the slit was oriented parallel to the raster to integrate out the effect of phosphor granularity.

The sampling slit in the photometer head was mounted on a motor-driven scanning stage with a 10 mm traverse range. A counter and voltage output indicated its position. A Gamma Scientific 342.6 cd/m^2 standard source was used to calibrate the photometer.

The PDP 11/10 computer both controlled the operation of the scanning stage, and converted and recorded the resulting data. The power supply for the scanning motor had been set to provide a 10 mm/min scan. For each scan, 6000 data points (luminance values) were digitized by the LPS-11 12-bit analog-to-digital converter and stored on 9-track magnetic tape.

The technique used for determining the modulation of the raster was a modification of that employed by Keesee (1976). Additional programs written by Maddox (1975) facilitated the transferral of data from magnetic tape to disk so that the data could be processed by the PDP 11/10 computer resident in the laboratory. The photometry techniques and equipment were used twice again, once for determination of the MTF of the entire video chain and again for calibration of the equipment used for determination of the observer threshold functions.

The photometric scanning and analysis sequence is illustrated in figure 7. Fourier analysis was employed on all photometric scan data to determine the modulation of the fundamental spatial frequency of the pattern and several, usually 10, of its harmonics. High levels of harmonic modulation would indicate distortion or nonlinearity of the pattern due to its deviation from a sine-wave luminance distribution.

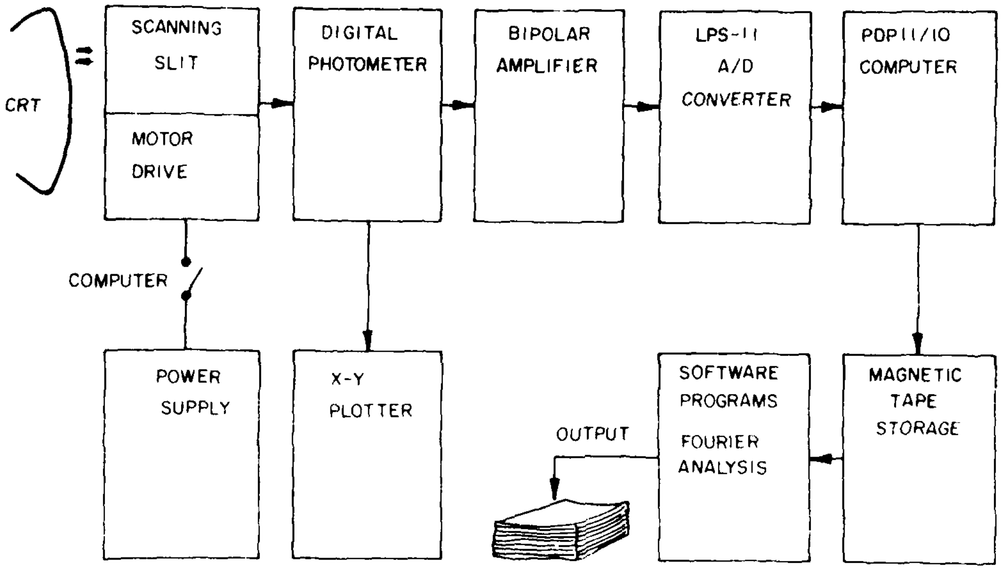

Figure 7: Photometric Scanning and Data Reduction

The programs which provided the power spectrum of the scanned sample calculated the appropriate modulation values in a sequence of steps (Keesee, 1976).

1. In addition to the 6000 luminance data points gathered by the computer, manual input of the number of integer cycles and the end point of the last whole cycle was required.

2. For this truncated set of data, a modified IBM FORIT subroutine calculated the sine and cosine coefficients for the fundamental spatial frequency defined by the truncated scan.

3. The luminance amplitude (P) for this frequency was calculated from the sine and cosine coefficients by the formula:

$$P = (A^2 + B^2)^{1/2}, \qquad (2)$$

where

P_ν = luminance amplitude at spatial frequency ν,

A_ν = sine coefficient at ν, and

B_ν = cosine coefficient at ν.

The modulation M was obtained by dividing the calculated P by the mean luminance which was the A_o term of the Fourier coefficients calculated by the FORIT subroutine. The derivation is:

$$M = (L_{max} - L_{min})/(L_{max} + L_{min})$$

$$(\Delta L)/(2 L_{mean})$$

$$= (2 P_\nu)/(2 L_{mean})$$

$$= (P_\nu)/(L_{mean}), \qquad (3)$$

where

M_ν = modulation at spatial frequency ν,

L_{max} = maximum luminance,

L_{min} = minimum luminance,

ΔL = change in luminance = $L_{max} - L_{min} = 2\ P_{\nu}$,

L_{mean} = mean luminance or $(L_{max} + L_{min})/2$, and

P_{ν} = peak luminance at spatial frequency ν,

$= (L_{max} - L_{mean}) = (L_{mean} - L_{min})$.

5. Since the sample length was truncated to approximately n integer cycles, some error in calculating the modulation was expected. This error was minimized by reducing the number of samples in small steps, and iteratively recalculating the modulation until a maximum was obtained and the next iteration produced a lower modulation (Keesee, 1976).

6. The number of samples which produced the maximum modulation for n integer cycles was then used to calculate the modulation of the fundamental and several (usually 10) of its harmonics.

By means of this procedure, the modulation of the raster pattern (and later other targets) was obtained for screen luminances of 25.7, 34.3, and 51.4 cd/m^2 as a function of spot wobble amplitude. Spot wobble voltage was varied from 0 to 6.5 V in 250 mV increments.

System MTF Determination

The optical equipment required to generate high modulation sine-wave patterns of constant amplitude and variable spatial frequency was not available for this research. An alternative approach of demonstrated utility is to present a slide of the USAF (1951) tri-bar (square-wave) resolution target via the normal projection path to the lens of the camera. Tri-bars were used to evaluate the system MTFs in the earlier spot wobble study (Beamon and Snyder, 1975), and indicated the characteristic decrement in high frequency response.

The same photometric and Fourier procedures and apparatus that had been applied toward determining the raster modulation as a function of spot wobble voltage were used to determine system MTFs, both parallel and perpendicular to the raster, for the six experimental spot wobble levels that had been chosen.

Test slides of the USAF (1951) tri-bar resolution chart with unity modulation were presented to the camera of the video system. Photometric scans of the patterns on the display were performed and Fourier analyzed by computer to determine the vertical and horizontal MTF of the entire video chain for each raster modulation condition. Tri-bar sizes used ranged from the largest in the series to the smallest which could be detected by Fourier analysis of the photmetric scans. Modulation values of the tri-bar fundamental spatial frequency were used to plot MTFs.

TARGET ACQUISITION TASK

The target acquisition task was chosen because (1) it provides a means of assessing differences in observer performance due to raster modulation, and (2) it is a typical and important use of military displays that might have a prominent raster due to screen size and viewing distance environmental constraints.

Experimental Design

Independent variables chosen for the experiment were six levels of spot wobble deflection voltage, and three levels of random noise voltage. Six spot wobble levels, rather than raster modulations, were chosen because they allowed the investigation of two redundant raster modulation levels which had different MTFs. The six levels are indicated in figure 8 by (1) through (6). There were two levels of 0.04 and two levels of 0.20 modulation, each with a different MTF.

Three noise levels of 0, 35, and 70 mV (RMS) were selected. The 0 mV level added no noise to the video signal; thus, it represented a "normal" display condition. The 35 mV and 70 mV levels served to obscure details in the scene, with the higher voltage making target acquisition

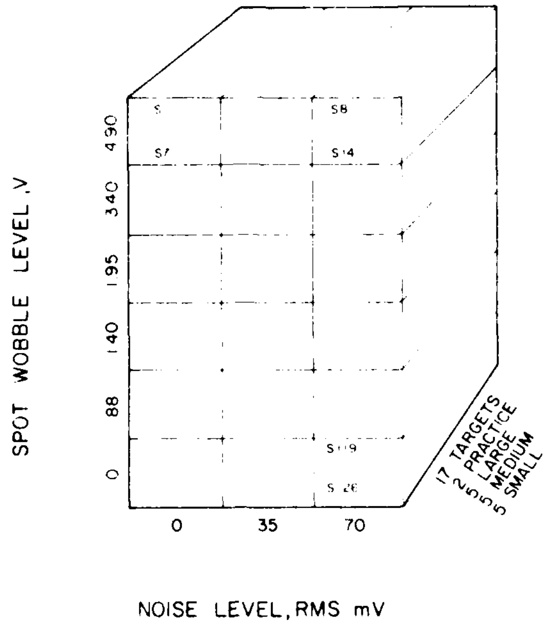

Figure 8: Experimental Conditions for the Target Acquisition Task

more difficult. The effect of the 35 mV level was less pronounced but it did serve to mask targets, particularly the smaller ones.

The six spot wobble levels and three noise levels were combined factorially to provide 18 between-subjects experimental conditions. The simulated air-to-ground search task was generated from a 35 mm film made from the North American Aviation/Columbus Division terrain model (Humes and Bauerschmidt, 1967). It simulated a level flight at a velocity of 500 ft/sec at an altitude of 10,000 ft. The field of view of the filming camera was 27 deg vertical by 21 deg horizontal, with a depression angle of 28 deg below the horizon. The film playback into the video system was at the rate of 30 frames/s.

Seventeen targets were selected in the terrain model film from among the more than 60 available. The 17 targets were interspersed among other scene details, and only one designated target was in the field of view at a time. Each of the targets had been allocated to a large, medium, or small category based on its dimensions (Humes and Bauerschmidt, 1968). The first 2 targets were used for practice; responses to the other 15 were converted to ground range and the number of correct responses as indices of observer performance. Target size was a within-subjects variable in the fixed effects mixed model.

One hundred twenty-six paid university students were screened for 20/20 near and far acuity and normal depth and color perception with a Bausch and Lomb Orthorater. Each subject was randomly assigned to one of the 18 experimental system conditions (figure 8). Each cell was assigned seven subjects, two female and five male. Data from five additional subjects were discarded due to equipment malfunctions and one instance of deliberate response misconduct.

Subjects' responses consisted of pressing the response button as soon as they were reasonably sure they saw the designated target and verbally reporting over the intercom which section of the screen the target was in. Incorrect (premature) responses could be negated by pressing the button again and reporting the new response. Each responsel latched a film frame counter which printed the film frame number.

Apparatus

Two adjacent experimental rooms were used for the experiment. The projection room contained the video camera and control unit, the film projector, film, a line monitor, an intercom, and the film frame counter and printer. It was the control room for the experimenter.

The second room was for the subject. Salient features included the chair and headrest which were used to keep viewing distance constant at 91.5 cm, the experimental monitor, and the noise and spot wobble equipment. Voltmeters were used to set and monitor noise and spot wobble levels. The photometer and calibration source were on hand to calibrate the luminance of the monitor before testing every other subject. The subject used a dim, glare-free lamp to examine the target book in the otherwise darkened room.

Procedures

Upon arrival in the laboratory, subjects were presented with written instructions and given the target book to study. The target book contained photographs of each of the targets in the proper sequence. Each photograph had the contextual cues removed, and each target was presented at a different scale and orientation. While studying the target book, the subject sat in the hallway outside the experimental room. The hallway was dimly lit to allow partial dark adaptation. At the appropriate time, the subject was seated with his/her forehead against the headrest. The operation of the pushbuttom and intercom were explained and the subject's lamp was adjusted for dim, glare-free illumination of the target book. The calibration of the monitor was checked with an eight-step gray scale slide. The appropriate spot wobble and noise levels were then set and the experimenter moved to the projection room. When the subject indicated he/she was ready via the intercom, the experimenter reset the frame counter to zero and started the projector. The subject could easily see the display or the target book in his/her lap. Targets in the book were numbered and labeled, and the only feedback given to a response was by the experimenter saying, "Turn to the next target, three small buildings" as the previous target went out of the field of view. This was the only form of prompting and was given for all subjects and for all targets. For each film, response film frame numbers were automatically recorded.

After the target acquisition task had been conducted, a single frame of typical terrain scenery was placed in the film gate. The subject was then randomly presented three spot wobble conditions of 0.65, 0.20, and 0.04 raster modulation (0, 0.88, and 1.95 V spot wobble) and asked, "Which produces the clearest picture for the task you just performed?" After recording the response, the subject was debriefed on the details of the experiment, paid, and dismissed.

Data for all subjects were converted from cards to magnetic tape for computer analysis.

OBSERVER THRESHOLD FUNCTIONS

Prior to this research, the effects of spot wobble on the observer's visual sine-wave threshold were unknown. In the previous spot wobble study (Beamon and Snyder, 1975), significant improvements in target acquisition performance occurred under conditions of reduced display resolution. In terms of the MTFA concept, this result implied that a suppressed raster may have increased observer sine-wave sensitivity, thus improving observer performance.

Prior to the experiment reported here, the effects of spot wobble on the perception of random noise on the display had not been studied. Schade (1973) had reported that noise was more easily perceived with a suppressed raster, but no empirical data were reported. Logically, spot wobble would expand the vertical dimension of the noise element, thereby lowering its spatial frequency perpendicular to the raster lines. When two or more raster lines overlap, luminance components add. Random noise in adjacent lines will tend to average out, but scene highlights common to the lines will add.

Experimental Design

Threshold data were required for each of the 18 combinations of 6 spot wobble levels and 3 noise conditions. Sine-wave gratings of adjustable modulation were displayed on the CRT and viewed by the subject, who was seated 91.4 cm from it. The spatial frequencies of 14 patterns, 6 oriented parallel to the raster (2, 3, 4, 5, 7, and 9 cycles/deg), and 8 perpendicular (2, 3, 4, 5, 7, 9, 12, and 15 cycles/deg), were selected. (The major axis of the display and therefore the raster were oriented vertically.) Six university subjects who had participated in the target acquisition task were trained to provide threshold responses to stimuli by using the method of adjustment. Averages of one ascending and one descending trial were used to estimate 50% threshold levels. Response measures of potentiometer voltage were converted to pattern modulation for analysis. Each subject was randomly presented each spatial frequency under each experimental condition twice for a total collection of 6048 data points (6 subjects x 2 responses x 2 trials x 14 targets x 18 system conditions), as indicated in figure 9. The averaging of each pair of ascending and descending trials provided 3024 data points used for calculating the vertical and horizontal threshold functions for the 18 conditions.

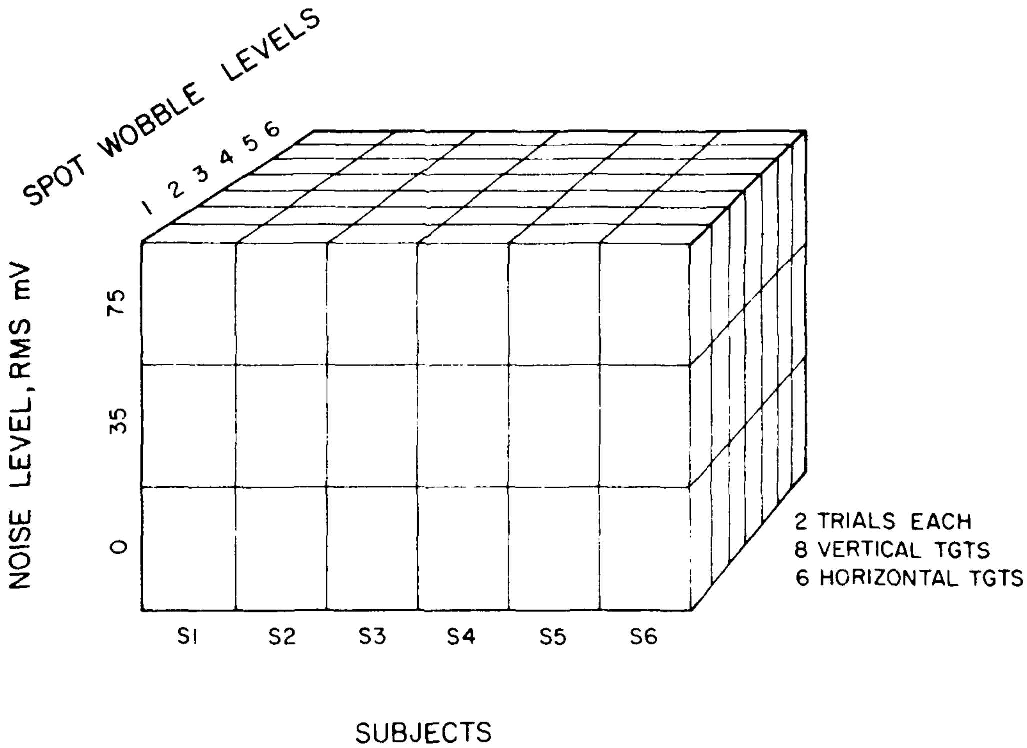

Figure 9: Experimental Conditions for Threshold Study

Apparatus

A special sine-wave generator used by Keesee (1976) was connected to the spot wobble monitor. The noise source and a 5 MHz filter were also added, along with voltmeters and other ancillary equipment necessary to generate and measure the grating (figure 10). Photometric equipment was also required to calibrate the monitor.

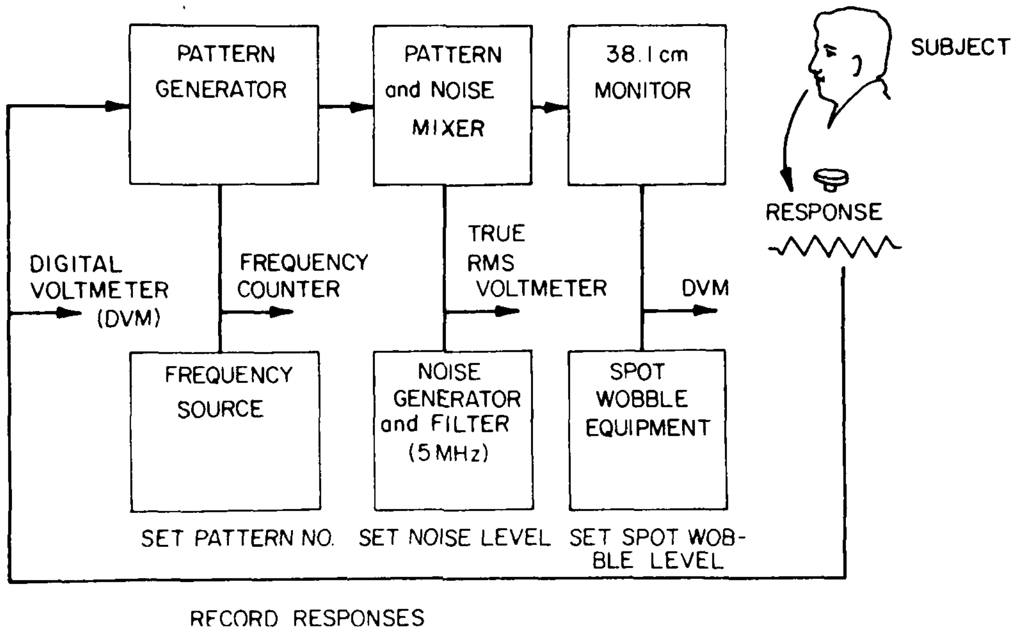

Figure 10: Threshold Experiment Equipment Arrangement

Sine-wave grating modulation was varied by means of a 7.6 cm knob attached to a multi-turn potentiometer. The output voltage of this potentiometer was sent to the sine-wave pattern generator and a voltmeter. Voltmeter readings were related in a curvilinear monotonic manner to the resulting grating modulation.

Photometric scans of the gratings were made from the CRT for six spot wobble levels with no noise added. Scans were made as spot wobble voltages were increased in 250 mV increments over the range of raster modulation likely to be required to determine thresholds for all display conditions. Fourier analysis of scan data yielded the resulting grating modulation levels. Modulation-to-potentiometer voltage data were converted to a nonlinear function by the method of least-squares from which the subjects' response voltages could be interpolated to yield threshold modulation data.

Observer Threshold Procedures

Each of the six subjects was trained to use the method of adjustments (Guilford, 1954) to indicate the threshold modulation of the sine-wave gratings, which were displayed in a 16.2 cm square window in the center of the screen. Ascending trials consisted of rotating the knob on the potentiometer to adjust the modulation of the pattern, starting well below threshold to a point where the grating could just be resolved. Repeat adjustments from below threshold were permitted. For descending trials, the threshold procedure was to decrease modulation slowly until the grating could no longer be resolved. Voltages for both responses were recorded, converted to modulation values, and averaged to provide one threshold data point for the particular grating frequency and system condition. These procedures had been used successfully by Keesee (1976) for a similar process of determining noise-limited thresholds.

Subjects entered the experimental room which was dimly lighted and were then seated in the chair and positioned for proper height and viewing distance. The luminance of the monitor, which had warmed up for at least one hour, was set with the telephotometer. Surround luminance on the screen was set to the mean grating luminance of 51.4 cd/m^2. The appropriate grating was set on the generator and checked with a frequency counter. Voltmeters were used to set the proper noise and spot wobble levels. Experimental sessions lasted about an hour at a time with 5- to 10-min rest breaks every half hour. The experiment was conducted in the evening and on weekends when the laboratory was relatively quiet.

MODULATION TRANSFER FUNCTION AREA CALCULATIONS

Procedures and Apparatus

System MTF functions for the six spot wobble conditions using the USAF (1951) tri-bar resolution targets as an input to the system were obtained by Fourier analysis for tri-bar targets oriented parallel and perpendicular to the raster. Modulation values for the fundamental spatial frequency of the targets were plotted point-to-point to yield the MTF.

The area under each MTF was calculated by summing the rectangular area between successive MTF values. Each rectangular area was calculated by finding the midpoint of two adjacent modulation values and multiplying by the difference between the two associated spatial frequencies. The area was calculated from a spatial frequency of 0 cycles/degree up to the spatial frequency associated with the intersection of the threshold and MTF curves. End points were obtained by extending the modulation of the lowest spatial frequency measured horizontally to the ordinate, and by linearly extending the function at the highest spatial frequency to the abscissa.

The area under the threshold curves, which was calculated in the same manner as the area under the MTF curves, was calculated between a spatial frequency of 0 cycles/degree and the spatial frequency associated with the intersection of the threshold and MTF curves. The endpoints for the threshold curves were obtained by horizontally extending the modulation associated with the lowest spatial frequency grating to the ordinate and by horizontally extending the modulation associated with the highest spatial frequency grating to the MTF curve. The area under the threshold function, when subtracted from the area under the MTF, provided the MTFA value (Snyder et al., 1974), as illustrated in figure 11. For each of the system conditions, vertical and horizontal, MTFAs were calculated.

OBSERVER TASK PERFORMANCE EVALUATION

For the target acquisition task, dependent variables of (1) the number correct, (2) the ground range of correct responses, and (3) ground range adjusted for incorrect responses were used to provide task performance indices. Ground range was adjusted for incorrect response and no-res-

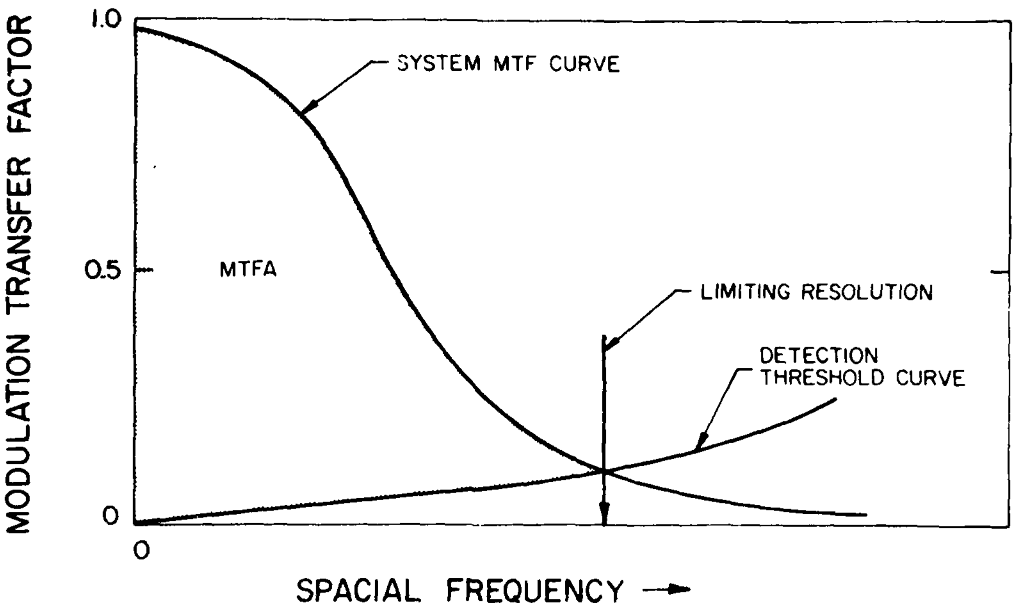

Figure 11: Modulation Transfer Function Area

ponse trials by substituting a ground range of zero to obtain the "zero" ground range data matrix, while in another analysis the minimum observable ground range (at the bottom of the display) was substituted for incorrect- and no-response trials to obtain the "minimum" ground range data matrix. These analyses have been previously used successfully (Snyder, 1976).

The data sets of observer task performance indices were correlated with MTFA values, the area under the MTF curve, the area under the threshold function, noise levels, spot wobble levels, and raster modulation. Further, the MTFA and its components, the MTF and threshold function, were examined in terms of their perpendicular and parallel components and combinations thereof. The effects of raster structure suppression are unidirectional, but, of course, the image extends in two directions. Thus, the perpendicular, parallel, geometric, and quadratic means of the MTF, MTFA, and threshold function components were correlated with observer performance indices.

RESULTS: DYNAMIC TARGET ACQUISITION EXPERIMENT

EFFECT OF SPOT WOBBLE ON RASTER MODULATION

Raster modulation as a function of spot wobble voltage had been obtained photometrically for blank screen luminances of 25.70, 34.26, and 51.39 cd/m^2. Spot wobble levels were increased from 0 to 6.5 V in 0.25 V increments, a point well beyond the second flat field condition. As was characteristic of the function obtained in the first study (Beamon and Snyder, 1975), modulation decreased monotonically from maximum to the first minimum, then increased again as voltage was raised and the raster lines overlapped. A second maximum of 0.20 was reached, followed by a decrease to 0.04 at the second minimum, and then an increase as indicated in figure 12.

From these data, the 0 V spot wobble level was selected to represent the normal screen condition. Both minima were selected; the 4.95 V level produced a decrease in the perpendicular MTF function greater than that resulting from the 1.95 V level, though raster modulation was the same (0.04). The second maximum at 3.4 V and a corresponding modulation level at 1.40 V were selected, as was the 0.88-V, level which yielded a modulation midway between the nonwobbled raster and the first minimum. These levels are indicated by arrows on the abscissa of figure 12.

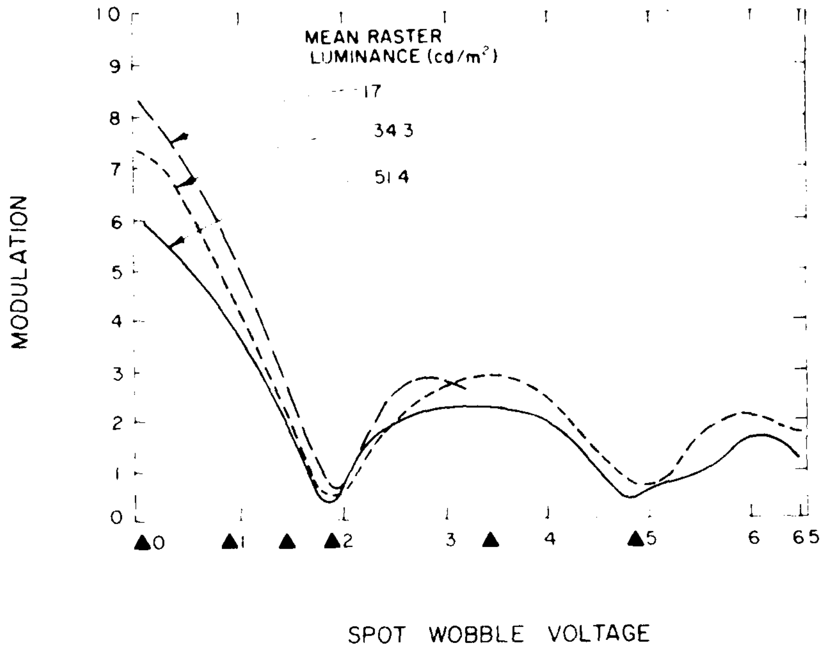

Figure 12: Raster Modulation with Spot Wobble

SYSTEM MODULATION TRANSFER FUNCTIONS

The modulation of the fundamental spatial frequency of a sequence of square-wave tri-bar targets was obtained by Fourier analysis of photometric scans of the CRT. These photometric scans were obtained for scanning slit (and tri-bar) orientations perpendicular and parallel to the raster. The resulting MTFs are plotted in figures 13 through 24.

The reduction in system response in the region beyond four cycles per degree for scans taken across the raster lines (slit parallel) is apparent for spot wobble voltages beyond the first minimum at 1.95 V. At the 4.95 V level, some blurring of high frequency detail was apparent, and the rolloff of the MTF was greatest.

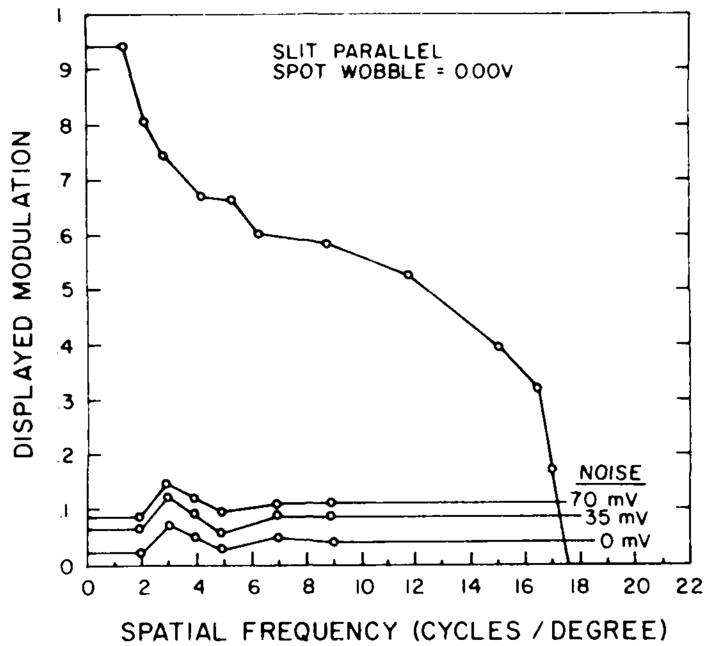

Figure 13: Parallel MTFA at Spot Wobble = 0.00 V

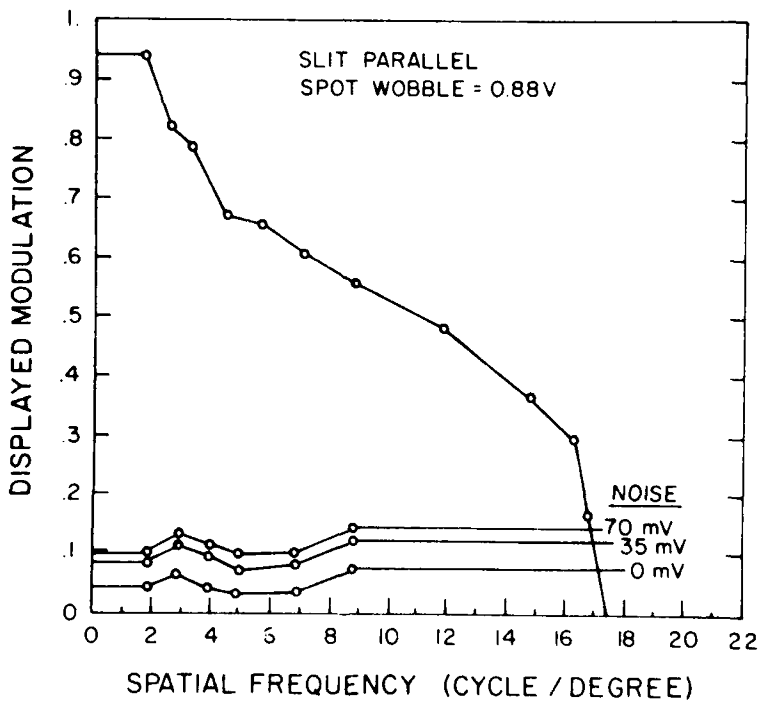

Figure 14: Parallel MTFA at Spot Wobble = 0.88 V

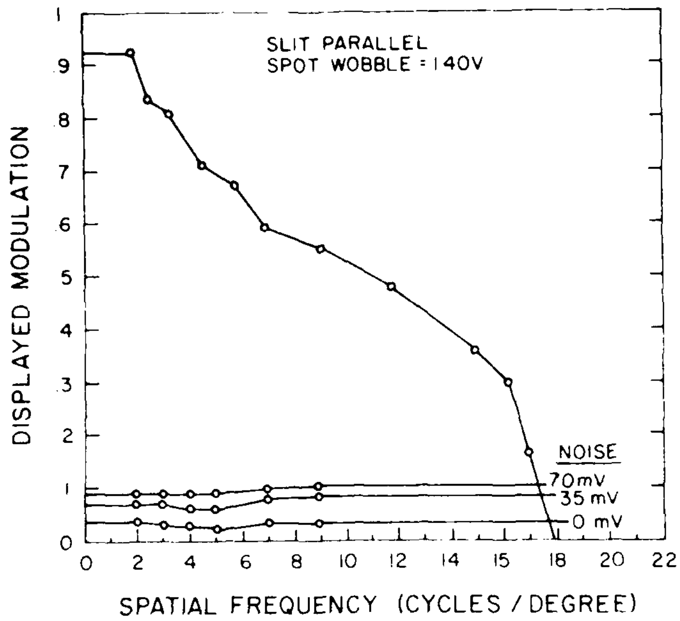

Figure 15: Parallel MTFA at Spot Wobble = 1.40 V

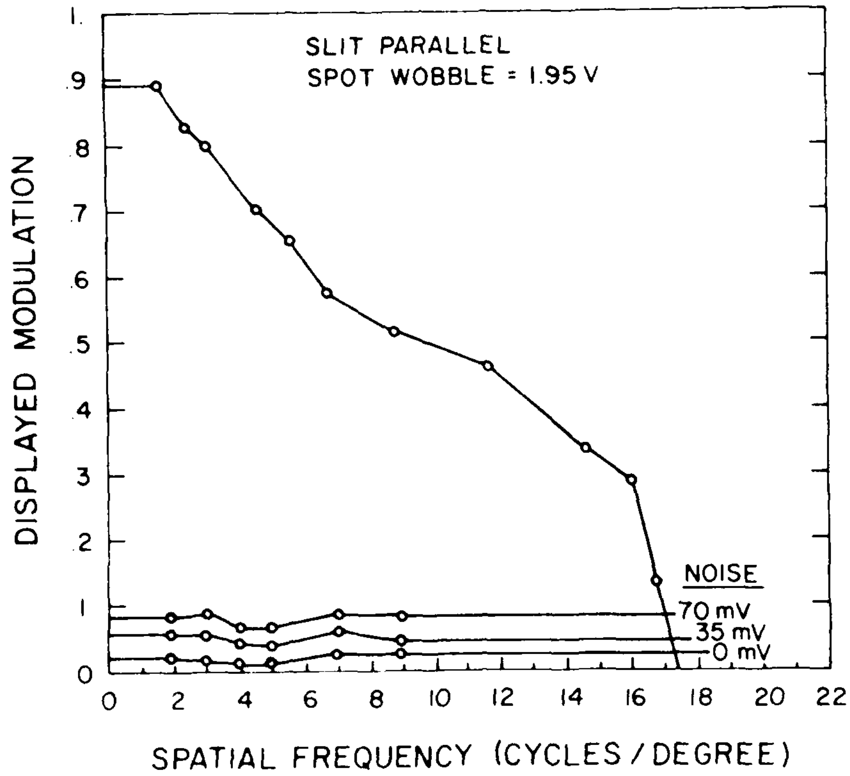

Figure 16. Parallel MTFA at Spot Wobble = 1.95 V

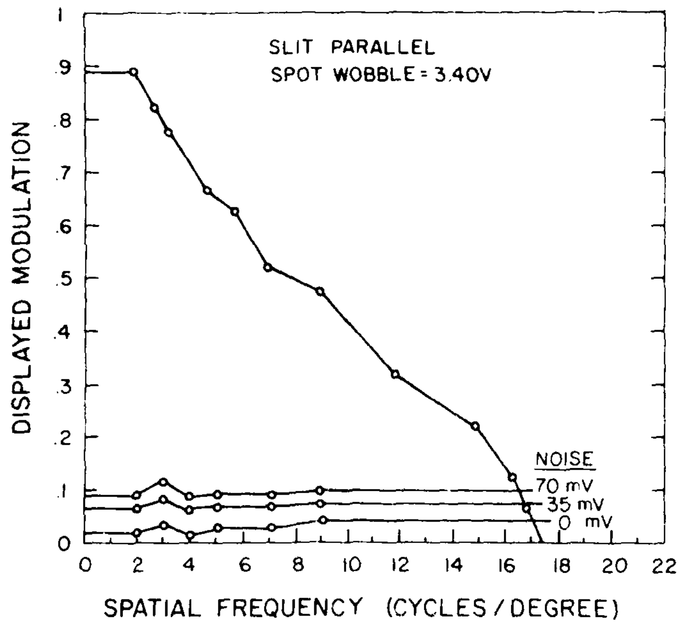

Figure 17: Parallel MTFA at Spot Wobble = 3.40 V

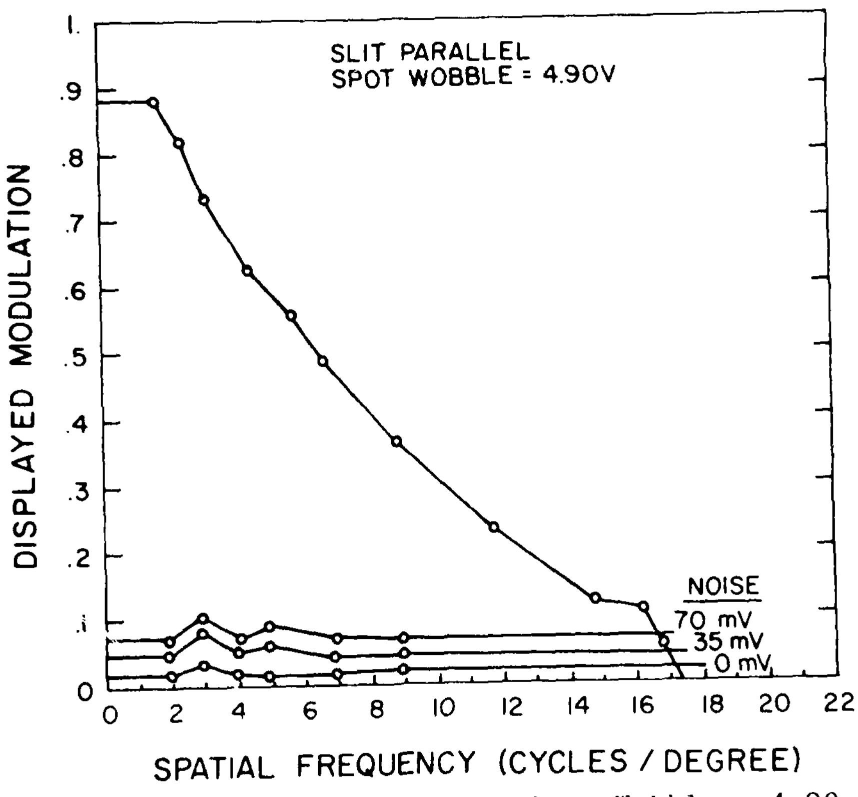

Figure 18: Parallel MTFA at Spot Wobble = 4.90 V

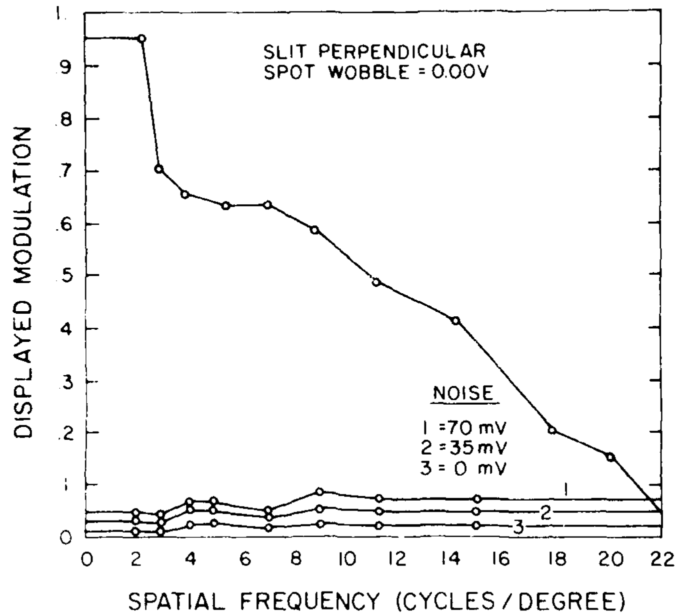

Figure 19: Perpendicular MTFA at Spot Wobble = 0.00 V

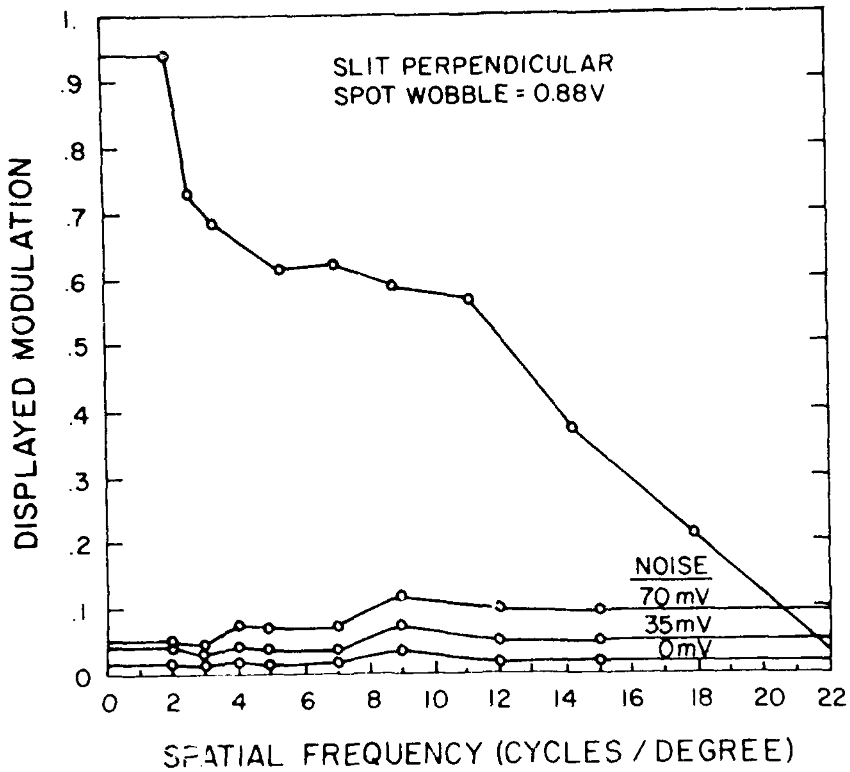

Figure 20: Perpendicular MTFA at Spot Wobble = 0.88 V

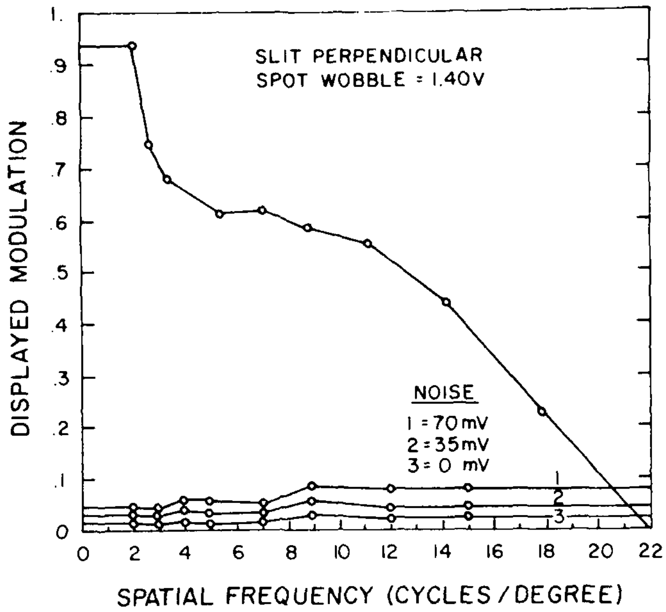

Figure 21: Perpendicular MTFA at Spot Wobble = 1.40 V

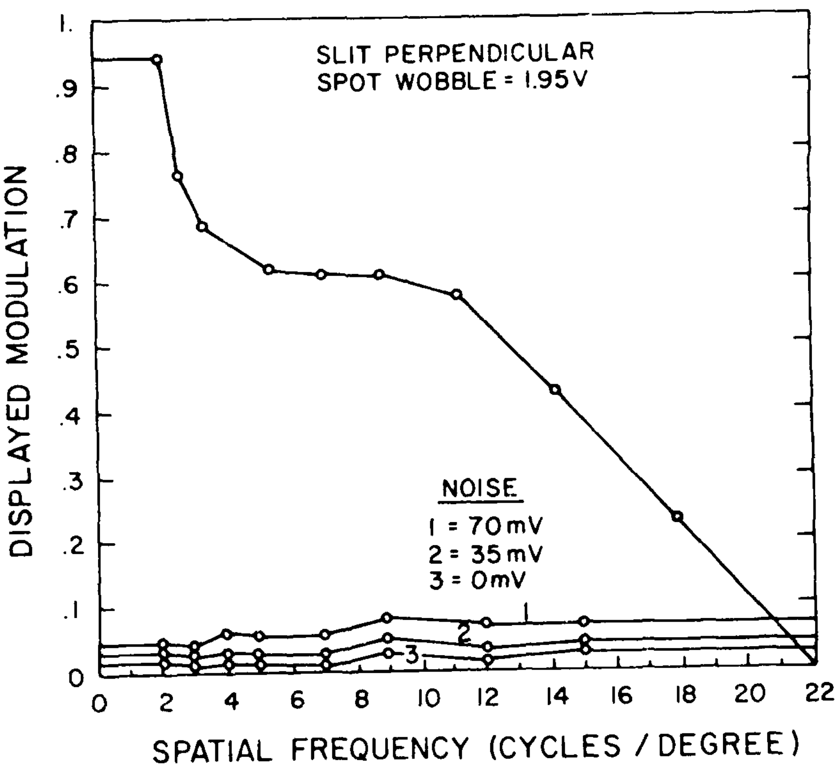

Figure 22: Perpendicular MTFA at Spot Wobble = 1.95 V

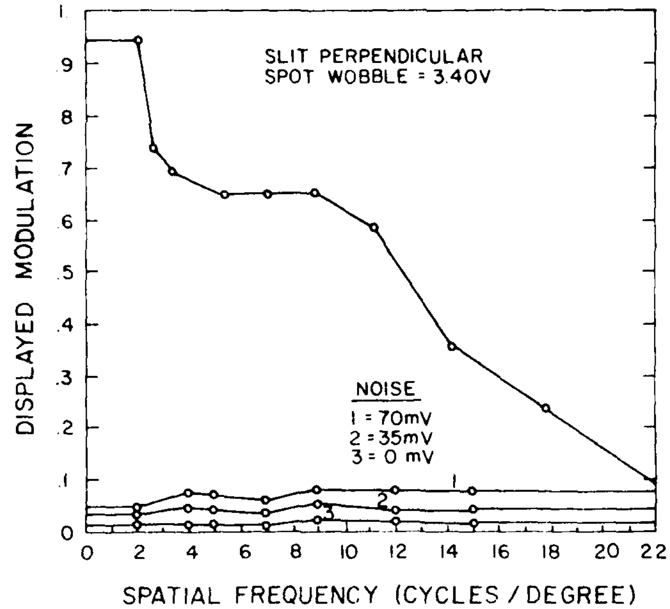

Figure 23: Perpendicular MTFA at Spot Wobble = 3.40 V

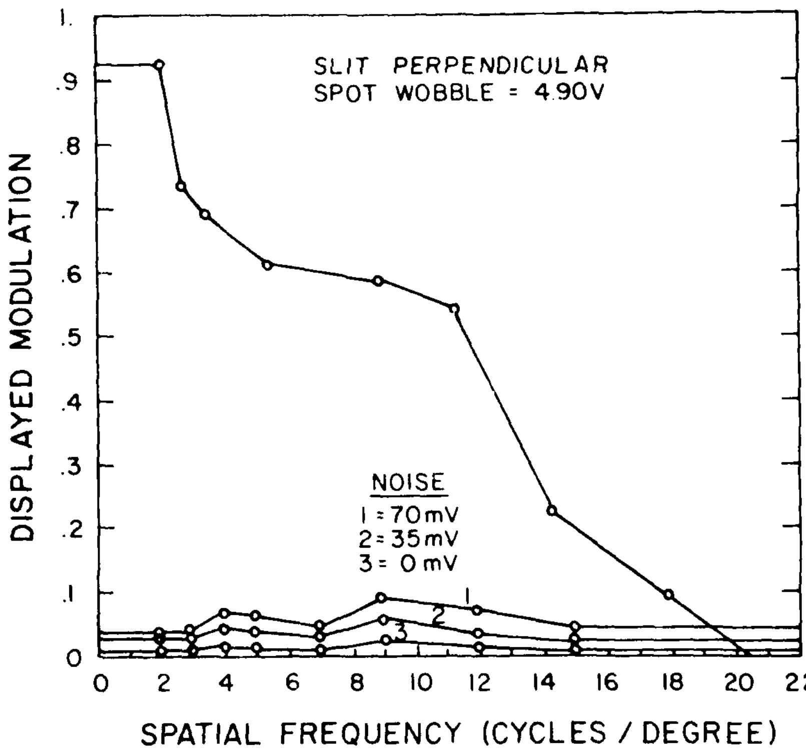

Figure 24: Perpendicular MTFA at Spot Wobble = 4.90 V

Scans taken along the raster lines (slit perpendicular) exhibit some reduction in system response for spot wobble levels beyond the first minimum. This rolloff occurs beyond 12 cycles per degree, and is less pronounced than the corresponding reduction in parallel MTF response. The sytem was slightly anisotropic due to the 8 MHz video amplifier bandwidth, as evidenced by horizontal limiting resolution extending approximately 4 cycles per degree beyond that available perpendicular to the raster (figure 19 vs. figure 13).

Perpendicular and parallel slit orientations were referenced to raster line orientation, not to the observer's horizon. The CRT had been rotated 90 deg to present the longer dimension of the screen and the raster line orientation vertical to the observer's horizon, as in previous experiments using this film imagery (Snyder et al. 1974).

OBSERVER THRESHOLD FUNCTION

Mean threshold sine-wave modulations for gratings oriented parallel and perpendicular to the raster were plotted with the MTFs for each of the noise by spot wobble conditions. The area between the MTF and threshold functions represents the MTFA, as depicted in figures 13 through 24.

Threshold functions are point-for-point higher for increasing noise levels, as expected.

As suggested in an earlier study (Beamon and Snyder, 1975), in which variation in the range data was not satisfactorily explained by variations in the MTF of the system caused by spot wobble, the threshold functions did seem to be sensitive to spot wobble. Areas under the threshold function are listed in tables 1 through 3, and plotted in figure 25. As one would expect, the thresholds for sine wave gratings parallel to the raster, and hence more sensitive to its interfering effects (Keesee, 1976), are significantly higher than the thresholds for gratings perpendicular to the raster (Sign test, $\underline{p} = 0.004$). It is of particular interest that the 4.9 V spot wobble level, which produced the second flat field display condition, resulted in the numerically smallest threshold area for each noise condition. The 1.95 V level, the first flat field condition, is the next smallest for each of the three conditions. These data indicate that the visual system is maximally sensitive to the sine wave gratings at the two conditions where the raster modulation is minimal. Or, conversely, a visible raster interferes with threshold grating detectability.

TARGET ACQUISITION PERFORMANCE

The data for the numbers of correct responses and the ground range of the target at the time of acquisition were subjected to analyses of variance procedures and <u>post hoc</u> Newman-Keuls tests. The data set NOCORR contained the num-

Table 1. THRESHOLD FUNCTION AT 0 mV NOISE LEVEL

Spot Wobble Voltage	A	B	(A+B)/2	$\sqrt{A^2+B^2}$
0.00	43.18	76.82	60.00	88.12
0.88	47.10	90.63	68.87	102.14
1.40	42.31	59.42	50.87	72.94
1.95	39.20	44.38	41.79	59.21
3.40	44.41	63.81	54.11	77.74
4.90	27.11	32.28	32.70	46.91

A = pattern perpendicular to raster

B = pattern parallel to raster

(A+B)/2 = mean value

$\sqrt{A^2+B^2}$ = quadratic mean

Table 2. THRESHOLD FUNCTION AREAS AT 35 mV NOISE LEVEL

Spot Wobble	A	B	(A+B)/2	$\sqrt{A^2+B^2}$
0.00 V	97.26	149.92	123.59	178.71
0.88 V	105.41	162.49	133.95	193.69
1.40 V	94.65	128.45	111.55	159.56
1.95 V	81.04	89.06	85.05	120.41
3.40 V	108.57	126.99	117.78	167.07
4.90 V	61.93	84.18	73.06	104.51

A = pattern perpendicular to raster

B = pattern parallel to raster

(A+B)/2 = mean value

$\sqrt{A^2+B^2}$ = quadratic

Table 3. THRESHOLD FUNCTION AREAS AT 70 mV NOISE LEVEL

Spot Wobble	A	B	(A+B)/2	$\sqrt{A^2+B^2}$
0.00 V	160.95	184.53	172.74	244.86
0.88 V	166.95	208.57	187.76	267.16
1.40 V	153.89	166.82	160.36	226.96
1.95 V	140.76	134.45	137.61	194.65
3.40 V	186.99	159.59	173.30	245.84
4.90 V	113.53	110.27	111.90	158.27

A = pattern perpendicular to raster

B = pattern parallel to raster

(A+B)/2 = mean value

$\sqrt{A^2+B^2}$ = quadratic

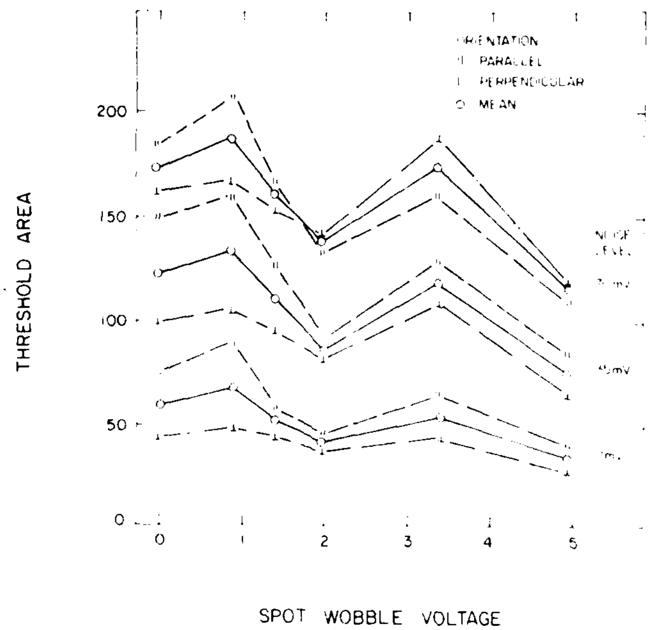

Figure 25: Areas Under Threshold Function

ber of correct responses. The data set WMEANS consisted of means of the ground range of correct responses only. The sets WZEROS and WMINS had a zero or minimum observable ground range (9453 ft) inserted for missing scores due to incorrect responses or no responses.

Number of Correct Responses

Table 4 contains the results of a 3 x 6 x 3 analysis of variance (Noise Level x Spot Wobble x Target Size) performed on the number of correct responses. Each cell in the design had a maximum of 35 correct responses (5 targets x 7 subjects). Noise, target size, and four of the interactions involving these variables were statistically significant, while the spot wobble main effect was not significant.

Table 4. ANALYSIS OF VARIANCE OF NUMBER OF CORRECT RESPONSES

Source of Variance	df	SS	MS	F	*p*
Between Subjects					
Noise (N)	2	140.111	70.056	101.590	< .0001
Spot Wobble (SW)	5	5.778	1.156	1.676	> .05
N x SW	10	6.587	0.659	.955	> .05
S/N,SW	108	74.476	0.690		
Within Subjects					
Target Size (T)	2	903.000	451.500	1929.653	< .0001
N x T	4	78.127	19.532	83.476	< .0001
SW x T	10	7.698	0.770	3.290	< .0001
N x SW x T	20	101.302	5.065	21.647	< .0001
T x S/N,SW	216	50.540	0.234		
Total	377	1367.619			

Figure 26 illustrates the expected result that small targets are recognized less often than are large ones.

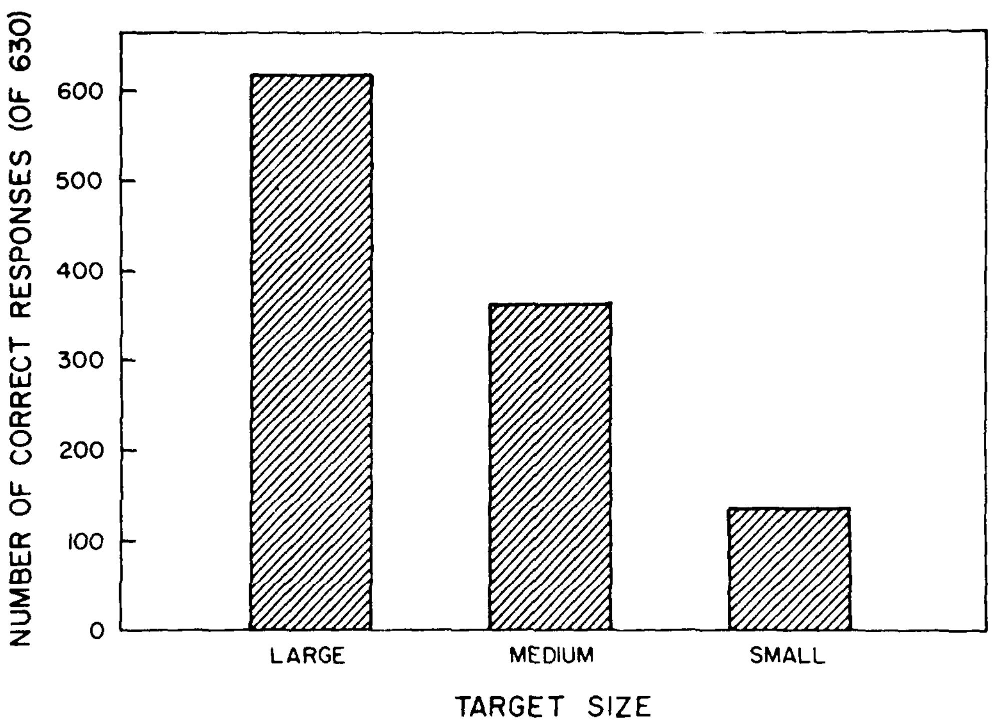

Figure 26: Number of Correct Responses by Target Sizes

Figure 27 depicts the number of correct responses at the three noise levels; as noise level increased, the number of targets correctly recognized decreased.

Newman-Keuls procedures were used to examine the significant noise and target main effects. Each of the levels was significantly different from the others for both main effects as shown in table 5.

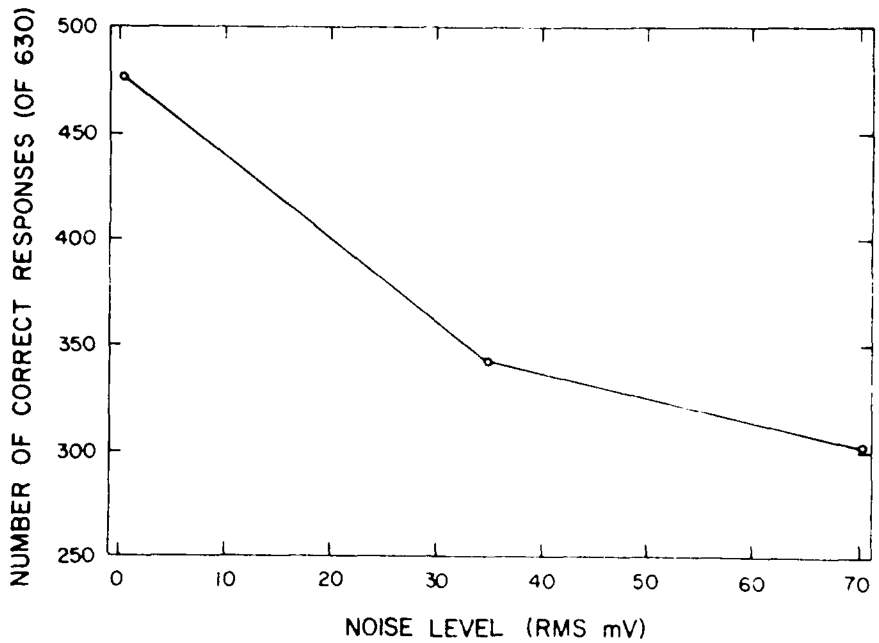

Figure 27: Number of Correct Responses by Noise Levels

Simple effects *F*-ratio tests were conducted for the significant noise by target size interaction (figure 28). The noise levels were not significantly different ($F_{2,108} = 2.98$, $p > 0.05$) for large targets. The *F* tests for noise for medium size targets and for small targets were significant, and Newman-Keuls procedures indicated each level to be significantly different from the other ($p < 0.01$), as listed in table 6.

The spot wobble by target size interaction was significant ($F = 3.29$, $p < 0.0001$). The effect of spot wobble was not significant for large targets, but was significant for medium targets ($F_{5,108} = 9.75$, $p < 0.001$), as summarized in table 7, table 8, and figure 29.

Table 5. NEUMAN-KEULS RESULTS FOR SIGNIFICANT NOISE LEVEL AND TARGET SIZE EFFECTS USING THE NUMBER OF CORRECT RESPONSE DATA

Total Number Correct	301	341	480
Noise Level	70 mV	35 mV	0 mV
70 mV	---	40*	179*
35 mV		---	139*
0 mV			---

Total Number Correct	137	371	614
Target Size	Small	Medium	Large
Small	---	234*	477*
Medium		---	243*
Large			---

* $p < 0.01$

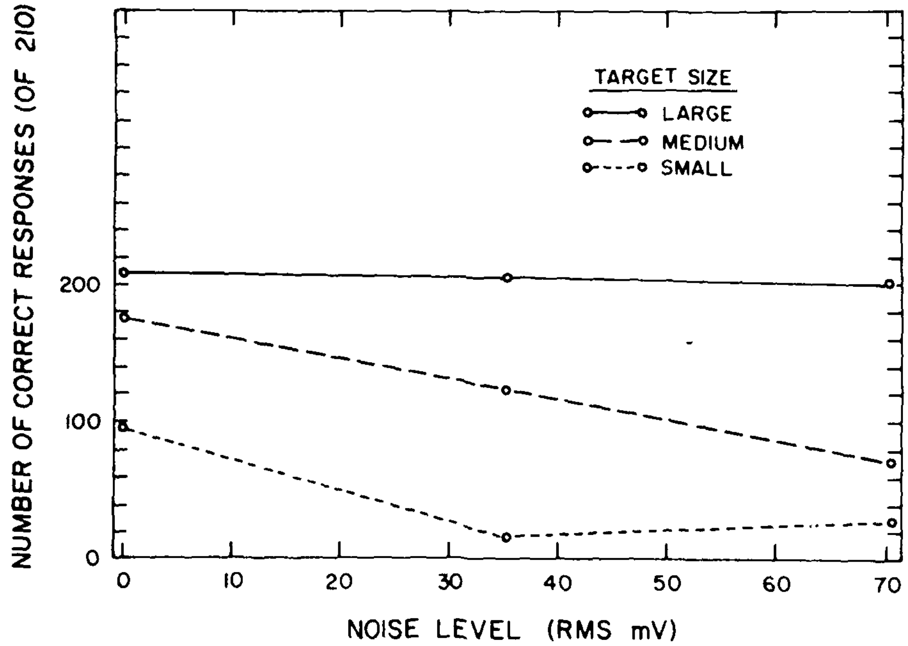

Figure 28: Number Correct Responses for Noise Level by Target Size

The data of figure 29 are replotted in figure 30 to illustrate the raster modulation measure and the differences provided by redundant 0.04 and 0.20 raster modulation levels. Figure 30 suggests that the lowest raster modulation at alternate line overlap (points 5,6), where some vertical smearing was evident, produced more correct responses than did the same raster modulation with a narrower line width (points 3,4). This is consistent with the earlier Beamon and Snyder (1975) results.

The significant triple interaction is illustrated in figure 31. It is caused largely by the relatively few correct responses to small, noisy targets and contributes little to an evaluation of the merits of spot wobble.

Table 6. NEUMAN-KEULS RESULTS FOR SIGNIFICANT NOISE BY TARGET SIZE INTERACTIONS USING THE NUMBER OF CORRECT RESPONSE DATA

Total Number Correct	15	22	95
Noise Levels for Small Targets	35 mV	70 mV	0 mV
35 mV	---	12*	68*
70 mV		---	80*
0 mV			---

Total Number Correct	73	121	177
Noise Levels for Medium Targets	70 mV	35 mV	0 mV
70 mV	---	48*	56*
35 mV		---	104*
0 mV			---

* $p < 0.01$

Table 7. NEUMAN-KEULS RESULTS FOR SPOT WOBBLE FOR MEDIUM TARGETS USING THE NUMBER OF CORRECT RESPONSE DATA

Number of Correct Responses	52	60	61	65	65	68
Spot Wobble Level	1.95 V	3.4 V	1.4 V	0 V	0.88 V	4.9 V
1.95 V	---	8*	9*	13*	16*	16*
3.4 V		---	1	5	5	8*
1.4 V			---	4	4	7*
0 V				---	0	3
0.88 V					---	3
4.9 V						---

*$p < 0.01$

Table 8. NEUMAN-KEULS RESULTS FOR SPOT WOBBLE FOR LARGE TARGETS USING THE NUMBER OF CORRECT RESPONSES

Number of Correct Responses	15	21	23	25	25	28
Spot Wobble Level	1.4 V	0 V	4.9 V	1.95 V	3.4 V	0.88 V
1.4 V	---	6*	8*	10*	10*	13*
0 V		---	2	4	4	7*
4.9 V			---	2	2	5
1.95 V				---	0	3
3.4 V					---	3
0.88 V						---

*$p < 0.01$

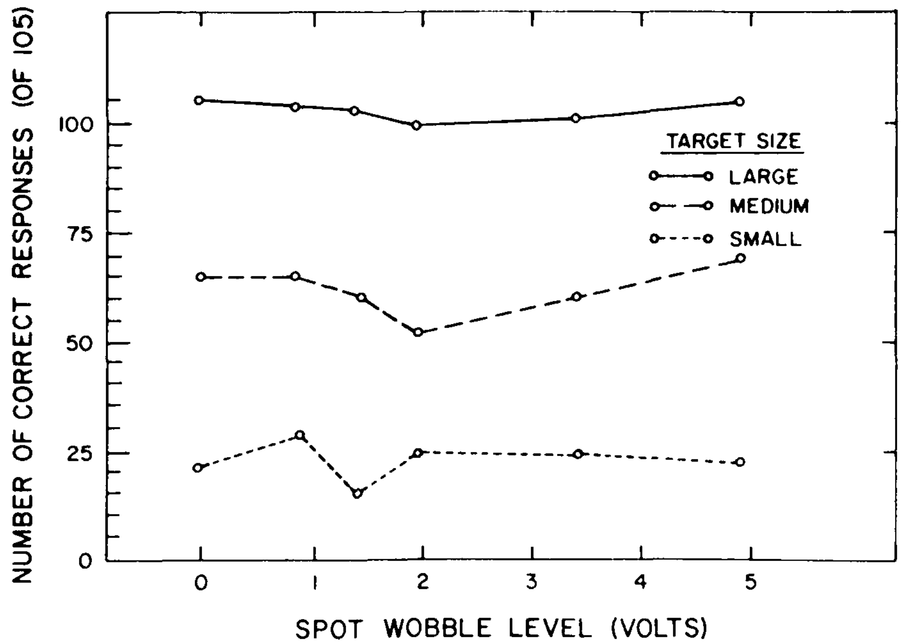

Figure 29: Number of Correct Responses for Target Size by Spot Wobble Level Interaction

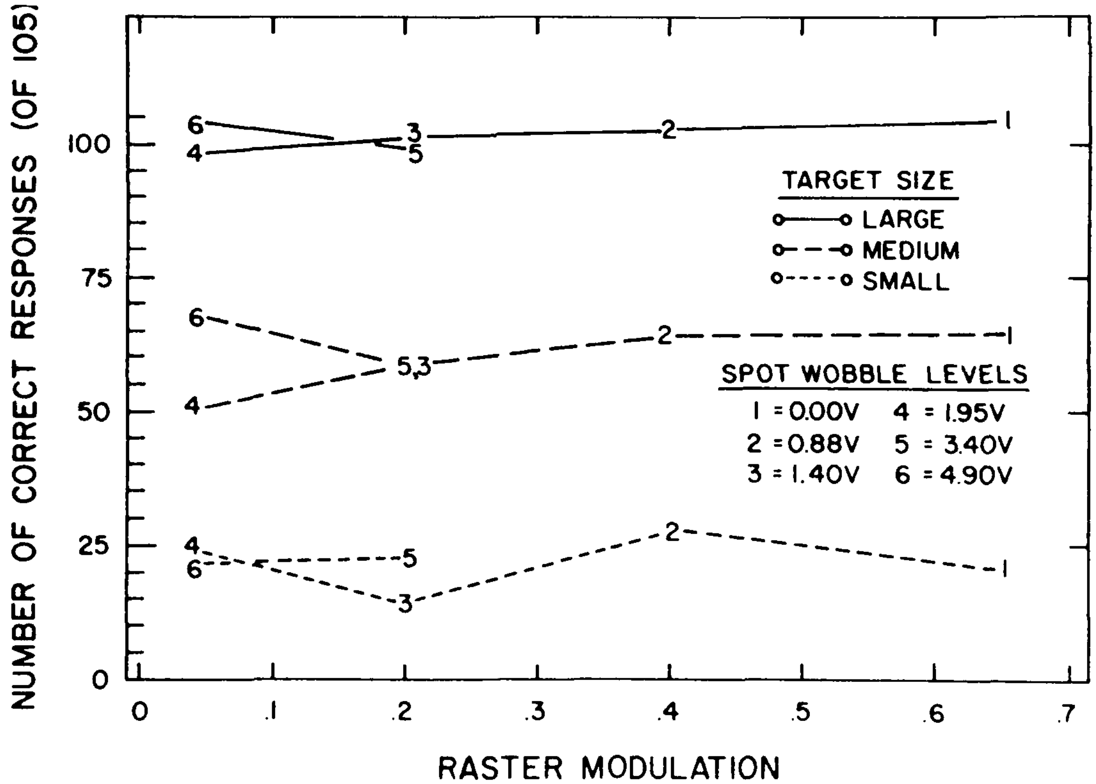

Figure 30: Number of Correct Responses for Target Size by Raster Modulation Interaction

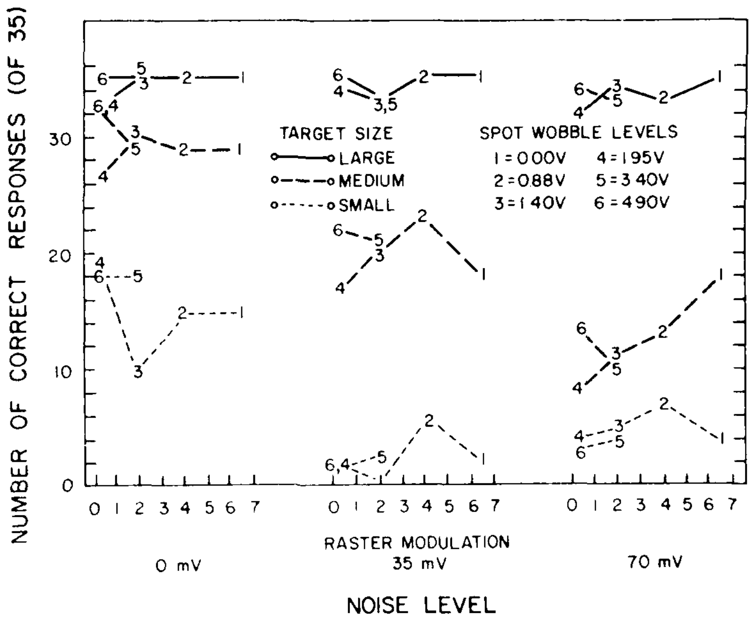

Figure 31: Number of Correct Responses for Target Size by Noise Level by Raster Modulation Interaction

Range for Correct Responses, WMEANS

Correct response range data were averaged within each cell to eliminate the "missing data" due to incorrect or no responses. Responses were also averaged across target size, due to the great proportion of small targets at high noise levels that were not correctly recognized.

The analysis of variance of these data is summarized in table 9. The only significant effect is that of noise, which is illustrated in figure 32. As expected, increases in noise cause decreases in ground range for correct recognition responses. A Newman-Keuls test (table 10) indicated that the ranges at 0 mV and 35 mV were significantly longer than the range at 70 mV.

Table 9. ANALYSIS OF VARIANCE OF RANGE OF CORRECT SCORES

Source of Variance	df	SS	MS	F	*p*
Noise (N)	2	140 184 285	70 092 142.3	11.292	< .01
Spot Wobble (SW)	5	23 509 750	4 701 950.1	0.758	> .05
N x SW	10	81 963 230	8 196 323.0	1.321	> .05
S/N,SW	108	670 345 636	6 206 987.4		
Total	125	916 011 901			

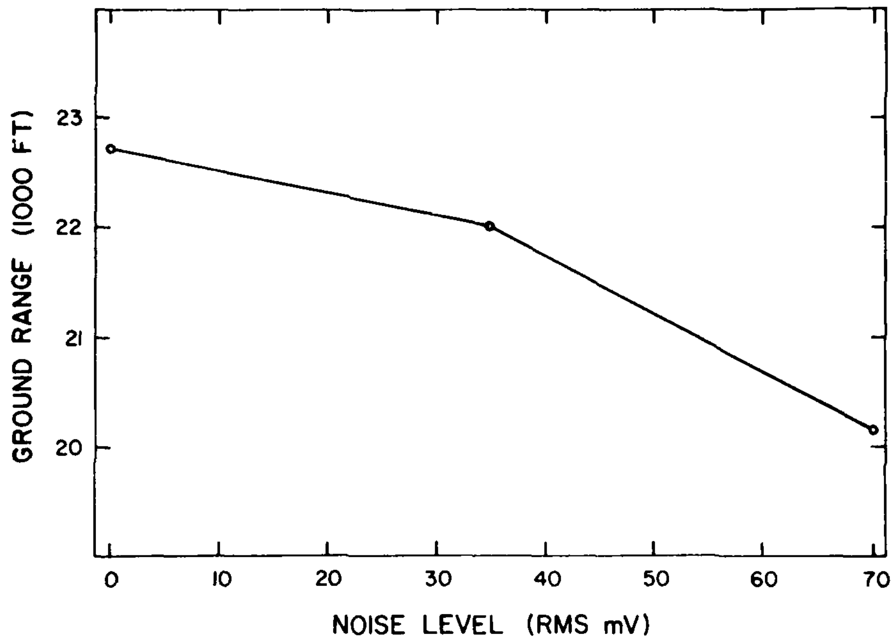

Figure 32: Ground Range for Three Noise Levels for Data Set WMEANS

The spot wobble main effect and the noise by spot wobble interaction were not significant ($p > 0.05$), although it was noted that ground ranges tended to be longer for the 0.04 raster modulation conditions at zero noise levels.

Range with Minimums, WMINS

An analysis of variance, summarized in table 11, was applied to the range data with minimum range substituted for incorrect or no responses.

As in the previous analysis, the noise effect ($p < 0.0001$) indicated decreases in range with increases in added noise, as illustrated in figure 33.

Table 10. NEUMAN-KEULS RESULTS OF NOISE MAIN EFFECT FOR CORRECT RESPONSE DATA

Mean Range	20 211.2	22 057.0	22 699.7
Noise Level	70 mV	35 mV	0 mV
70 mV	---	1845.8*	2488.5*
35 mV		---	642.7
0 mV			---

* $p < 0.01$

Table 11. ANALYSIS OF VARIANCE OF GROUND RANGE WITH MINIMUMS

Source of Variance	df	SS	MS	F	*p*
Between Subjects					
Noise (N)	2	1 332 836 665	666 418 332	99.142	< .0001
Spot Wobble (SW)	5	36 655 139	7 331 028	1.091	> .05
N x SW	10	119 626 449	11 962 645	1.780	< .07
S/N,SW	108	725 959 884	6 721 851		
Within Subjects					
Target Size (T)	2	8 796 541 242	4 398 270 621	939.206	< .0001
N x T	4	499 734 544	124 933 636	26.678	< .0001
SW x T	10	63 630 413	6 363 041	1.359	> .05
N x SW x T	20	35 033 052	1 751 653	0.374	> .05
T x S/N,SW	216	1 011 520 372	4 682 965		
Total	317	12 621 537 760			

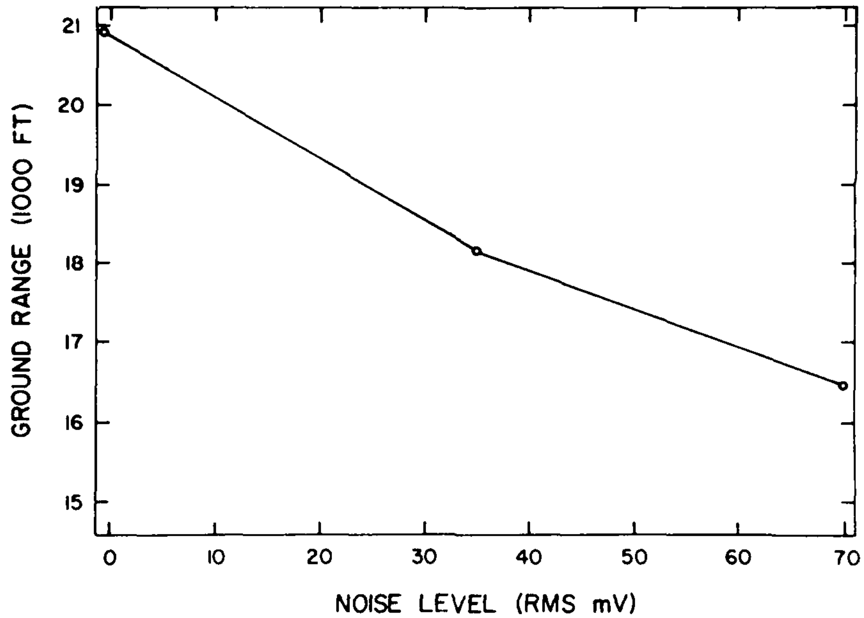

Figure 33: Ground Range for Three Noise Levels for Data Set WMINS

Target size also had a strong effect upon range, as shown in figure 34. A Newman-Keuls test, table 12, indicated that each increase in nominal target size produced a significant ($\underline{p} < 0.01$) increase in range.

The spot wobble main effect was clearly not significant, although the noise by spot wobble interaction approached statistical significance ($\underline{p} < 0.07$). Because of the central importance of this interaction in the application of spot wobble to noisy displays, it was decided to treat this interaction as intrinsically meaningful and perform further statistical analyses on it. Schade (1973), for example, suggested that spot wobble would increase the visibility of

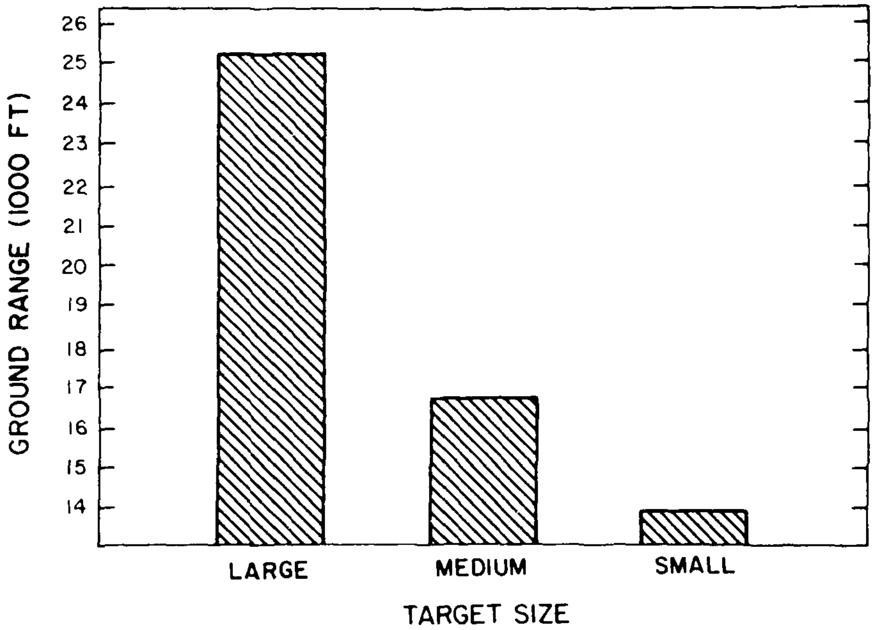

Figure 34: Ground Range for Three Target Sizes for Data Set WMINS

low frequency noise. Because of the strong influence of low frequency noise on visual thresholds (Keesee, 1976), this interaction is of critical importance.

The noise by spot wobble interaction is shown in figure 35, and is replotted in figure 36 as a function of raster modulation rather than spot wobble voltage. As seen in either of these figures, the interaction is due largely to the differential effect of spot wobble on the zero noise condition. The spot wobble simple effect was not statistically significant at either the 35 mV or 70 mV noise levels; that is, mean range was essentially constant over all spot wobble levels when either amount of noise was added ($F < 1$).

Table 12. NEUMAN-KEULS FOR TARGET SIZE MAIN EFFECT USING WMINS DATA

Mean Range	13 867.2	16 494.5	25 158.6
Target Size	Small	Medium	Large
Small	---	2629.3*	11 291.4*
Medium		---	8662.1*
Large			---

* $p < 0.01$

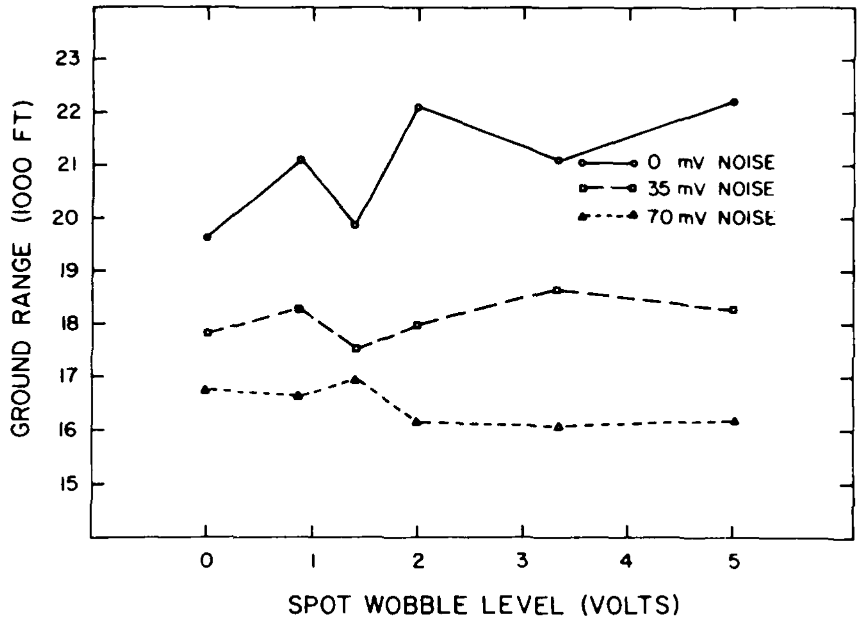

Figure 35: Ground Range for Noise Levels by Spot Wobble Levels for Data Set WMINS

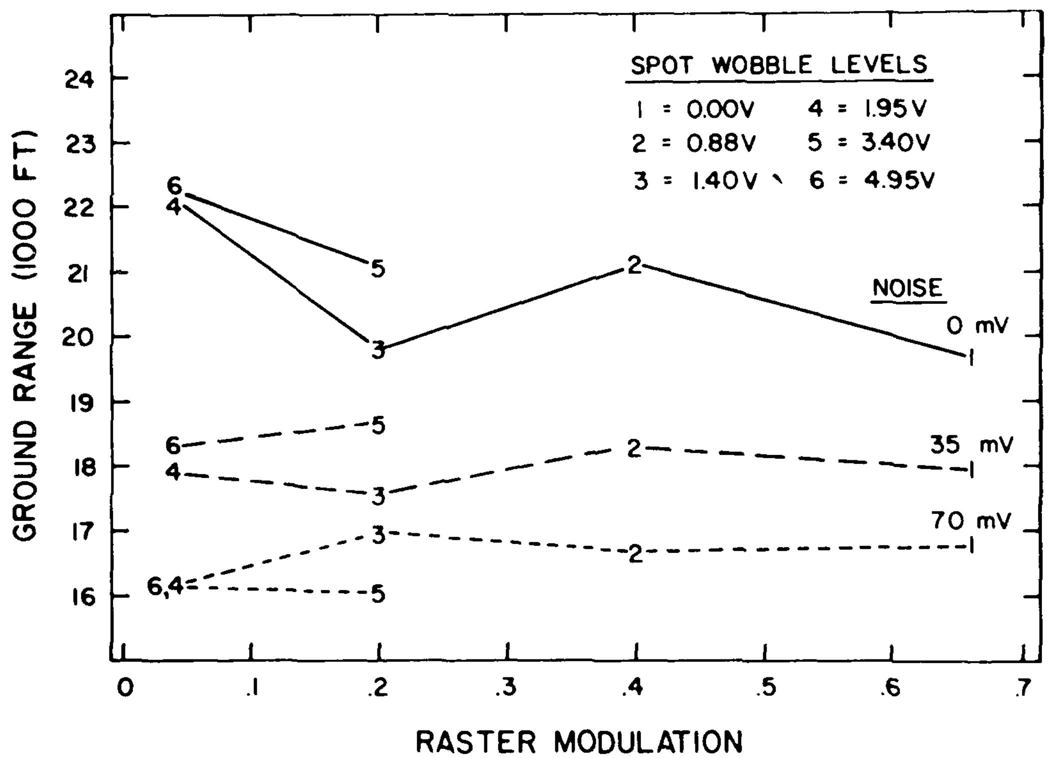

Figure 36: Ground Range for Noise Levels by Raster Modulation for Data Set WMINS

At the zero noise level, however, the spot wobble simple effect was statistically significant ($\underline{F}_{5,108} = 3.73$, $\underline{p} < 0.01$). A Newman-Keuls test, summarized in table 13, indicated that mean ranges were larger for each of the 0.04 raster modulation levels (1.95 and 4.90 V). This result is in complete agreement with the previous experiment by Beamon and Snyder (1975), which was conducted under noise-free conditions. There was no significant difference between the two 0.04 modulation conditions.

Thus, the data support the contention that a spot wobble amplitude sufficient to produce essentially a flat field yields an increase in recognition range, but apparently only for noise-free displays. For a noisy display, spot wobble neither helps nor hinders performance.

The noise-by-target size interaction was also statistically significant ($\underline{p} < 0.0001$). Each of the simple effects for target size at the three noise levels was also significant at $\underline{p} < 0.0001$ ($\underline{F}_{2,216} = 491$, 332, and 167).

Figure 37 depicts the noise level by target size interaction. The decrease in range for large targets was somewhat greater than for the small targets. The decrease in range is due, in part, to the substitution of minimum ground range on incorrect and no-response trials, which were more frequent for small targets.

Table 13. NEUMAN-KEULS TEST ON SPOT WOBBLE LEVELS AT 0 V NOISE CONDITION FOR WMINS DATA

Range WMINS	19 579.40	19 864.17	21 070.04	21 157.66	22 064.64	22 225.91
Spot Wobble Level	0 V	1.4 V	3.4 V	0.88 V	1.95 V	4.9 V
0.00 V	---	284.77	1490.64	1578.26	2485.24*	2646.51*
1.40 V		---	1205.87	1293.49	2200.47*	2361.74*
3.40 V			---	87.62	994.6	1155.87
0.88 V				---	906.98	1068.25
1.95 V					---	161.27
4.95 V						---

* $p < 0.05$

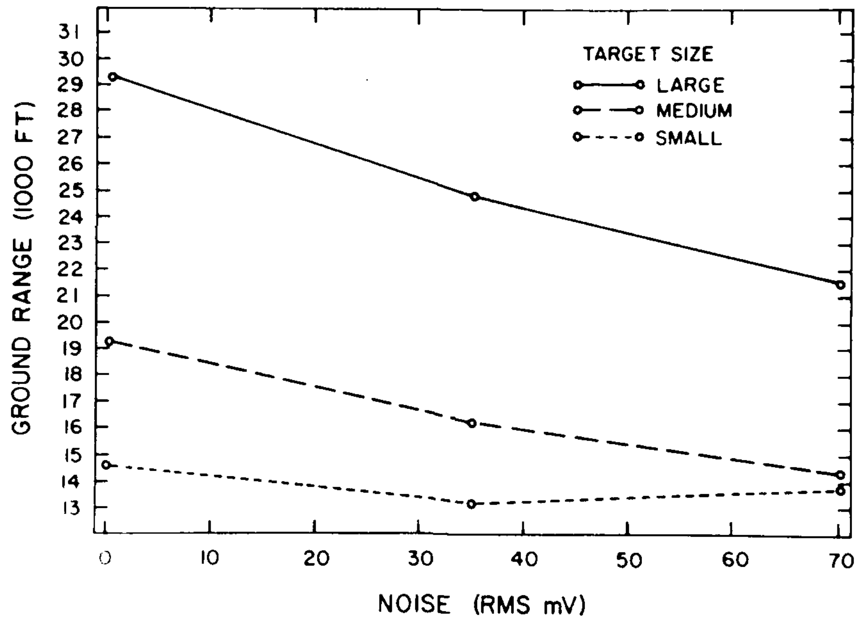

Figure [illegible] Range for Noise Level by Target Size [illegible]ion for Data Set WMINS

Newman-Keuls [illegible] noise-by-target size combinations are listed in [illegible]

Range with Zeros, WZEROS

The analysis of variance per[illegible] ground range data with zeros substituted for in[illegible]s yielded results that were very comparable to [illegible]nalysis performed on the data with minimum grou[illegible]i-tuted.

As summarized in table 15, the noise main eff[illegible] 38) was highly significant ($p < 0.0001$). Newm[illegible] procedures (table 16) indicated each level to be sig[illegible]

Table 14. NEUMAN-KEULS RESULTS FOR TARGETS BY NOISE INTERACTION USING WMINS DATA

Mean Range	14 662.2	19 180.8	29 137.9
Targets @ 0 mV Noise	Small	Medium	Large
Small	---	4518.6*	14 475.7*
Medium		---	9957.1*
Large			---

Mean Range	13 168.2	16 159.6	24 889.5
Targets @ 35 mV Noise	Small	Medium	Large
Small	---	2991.4*	11 721.3*
Medium		---	8729.9*
Large			---

Mean Range	13 771.2	14 149.0	21 448.4
Targets @ 70 mV Noise	Small	Medium	Large
Small	---	377.8	7677.2*
Medium		---	7299.4*
Large			---

* $p < 0.01$

cantly different from either of the other two. The spot wobble main effect was not significant.

The spot wobble-by-noise level interaction was not quite significant at the conventional 0.05 level, but for the reasons indicated previously it was subjected to further examination to determine possible spot wobble effects at each noise level (figures 39, 40).

Simple effects $\underline{F}$ tests indicated that spot wobble at 0 mV noise, the normal noise-free display condition, was significant ($\underline{F}_{5,108} = 2.99$, $\underline{p} < 0.025$). Spot wobble levels at 35 mV and 70 mV noise levels were not, however ($\underline{F}_{5,108} <$ 1.016).

A Newman-Keuls procedure was used to examine the differences in mean ground range as a function of spot wobble voltage at the 0 mV noise level, as summarized in table 17. The 4.9 V spot wobble level was significantly better than the 1.4 V and 0 V normal screen conditions ($\underline{p}$s < 0.05). Thus, the flat field, structure-free display produced by the highest spot wobble voltage, where some vertical smearing of small detail was evident, produced a 21.07% improvement in target acquisition performance when no noise was added to the video signal.

The target size main effect (figure 41) was highly significant. The significance is due, in part, to the effects of

Table 15. ANALYSIS OF VARIANCE OF GROUND RANGE DATA WITH ZEROS SUBSTITUTED FOR INCORRECT RESPONSES

Source of Variance	df	SS	MS	F	*p*
Between Subjects					
Noise (N)	2	4 327 272 908	2 163 636 454	152.444	< .0001
Spot Wobble (SW)	5	90 875 009	18 175 002	1.281	> .05
N x SW	10	259 808 051	25 980 865	1.831	∿ .06
S/N,SW	108	1 532 840 989	14 192 972		
Within Subjects					
Target Size (T)	2	27 961 019 120	13 580 509 560	1076.722	< .0001
N x T	4	592 224 526	148 056 131	11.403	< .0001
SW x T	10	153 119 318	15 311 932	1.179	> .05
N x SW x T	20	100 735 168	5 036 758	0.388	> .05
T x S/N,SW	216	2 804 613 636	12 984 322		
Total	377	37 822 508 724			

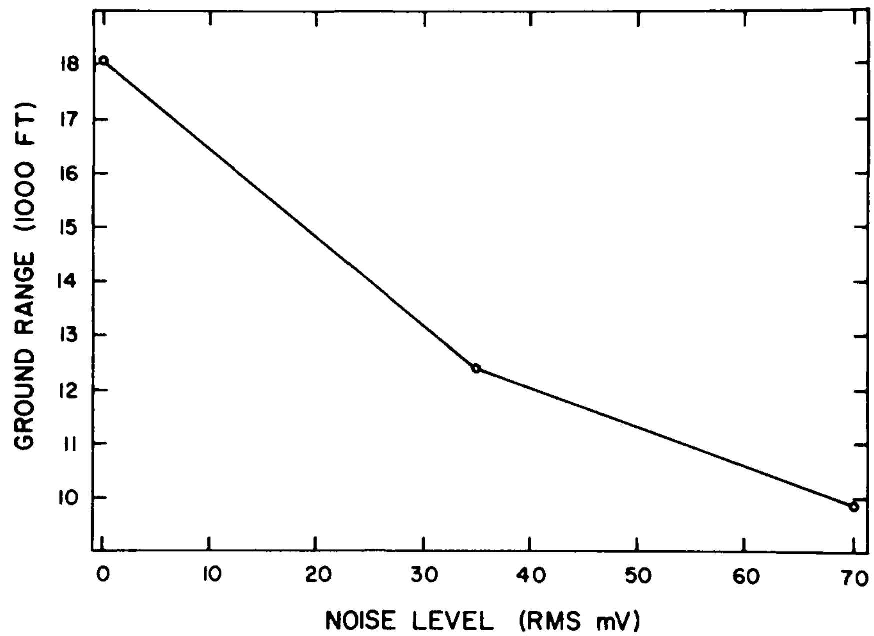

Figure 38: Ground Range for Three Noise Levels, Data Set WZEROS

substituting a zero for incorrect responses, which occurred most frequently for the small targets.

The noise by target size interaction was also significant. As indicated in figure 42, high noise levels made detection of large-sized and medium-sized targets more difficult. The mean ground range reported for small targets was bounded by the inclusion of zeros for a high proportion of incorrect and missed responses. Newman-Keuls results are contained in table 18.

The analyses of data with minimum ground range substituted for incorrect responses and with zeros substituted provided similar results. As the data sets were not independent, this was to be expected.

Table 16. NEUMAN-KEULS RESULTS OF NOISE MAIN EFFECT USING WZEROS DATA

Mean Range	9961.04	12 367.00	18 032.33
Noise Level	70 mV	35 mV	0 mV
70 mV	---	2405.96*	8071.29*
35 mV		---	5665.32*
0 mV			---

* $p < 0.01$

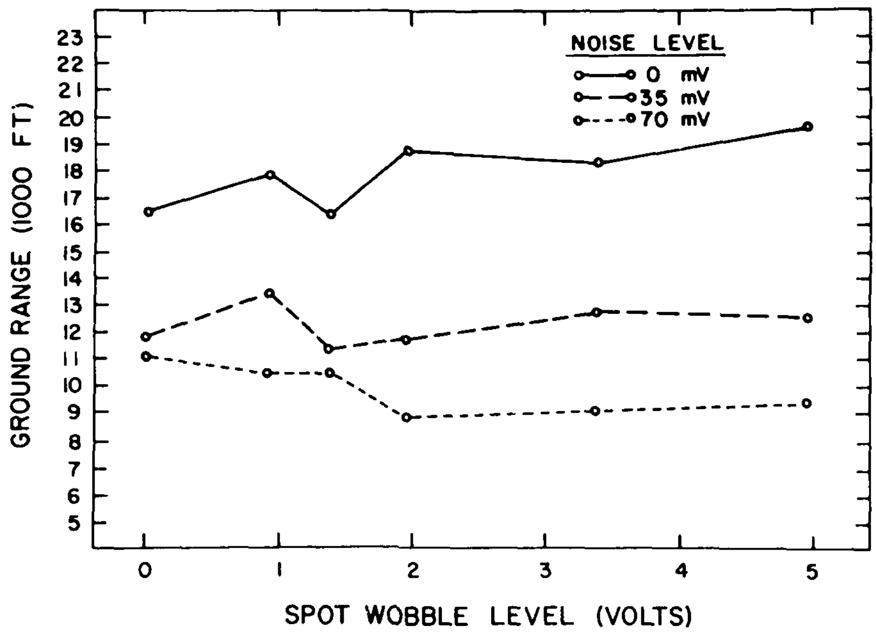

Figure 39: Ground Range for Spot Wobble by Noise Level Interaction for Data Set WZEROS

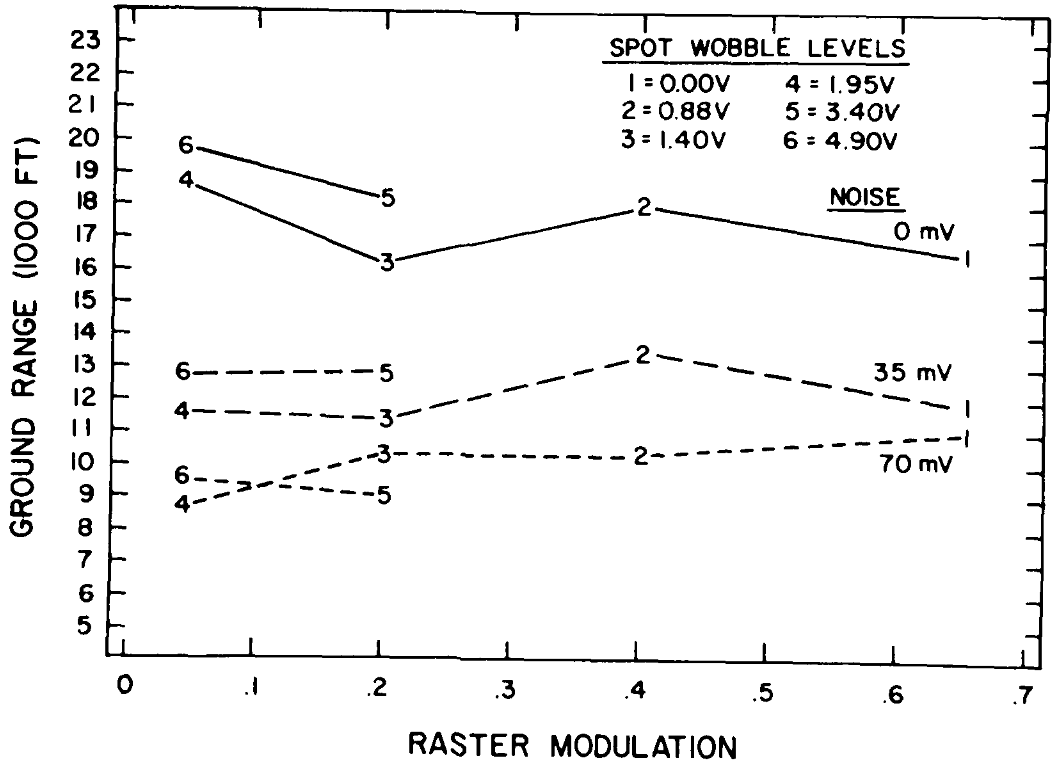

Figure 40: Ground Range for Raster Modulation by Noise Level Interaction for Data Set WZEROS

Table 17. NEUMAN-KEULS RESULTS FOR SPOT WOBBLE LEVELS AT 0 mV NOISE WITH WZEROS DATA

Mean Range (feet)	16 310.60	16 499.64	18 077.90	18 345.64	18 984.88	19 975.32
Spot Wobble @ 0 mV Noise	1.40 V	0.00 V	0.88 V	3.40 V	1.95 V	4.90 V
1.40 V	---	189.04	1767.30	2035.04	2674.28	3664.72*
0.00 V		---	1578.26	1846.00	2485.24	3475.68*
0.88 V			---	267.74	906.98	1897.42
3.40 V				---	639.24	1629.68
1.95 V					---	990.44
4.90 V						---

* $p < 0.05$

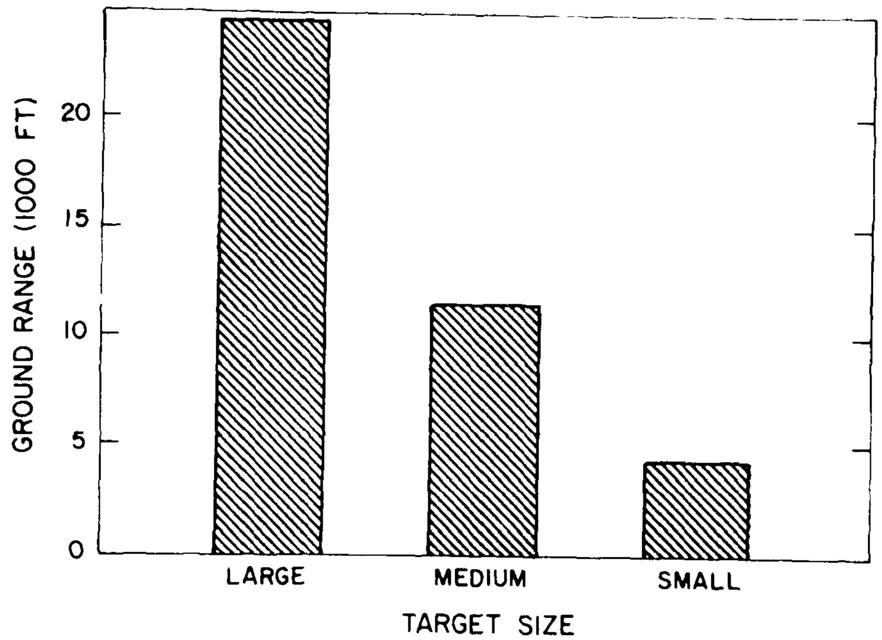

Figure 41: Ground Range for Three Target Sizes for Data Set WZEROS

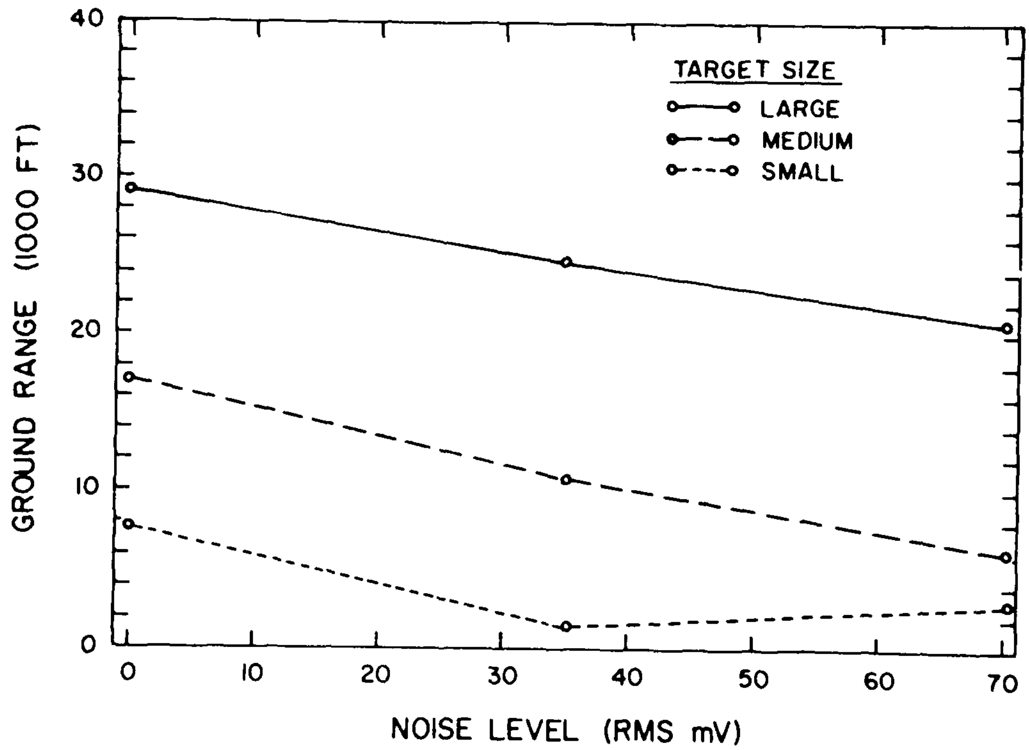

Figure 42: Ground Range for Noise Level by Target Size Interaction for Data Set WZEROS

Table 18. NEUMAN-KEULS RESULTS FOR TARGETS BY NOISE INTERACTION FOR WZEROS DATA

Mean Range	7851.2	17 107.9	29 137.9
Targets @ 0 mV Noise	Small	Medium	Large
Small	---	9256.7*	21 286.7*
Medium		---	12 030.0*
Large			---

Mean Range	1619.1	10 888.5	24 593.4
Targets @ 35 mV Noise	Small	Medium	Large
Small	---	9269.4*	22 974.3*
Medium		---	13 704.9*
Large			---

Mean Range	2932.8	6035.0	20 915.3
Targets @ 70 mV Noise	Small	Medium	Large
Small	---	3102.3*	17 982.6*
Medium		---	14 880.3*
Large			---

* $p < 0.01$

Summary of Target Acquisition Results

A summary of the statistical analyses is presented in table 19. For each analysis, noise was a statistically significant source of performance variation. The spot wobble main effect was not statistically significant in each instance. Target size and noise by target size interactions (not obtained in the WMEANS analysis) were consistently significant.

Compensation for incorrect responses, as included in the analyses of WMINS and WZEROS data sets, suggests that some noise by spot wobble interaction was present, although the effect was not quite significant at the 0.05 level. Data obtained from the 0 V noise level of this interaction were consistent with the results of the previous spot wobble study (Beamon and Snyder, 1975).

For the analysis of the number of correct responses, target size and all interactions involving target size were significant. Factors which influence target acquisition affect small targets first, then larger ones.

While range data obtained from correct responses were not particularly sensitive to spot wobble levels and interactions of spot wobble with other factors, data for the number of correct responses were sensitive to interactions involving spot wobble.

Table 19. SUMMARY OF ANALYSES OF VARIANCE PROBABILITY VALUES OF OBSERVER PERFORMANCE DATA

Source of Variance	WMINS	WZEROS	WMEANS	NOCORR
Noise (N)	< .0001	< .0001	< .0002	< .0001
Spot Wobble (SW)	NS	NS	NS	NS
N x SW	< .0725	< .0632	NS	NS
Target Size (T)	< .0001	< .0001	*	< .0001
N x T	< .0001	< .0001	*	< .0001
SW x T	NS	NS	*	< .0001
N x SW x T	NS	NS	*	< .0001

* Data averaged across target size; thus, these effects were not analyzed.

Noise and spot wobble influence threshold levels which, in turn, have important implications for the ability of the visual system to meaningfully convey information related to target size. This will be discussed in the next section.

Correlations of System Parameters with Observer Performance Data

Based on the results of the threshold data, a multiple predictor approach was undertaken for examining the effects of the MTFA components on target acquisition performance. The MTFAs were calculated for MTF curves of both linear and logarithmic modulation values. Task and Verona (1976) suggested that $\log_{10}$ values of modulation be employed to compensate for the nonlinear brightness/intensity relationship. The linear and log MTFAs were computed for axes parallel and perpendicular to the raster. Combined measures of MTFA were obtained by calculating the mean and the quadratic sum of the parallel and perpendicular MTFAs.

Correlations (Pearson r) were calculated between the various MTFA components and observer performance data. The following ranges and numbers of correct response data sets were used:

1. WMINS, where minimum visible ground range was substituted for incorrect responses,

2. WZEROS, where zero range was substituted for incorrect responses,

3. WMEANS, the means of correct responses only, and

4. NOCORR, the number of correct responses to targets.

The following MTF, threshold, and raster modulation measures were correlated with each of the four response data sets:

1. MPERIN; the Modulation transfer function area, PERpendicular, lINear

2. MPARIN; MTFA, PARallel, lINear

3. MMEAIN; MTFA, MEAns, lINear

4. MQUAIN; MTFA, QUAdratic parallel and perpendicular, lINear

5. MPEROG; MTFA, PERpendicular, lOGarithmic

6. MPAROG; MTFA, PARallel, lOGarithmic

7. MMEAOG; MTFA, MEAns, lOGarithmic

8. MQUAOG; MTFA, QUAdratic, lOGarithmic

9. TPERIN; area under Threshold function, PERpendicular, lINear

AD-A083 090 VIRGINIA POLYTECHNIC INST AND STATE UNIV BLACKSBURG --ETC F/G 17/2
AN EVALUATION OF THE EFFECT OF SPOT WOBBLE UPON OBSERVER PERFOR--ETC(U)
JAN 80 H L SNYDER, W S BEAMON, J C GUTMANN F33615-76-C-5022

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10. TPARIN; Threshold area, PARallel, lINear

11. TMEAIN; Threshold area, MEAns, lINear

12. TQUAIN; Threshold area, QUAdratic sum, lINear

13. TPEROG; Threshold area, PERpendicular, lOGarithmic

14. TPAROG; Threshold area, PARallel, lOGarithmic

15. TMEAOG; Threshold area, MEAns, lOGarithmic

16. TQUAOG; Threshold area, QUAdratic, lOGarithmic

17. SPOTW; SPOT Wobble levels

18. RASMOD; RASter MODulation

The matrix of correlations is listed in table 20. The highly significant negative correlations between observer task performance measures and areas under the threshold functions were unexpected. The highest correlation of threshold area with performance data was TPERIN with correlations of $-0.859 < r < -0.687$ ($p < 0.0001$). The combined linear metric of TMEAIN, which incorporated both horizontal and vertical thresholds, was also significant ($p < 0.003$), with correlations of $-0.854 < r < -0.664$. Corresponding correlations of log threshold areas were numerically not as great, although each was statistically significant. Negative correlations are due to a reduction in threshold areas as visual sensitivity (and target acquisition performance) increases.

Table 20. CORRELATION OF OBSERVER PERFORMANCE WITH SYSTEM PREDICTORS

	WMINS	WZEROS	WMEANS	NOCORR
TPARIN	-0.80636***	-0.78861***	-0.60761**	-0.74318***
TPEROG	-0.72352***	-0.71617***	-0.56379	-0.68582**
TPAROG	-0.79875***	-0.78137***	-0.59160**	-0.73662***
TMEAIN	-0.85405***	-0.84316***	-0.66392C*	-0.80466***
TMEAOG	-0.78553***	-0.77314***	-0.59747**	-0.73485***
TQUAIN	-0.85091***	-0.83912***	-0.66268**	-0.79961***
TQUAOG	-0.78127***	-0.79632***	-0.59591**	-0.73168***
TPERIN	-0.85869***	-0.85536***	-0.68712**	-0.82590***
MPERIN	0.53878*	0.51641*	0.61467**	0.47322*
MPARIN	0.29634	0.30713	0.37093	0.31180
MPEROG	0.42524	0.40479	0.53392*	0.36734
MPAROG	0.17498	0.19635	0.25367	0.21750
MMEAIN	0.42747	0.42426	0.50836*	0.40788
MMEAOG	0.29996	0.30614	0.40012	0.30502
MQUAIN	0.44264	0.43777	0.52348*	0.41890
MQUAOG	0.32536	0.32840	0.42699	0.32267
RASMOD	-0.10418	-0.02300	-0.16236	0.07930
NOISE	-0.93329***	-0.93667***	-0.72760***	-0.91317***
SPOT WOBBLE	0.10993	0.07312	-0.00904	0.02471

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

There were fewer significant correlations of range and number of correct response data with the various linear and log MTFA values. Linear, perpendicular MTFA values, MPERIN, provided the highest numerical correlations with performance data that were statistically significant. Correlations ranged from $\underline{r}$ = 0.615 with WCORR to $\underline{r}$ = 0.473 with NOCORR, the number of correct responses. The only other significant correlations of MTFA values were WMEANS with MPEROG, MMEAIN, and MQUAIN. These correlations ranged from $\underline{r}$ = 0.508 to $\underline{r}$ = 0.534, and generally agree with correlations similarly obtained by Snyder (1976).

METHOD: STATIC TARGET RECOGNITION EXPERIMENT

This static experiment was similar to the previously described dynamic display experiment in that (1) it investigated the effects of spot wobble (or raster modulation) and noise upon observer performance, and (2) it permitted an evaluation of the MTFA measure of image quality.

EXPERIMENTAL DESIGN

Figure 43 illustrates the experimental design for this static experment. The four spot wobble levels correspond to raster modulations of 0.60 (0 V), 0.30 (1.00 V), 0.04 (1.50 V), and 0.04 (4.50 V). The last two levels are equivalent in raster modulation, but the 4.50 V spot wobble level produces a spot with greater vertical spread and, hence, a "softer" appearing image. These spot wobble or raster modulation levels correspond to the 0, 1.40, 1.95, and 4.90 V levels in the dynamic experiment. The voltage values are slightly different due to slight modifications made to the apparatus between the conduct of the two experiments; however, the raster modulations are essentially equivalent, and were determined by the photometric techniques described in the previous experment.

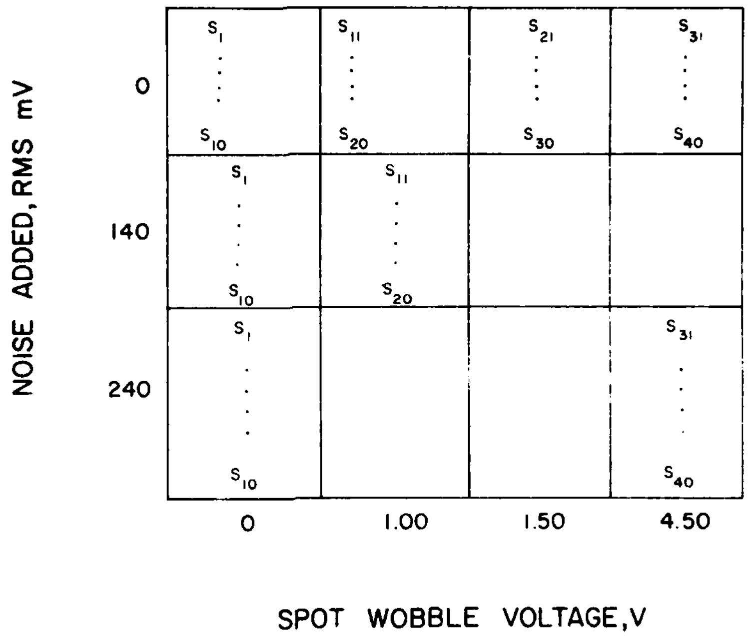

Figure 43: Static Experiment Design

The three noise levels were 0, 140 mV, and 240 mV rms, selected to provide no apparent noise, a prceptually intermediate level, and a very large amount of visual noise on the display. Apparatus for generating and monitoring the noise was the same as that used in the previous experiment.

Ten subjects were randomly assigned to each of the four spot wobble levels. Each subject received two blocks of 17 trials per block at each of the three noise levels, for a total of 102 trials. The selected target for each of the 34 trials per noise level was one of the complete set of 34 alphanumerics (2-9, A-Z). Zero and one were deleted to avoid confusion with O and I, respectively. Each block of 17 trials had a randomly selected half of the 34 targets, while the other 17-trial block per noise condition used the remaining 17 targets. Thus, each subject received all 34 alphanumeric targets three times, once each under each noise level. The three noise levels were randomly ordered across the six blocks for each subject.

APPARATUS

The alphanumeric targets were generated from randomly located Leroy-lettered alphanumerics lettered in black on 8 x 10 inch white paper. These plates were then photographed on 35 mm black-and-white slides. The slides were projected on a high-gain screen in a 6-ft enclosed box and viewed by the vidicon camera described in the previous experiment. When presented to the subject on the TV monitor, the letters and numerals each subtended 8 arcmin vertically and 5 arcmin horizontally. This apparatus is described in more detail in Snyder et al. (1974).

Thirty such slides were used randomly throughout the experiment to avoid learning of position cues by the subjects. Each subject began his/her 102 trials with a different slide and received a different order of presentation of the slides. All slides had 100% modulation of the black alphanumeric characters on the white background.

The camera, camera control unit, video mixer, noise generator, and display are the same as those used in the previous experiment. Adjustment of the TV equipment was essentially the same as in the previous experiment. The video voltage into the display, from the camera control unit, was adjusted to 0.3 V, peak to peak, which provided 50% modulation of the characters on the display in the absence of any added noise. This was done to avoid saturation (clipping) of the noise signal when added to the video signal.

SUBJECTS

The subjects were 40 undergraduates ranging in age from 18 to 27. All were screened for 20/23 near and far visual acuity, corrected or uncorrected, using a Bausch and Lomb Orthorater. Each was paid for his/her participation. Subjects were randomly assigned to the experimental conditions regardless of sex.

PROCEDURE

Subjects were informed that the experiment was an investigation of the effects of visual noise on alphanumeric character recognition, seated in an adjustable chair, and positioned so that their eyes were 88.9 cm from the TV display. Subjects were given a hand-held button by which to indicate their responses. An intercom system permitted conversation between the subject and the experimenter, located in the next room.

Each trial began when the experimenter told the subject, via the intercom, which alphanumeric to look for on the following display presentation. The subject then depressed the hand-held button which caused the slide to be displayed (at the appropriate noise level) on the monitor. When the subject visually recognized the target alphanumeric, he depressed the button a second time, which removed the image from the display. (Video switches and a constant input voltage maintained the space average luminance of the display at 50 cd/m^2 during and between trials.) The subject then told the experimenter, via the intercom, which sixth (two sections vertically by three sections horizontally) of the display in which he/she found the target. Verbal responses of upper left, lower left, upper center, . . . lower right were used. The experimenter recorded the automaticaly measured time of the subject's search and the location response. The experimenter then advanced the projector for the next trial.

Each subject was given 10 practice trials prior to the 102 search trials to become familiar with the three noise levels and the response procedures.

Following the 102 search trials, subjects were asked to rate four target slides which differed only by the spot wobble level. Each of the four levels was presented in a random order to each subject, and the subject could view each level as long as he/she wished. No noise was added to the image. After viewing all four levels, the four were presented again in the same order, and the subject was asked to rank order them in "picture quality."

Subjects were then shown the same images again, and were asked to estimate the quality of each on a nine-point scale, ranging from one ("poor") through five ("marginally acceptable") to nine ("excellent"). The order of presentation of the four spot wobble levels was the same for each subject as in the ranking procedure. Following these ratings, subjects were debriefed on the nature of the spot wobble concept and dismissed.

PHOTOMETRIC MEASUREMENTS

Scanning slit photometry, followed by Fourier analysis, was done in a manner similar to that of the first experiment, to obtain raster modulation and system MTF curves. The results of these scans, along with observer performance data, are presented in the next section.

RESULTS: STATIC TARGET RECOGNITION EXPERIMENT

TARGET RECOGNITION PERFORMANCE

Separate analyses were conducted for the correctness of recognition responses and search time. Analyses of variance were Newman-Keuls post hoc comparison tested, as appropriate.

Number of Correct Responses

The number of correct responses, of 34 trials, per subject per experimental condition were subjected to an analysis of variance, which is summarized in table 21. As shown in this table, neither of the main effects nor their interaction were statistically significant. This result was probably due to the fact that neither the noise added nor the spot wobble amplitude reduced performance substantially below 100 percent. The overall percent correct for the experiment was 92.9%.

Search Time

The search times for all correct responses per subject per condition were averaged and subjected to an analysis of variance, which is summarized in table 22. As indicated, the only source of variance which is statistically signifi-

Table 21. SUMMARY OF ANALYSIS OF VARIANCE OF PERCENT CORRECT RESPONSES

Source	df	SS	MS	F	*p*
Spot Wobble (SW)	3	0.0012	0.0004	< 1	> .05
Noise (N)	2	0.0070	0.0035	1.08	> .05
SW x N	6	0.0161	0.0027	< 1	> .05
Subjects (S)/SW	36	0.1493	0.0041	---	---
N x S/SW	72	0.2340	0.0032	---	---
Total	119				

cant is the noise level effect ($p < 0.0001$). This effect is illustrated in figure 44, which shows that increases in noise cause increases in search time. Each noise level mean search time is significantly different from the other means ($p < 0.001$), as indicated by a Newman-Keuls test.

SPOT WOBBLE SUBJECTIVE EVALUATION

Ranking of Spot Wobble Levels

Table 23 shows the number of subjects ranking each spot wobble level in each rank. Using 1, 2, 3, and 4 as rank values, the mean ranks for the spot wobble levels are 2.60, 2.05, 1.98, and 3.38, respectively. Thus, the subjects generally ranked the 1.5 V spot wobble highest, and the 4.5 V spot wobble value lowest in subjective quality rank. This result agrees with that of Beamon and Snyder (1975), who found that the second minimum spot wobble level was judged poorest in quality (even though it produced the best performance).

Subjective Quality Ratings by Spot Wobble Level

Table 24 gives the numbers of subjects who assigned each quality rating to each spot wobble level. Again, the first minimum raster modulation level (0.04 modulation, 1.5 V) was judged best in quality, while the second minimum (0.04 modulation, 4.5 V) was judged poorest.

Table 22. SUMMARY OF ANALYSIS OF VARIANCE OF STATIC EXPERIMENT SEARCH TIMES

Source	df	SS	MS	F	*p*
Spot Wobble (SW)	3	0.80	0.27	< 1	> .05
Noise (N)	2	26.74	13.37	35.40	< .0001
SW x N	6	1.06	0.18	< 1	> .05
Subjects (S)/SW	36	106.99	2.97	---	---
N x S/SW	72	27.20	0.38	---	---
Total	119				

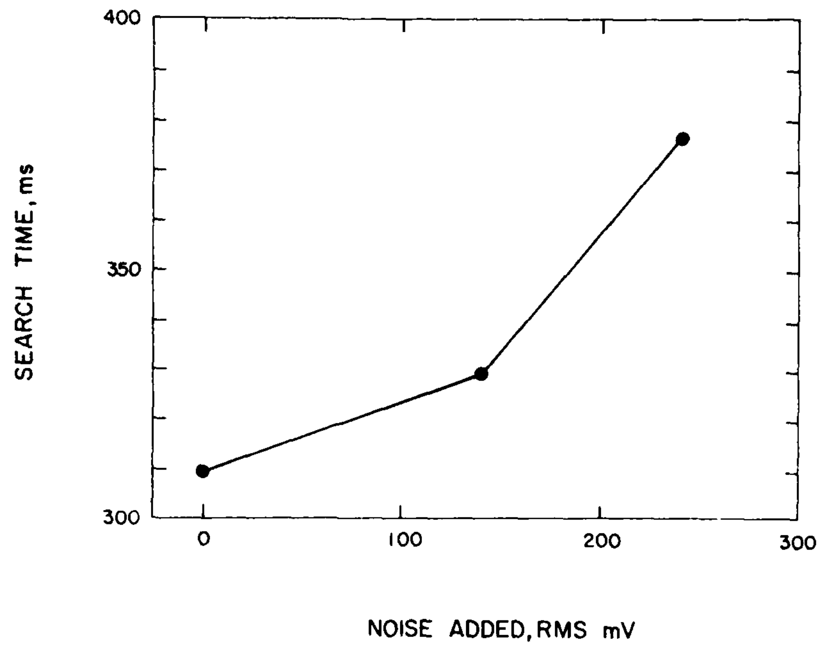

Figure 44: Effect of Noise Level on Static Display Search Times

MTFA EVALUATION

System modulation transfer functions for the display were previously obtained and plotted in a preceding section. Similarly, observer threshold curves were obtained from the dynamic experiment and applied to this experiment. The calculational procedure and resulting values are described below.

System MTF

To facilitate MTFA calculations, the Fourier coefficients obtained from the photometric scans were fitted with a function of the form

$$MTF = a\,(SF)^2 + i \, , \qquad (4)$$

Table 23. SUBJECTIVE RANKINGS, STATIC EXPERIMENT

Spot Wobble Level	Number by Rank First	Second	Third	Fourth	Mean Rank
0.00 V	7	11	13	9	2.60
1.00 V	14	13	10	3	2.05
1.50 V	18	11	5	6	1.98
4.50 V	1	5	12	22	3.38

Table 24. QUALITY RATINGS, STATIC EXPERIMENT

Rating	Spot Wobble Level 0.00 V	1.00 V	1.50 V	4.50 V
1 (Poor)	0	0	0	0
2	0	1	0	1
3	3	1	0	7
4	3	6	2	8
5 (Marginally Acceptable)	8	7	8	7
6	10	5	8	12
7	8	10	16	3
8	8	9	6	2
9 (Excellent)	0	1	0	0
Mean Rating:	6.03	6.13	6.40	4.98

where

MTF = modulation transfer factor at any spatial frequency,

a = best-fit slope,

SF = spatial frequency in cycles/degree, and

i = intercept at SF = 0.

A least-squares, best-fit equation of this form was fit to obtain a functional form MTF equation for each spot wobble level, both perpendicular to and parallel to the raster. While other nonlinear functions could be fit more closely to individual spot wobble/direction combination, the function in equation (6) was found to provide the best overall fit to the eight combinations. Table 25 lists the values of a and i, plus the value of R^2 (proportion of predicted variance) for each condition.

Threshold Response Curves

The threshold curves obtained in the previous experiment were also fit by functional form equations and applied to the calculation of the MTFAs for this study. Table 26 lists the values of the variables in the following equation which fit the parallel data quite well:

$$MODT = b(SF) + I(\log_e (N + 1)) , \qquad (5)$$

where

MODT = threshold modulation,

Table 25. FUNCTION FORMS OF SYSTEM MTFs.

Spot Wobble Level	Target Orientation	a*	i*	R^2
0.00 V	Parallel	-0.00448	0.9824	0.90
	Perpendicular	-0.00534	0.8025	0.56
1.00 V	Parallel	-0.00417	0.9138	0.49
	Perpendicular	-0.00976	0.9558	0.85
1.50 V	Parallel	-0.00493	0.9811	0.79
	Perpendicular	-0.01113	0.9491	0.74
4.50 V	Parallel	-0.00865	0.9412	0.72
	Perpendicular	-0.00423	0.7585	0.53

*Functional form equation: $MTF = a(SF)^2 + i$

b = best-fit coefficient of spatial frequency,

SF = spatial frequency in cycles/degree,

i = best-fit intercept, and

N = noise level, in millivolts.

Similarly, the thresholds for sine-wave gratings perpendicular to the raster are fitted well by an equation of the form:

$$MODT_T = b(SF) + i(N) \quad (6)$$

Values of b and i for these curves are given in table 27.

Thus, the functional form threshold curves fit the data quite well, predicting between 89% and 97% of the variance. In fact, these values of R^2 are in excess of those reported by Keesee (1975) for individual subject means, and are comparable to his group means. Unfortunately, apparatus differences preclude a direct application of Keesee's equations to the present studies. In addition, Keesee did not obtain threshold data for suppressed raster conditions.

MTFA Calculations

Using the functional forms defined above, along with their best-fit parameters, one can obtain MTFA values analytically by subtracting the integral of the noise threshold curve from the integral of the MTF. The upper limit of

Table 26. THRESHOLD FUNCTION VALUES OF b AND i FOR PARALLEL TO RASTER DATA

Spot Wobble Level	b	i	R^2
0.00 V	0.00496	0.019	0.91
1.00 V	0.00410	0.015	0.97
1.50 V	0.00251	0.013	0.96
4.50 V	0.00176	0.014	0.91

Table 27. THRESHOLD FUNCTION VALUES OF b AND i FOR PERPENDICULAR TO RASTER DATA

Spot Wobble Level	b	i	R^2
0.00 V	0.00212	0.00073	0.93
1.00 V	0.00205	0.00074	0.97
1.50 V	0.00172	0.00069	0.96
4.50 V	0.00113	0.00074	0.89

integration is the intersection of the two curves, while the lower limit is zero spatial frequency. The resulting MTFA values are given in table 28.

The calculated MTFAs vary as expected. The largest MTFA values are obtained at zero noise levels. Increases in noise are generally accompanied by decreases in MTFA, both perpendicular to and parallel to the raster. The product-moment correlations between MTFA and search time are $\underline{r}$ = -0.52 for the parallel MTFA and $\underline{r}$ = -0.88 for the perpendicular MTFA, both based upon all 12 SW x N combinations. Thus, while the correlations are appropriately negative, the parallel MTFA, which should be primarily affected by spot wobble, has a lower correlation with performance than does the perpendicular MTFA.

There is some suggestion in table 28 that the MTFA values are smallest for the 4.5 V spot wobble level, and perhaps largest for the 0 V and 1.5 V levels. These MTFA values cannot be correlated logically with target recognition performance because there was no significant variation in either percent correct recognition or search time as a function of spot wobble level. However, it is clear that the subjective ratings of image quality correspond well with these MTFA values for the parallel MTFA values, as might be expected, for spot wobble affects the parallel modulation directly (figure 45). However, the plot, in figure 45, of

Table 28. CALCULATED VALUES OF MTFA

Spot Wobble Level, V	Noise Level, mV	MTFA Parallell	MTFA Perpendicular
	0	9.169	6.396
0.00	140	8.842	5.476
	240	7.721	4.395
	0	8.578	6.208
1.00	140	8.372	5.401
	240	7.436	4.555
	0	8.977	5.771
1.50	140	8.550	5.042
	240	7.989	4.324
	0	6.452	6.668
4.50	140	5.933	5.511
	240	5.681	4.448

MTFA perpendicular to the raster versus subjective quality shows an inverse relationship; that is, as the perpendicular MTFA increases, the subjective image quality appears to decrease. Since only four data points exist for each of these curves, no statistical significance can be attached to any correlations computed for them; nonetheless, the plots appear to be consistent and perhaps thought provoking.

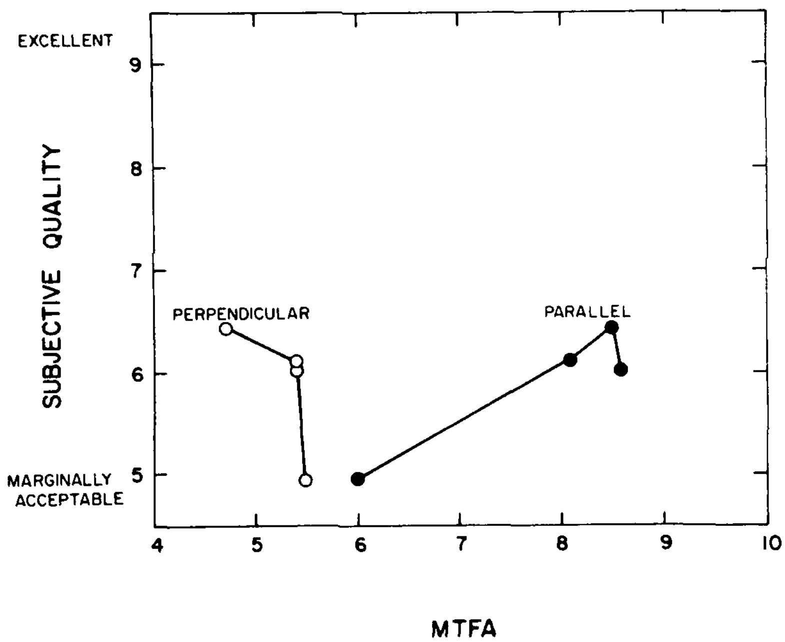

Figure 45: Relationship Between MTFA and Subjective Quality Estimates

DISCUSSION AND CONCLUSIONS

In general, the results support the advantages of raster suppression as an aid to target acquisition performance. In the dynamic experiment, performance was significantly improved under noise-free conditions by setting the spot wobble amplitude to yield a flat field, or nonvisible, raster. In the static experiment, the data were suggestive of the same result, though clearly not significant in a statistical sense. Without doubt, on the other hand, the use of spot wobble or raster elimination in a noisy display offers no demonstrable advantages in observer performance. Thus, the data are consisent with the results of previous studies which found that spot wobble can improve performance in noise-free displays (Beamon and Snyder, 1975), and that observers prefer flat-field displays (Thompson, 1957).

The data also provided modest support for the MTFA concept as a measure of image quality. Correlations between MTFA and performance in the two experiments were positive and generally significant, thus substantiating previous experimental results (Snyder, 1973; Snyder, 1976; Snyder et al., 1974 Task, 1979). However, the degree of correlation obtained indicated that considerable unpredicted performance variance remains. That is, the obtained correlations in these and similar studies only predict about 40% to 60% of the variance in operator performance. For this reason, the use of the MTFA as a deciding design criterion cannot be strongly recommended. As Task (1979) has suggested, unitary figures of merit or image quality metrics may, in fact, be infeasible as single evaluation criteria. It may simply not be possible to linearly combine all pertinent image quality variables into one unitary metric. Rather, multidimensional approaches perhaps warrant further investigation in this problem area.

Although the results of the static recognition experiment were insensitive to the effects of the spot wobble variable, the dynamic target acquisition study clearly demonstrated a wide range of performance. Of particular interest is the fact that the area under the threshold curve was a more accurate predictor of observer performance than was the MTFA. Stated another way, the system MTF had much less effect upon performance than did the change in the threshold curve due to noise and spot wobble effects. This result tends to confirm a suggestion offered originally by Snyder _et al_. (1974).

Specifically, it seems likely that the MTFA is decidedly anisometric. That is, all areas between the MTF and the threshold curve do not make equal contributions to effective image quality. Rather, the area immediately above the threshold curve should be weighted much more than should the area nearest the MTF curve. The logic behind this assertion, which is supported by the present dynamic study and by the very recent data of Gutmann, Snyder, Farley, and Evans (1979), is as follows:

1. To be correctly recognized and identified, targets must first be detected. The target detection task is one that is highly dependent upon visual search (looking at the right place at the right time) and upon the target having a modulation above threshold for its spatial frequency spectrum. If the target is substantially above threshold, elevating it further above threshold by increasing its modulation is of little benefit. Fundamentally, the detection task is heavily dependent upon visual search and is a near threshold task.

2. Further increases in target modulation or (typically) decreases in spatial frequency effected by moving closer to the target will not greatly improve the recognizability of the target if its power spectrum is already well above threshold. That is, if the observer can resolve details at all pertinent spatial frequencies, then increasing the modulation at these spatial frequencies is of little value as long as the observer has already detected and is looking at the target.

3. Of course, different observers have different contrast sensitivity (threshold) curves. Further, different observers may exhibit maximum sensitivity in different parts of the spatial frequency spectrum (Ginsburg, 1979). As a result, elevating the power spectrum of a target further above threshold is somewhat likely to improve performance, on the average across observers. Stated another way, personnel selection on the basis of contrast sensitivity functions may well serve to significantly improve average total system performance (Ginsburg, 1979).

4. Variables which have a significant effect on contrast sensitivity (threshold) elevation will be more critical to the target acquisition task than will equivalent shifts in the ordinate value of the MTF. Such variables include noise level, and noise passband in particular (Keesee, 1976); high raster modulation (Beamon and Snyder, 1975; Snyder and Maddox, 1978); and target motion (e.g., Snyder and Greening, 1966). Similarly, even gross changes in an MTF curve which is well above the threshold curve may have little or no effect on observer performance (Gutmann et al. 1979).

5. Because the detection task is a near-threshold task, it is critical that the observer image the target on or near the fovea. Thus, visual search efficiency and speed are critical in target detection/ recognition. Variables which lengthen eye movement fixation durations and shorten inter-

fixation distances will significantly reduce target acquisition performance levels. Dynamic video noise is one such variable (Gutmann et al., 1979) which affects both the contrast sensitivity function (Keesee, 1976) and eye movement/search behavior.

6. The above is not meant to imply that MTF changes in an imaging system will have no effect on observer performance, for such is clearly not the case (Task, 1979). Rather, MTF changes will affect performance in air-to-ground target acquisition tasks, all other variables being constant. Similarly, observer tasks which are greatly dependent on high spatial frequency information will also be most sensitive to MTF shifts; such tasks include photo interpretation, image processing, radiographic image analysis, and the like. The air-to-ground target acquisition task, however, is characterized by large amounts of clutter and terrain masking which cause the target to "pop out" suddenly from its background; thus, high spatial frequency content is of little importance as most targets subtend over 0.5 to 1.0 arcdegree at detection. Similarly, alphanumeric characters, as presented in this study had spectra well above threshold and therefore benefited little from MTF changes. In general, thus, the relative importance of the MTF shift versus the contrast sensitivity (threshold) function shift may well depend upon the observer's task and the spatial frequency power spectra of the target.

Finally, the conclusions of any evaluation of any image quality metric will be affected by the experimental techniques selected. Wide ranges of image quality variation are more likely to produce high correlations due to their lack of the range restriction effect (Guilford, 1954); yet, they may also result in nonlinear correlations which, while meaningful and useful, may remain undiscovered if the investigator evaluates the relationships with only a linear regression model. Nonlinear transforms should be considered in such cases, as they have been successfully applied in related experiments (e.g., Keesee, 1976; Snyder and Maddox, 1978). Similarly, image quality variation along a single dimension, such as MTF (Task, 1979) may yield higher correlations than quality variation along two or more dimensions, as in the present experiments. Multidimensional scaling techniques should be applied to better understand these relationships.

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