# PREFACE

This report covers the work accomplished during the period 29 January 1974 through 21 November 1974 under Contract F33615-74-C-3065; Dot Matrix Symbology Study. This work was sponsored by the Flight Dynamics Laboratory of the Air Force Systems Command under Project 20200007, Multimode Matrix Displays, Capt. Wayne R. Clements, Program Manager. Capt. Gregory L. Peters (AFFDL/FGR) provided the technical direction through work unit 20200007.

The work was accomplished by the Display Systems and Human Factors Department of Hughes Aircraft Company, Centinela & Teals Streets, Culver City, California under the direction of Mr. R. J. VanderKolk, who was Project Manager.

Special acknowledgment is given to the following individuals who contributed to the project: Mr. M. D. Pruznick, who was responsible for electronic design of the simulation equipment; Mr. T. A. Bosseler, who was responsible for the development of the simulation software; and Mr. D. F. Guerin for his assistance in planning the experiments. Ms. Anita Stoudt was responsible for final editing and assembly of this technical report which was submitted on 9 May 1975.

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This report describes a concentrated effort to identify and quantify the parameters involved in the design of matrix displays for legibility and to assess the design trade-offs against the criterion of symbol legibility. A literature survey was conducted to determine what information previously existed and its applicability to matrix displays. The literature survey is included as an appendix to this report.

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20. ABSTRACT (Continued)

A series of laboratory experiments was conducted to gather data on legibility parameters where the literature survey had indicated existing data to be lacking. The following parameters were examined either in the literature survey, the laboratory studies, or both and were assessed for their effect on matrix symbol legibility: emitter size, emitter spacing, emitter shape, emitter color, active area, viewing distance, symbol subtense, viewing angle, contrast, surround luminance, symbol orientation, symbol rotation, symbol definition, x-translation, y-translation, character font, and vibration.

The following primary conclusions have been drawn as a result of the laboratory studies on matrix symbol legibility: (1) Active area has a more direct effect on legibility than have emitter size and emitter spacing individually, (2) Existing data for stroke written symbology may be drawn on to obtain design tradeoff data on symbol subtense for matrix displays, (3) For static and upright symbology, 5 x 7 matrix symbology is equally legible when compared to higher values of symbol definition, (4) When symbology is rotated within a fixed X-Y matrix array, 5 x 7 symbology is illegible; 8 x 11 symbology is marginal; and 15 x 21 symbology is equally legible when compared to stroke written symbology, (5) Illuminated symbol area may be traded directly against emitter luminance, (6) Blackwell's (1946) data with appropriate field factors may be used to obtain emitter luminance requirements.

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# 1.0 INTRODUCTION AND SUMMARY

In recent years, interest in matrix type displays has been stimulated by the development of a number of different types of flat-panel displays which utilize arrays of discrete display elements for the presentation of alphanumeric and symbolic information. The driving force behind the development of flat-panel displays has been the reduction of display volume, weight, and power requirements, all of obvious importance in aerospace applications. Typical of this class of display are light emitting diode (LED), plasma, flat panel cathode ray tubes (e.g., the Digisplay), liquid-crystal, magneto-optic, and dipole suspension displays. While a concentrated effort has been directed toward solving the engineering problems in the development of these displays, little work has been done in identifying and quantifying the parameters involved in the design of dot-matrix displays for legibility or the assessment of design trade-offs against the criterion of legibility. Although a large body of data exists on the legibility of displayed symbology, few data were obtained for dot-matrix type displays. This lack of data was recognized by the Air Force Flight Dynamics Laboratory at Wright-Patterson Air Force Base. As a result, a human factors research task was initiated as part of the Air Force's Multimode Matrix Displays program. This report describes the research performed by Hughes Aircraft Company which was one part of the Multimode Matrix Display Human Factors Research Task. The research performed by Hughes was designed to be basic in nature and applicable to matrix displays in general. The displayed symbology used in the laboratory research consisted of single alphanumeric and geometric symbols.

The work reported herein includes: 1) a literature survey, 2) a pilot study, 3) a screening study, 4) a symbol subtense study, 5) a study of the effects of symbol orientation, symbol definition, and symbol rotation, 6) a study of the effects of symbol luminance, display surround luminance, and active area, and 7) a modulation sensitivity function study.

## 1.1 LITERATURE SURVEY

The literature survey was conducted to extract the available information on legibility of matrix displays and to assess the applicability of conventional type display legibility information to dot-matrix displays. Information from 89 source documents was examined and compiled under the following topic headings:

1) Percent active area (ratio of total emitter area to total display area times 100),
2) Symbol definition (number of active elements per symbol height and symbol width),
3) Symbol subtense (angle subtended at the eye by the vertical dimension of a displayed symbol),
4) Symbol placement (the location of symbols on the display),
5) Symbol shape (geometry of non-alphanumeric symbols),
6) Emitter color (spectral characteristics of display emitter),
7) Viewing angle (angle between display axis and viewer's line-of-sight),
8) Symbol orientation (orientation angle of symbol with respect to the horizontal),
9) Symbol motion (vertical and horizontal translation and rotation about symbol centroid),
10) Character font (style of alphanumeric characters),
11) Emitter placement (physical geometry of the matrix of the active display elements),
12) Vibration (forcing function waveform applied to the viewer and the display),
13) Display surround luminance (luminance of area surrounding symbol),
14) Contrast (ratio of luminance difference to background luminance, $(B_{max} - B_{min})/B_{min}$).

From the literature survey, information was obtained to select the parameters and parameter levels used in the pilot and screening laboratory studies. The literature survey is included as Appendix A of this report.

## 1.2 LABORATORY STUDIES

The results of the literature survey revealed a general lack of information concerning many display and environmental parameters that could uniquely affect matrix display legibility. Hence, a large number of parameters was identified for investigation in the laboratory studies. This necessitated an approach to the experimental studies that would narrow down the parameters to those that had an operationally important and statistically reliable effect on legibility. The result of this approach was a serial set of studies beginning with a pilot study and a screening study designed to identify the most important parameters. These were followed by complete factorial parametric laboratory studies designed to obtain design trade-off data on the remaining parameters.

### 1.2.1 Laboratory Equipment

A digitally driven cathode ray tube (CRT) was used to simulate a matrix display. The approach used a mini-digital computer, symbol and dot generation equipment, CRT deflection amplifiers, a CRT with a P-4 phosphor and a 2-mil spot size, and equipment to modify the spatial-intensity distribution of a Gaussian shaped CRT spot to approximate the nearly uniform distribution of matrix displays. Other ancillary equipment was used to control ambient illumination, data recording, and the like. The symbols generated by the equipment were N, Q, U, V, I, 1, 3, 8, Δ, and □. Figure 1 shows what the symbols 8 and V looked like at different symbol definitions and rotations.

The laboratory equipment and the procedures used were largely the same for the six laboratory studies performed. Section 2.0 of this report contains a description of the laboratory equipment and the procedures used in each of the laboratory studies.

In Section 3.0 of this report, each of the six laboratory studies are described in detail A summary of the laboratory studies is provided in the remainder of this introduction and summary.

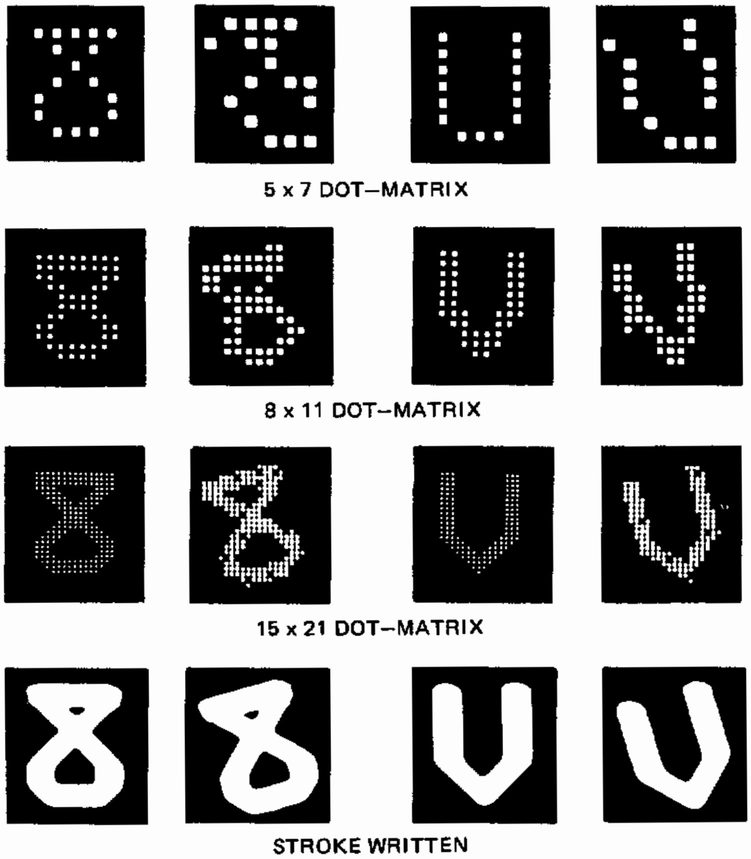


Figure 1. Examples of symbols used in the studies at four symbol definitions and two orientations.

### 1.2.2 Pilot Study

Matrix display geometry can be expressed by several parameters, namely, emitter size, emitter spacing, symbol definition, percent active area, symbol subtense, symbol height, and viewing distance. These parameters are not all independent; hence, the question of which parameters should be variable in the studies had to be resolved. The pilot study was conducted to answer this question. The results showed that percent active area, symbol definition, and symbol subtense are the parameters that should be controlled (independent variables) in the studies.

### 1.2.3 Screening Study

From the literature survey and the pilot study, ten parameters were identified as being potentially important for matrix display legibility. Because of the time and cost required to investigate 10 parameters at three or more levels and because such a large study is an inefficient method of obtaining the required information, the screening study was conducted to identify those parameters important for legibility of matrix displays.

Each of the 10 parameters was investigated at two levels (see Table 1) using a one-eighth replication fractional factorial design. With this design all main effects and two factor interactions were measurable.

Of the 10 parameters investigated, percent active area, display surround luminance, contrast, symbol subtense, and the interaction between symbol definition and symbol orientation were found to be statistically reliable and have meaningful effects on matrix symbol legibility. These parameters accounted for 56 percent of the study variance.

### 1.2.4 Symbol Subtense Study

Although symbol subtense was found to have a significant effect on matrix display legibility, it was hypothesized that the effect is common to both matrix and stroke written symbology. If the effect of symbol subtense

TABLE 1. SCREENING STUDY PARAMETERS

| Study Parameter | Levels |
|---|---|
| Percent Active Area | 11 and 64 percent |
| Symbol Definition | 7 and 21 dots/symbol height |
| Symbol Subtense | 15 and 30 arc-minutes |
| Viewing Angle | 0 and 45 degrees |
| Symbol Orientation (Static) | 0 and 15 degrees |
| Surround Luminance | 0.05 and 100 foot/Lamberts |
| Contrast | 0.5 and 3 |
| X Translation | 0 and 0.1 inches/sec |
| Y Translation | 0 and 0.1 inches/sec |
| Rotation (Dynamic) | 0 and 10 degrees/sec |

is common to stroke and matrix symbology (symbol writing mode) then the large body of existing data on symbol subtense could be applied to matrix display design and symbol subtense could be eliminated as a variable in the later parametric studies.

To test this hypothesis, matrix and stroke written symbols were investigated with 15 and 30 arcminute symbol subtenses. Surround luminances of 0.05 and 100 fL were also investigated to test for a possible three factor interaction between symbol subtense, writing mode, and an environmental parameter, i.e., surround luminance.

The results of this study showed that although the main effect of symbol subtense was statistically reliable, there was no appreciable interaction between symbol subtense and symbol writing mode, nor was there an appreciable interaction between symbol subtense, symbol writing mode, and surround luminance. It was therefore concluded that no differential effect of symbol subtense on matrix as opposed to stroke written symbology exists and that data for stroke written symbology is directly applicable to matrix display symbology.

### 1.2.5 Symbol Orientation, Symbol Definition, Symbol Rotation Study

During the course of the pilot and screening studies, it was observed that the parameters under investigation formed a dichotomy. Surround luminance, symbol luminance, contrast and percent active area have implications in terms of basic visual perception, i.e., the inherent visibility of an object. Symbol definition, rotation, and orientation are related to "higher' mental processes, involving information processing, i.e., the organization of information that is visible. As a result of this distinction, two separate performance measures were derived. For those studies investigating "information-processing" related variables, time was selected as the measure. For the study of those variables of a more psychophysical nature, display luminance or its correlates (modulation and contrast) was chosen as being a more sensitive measure.

Symbol orientation, definition, and rotation are "information-processing" related parameters and hence formed the basis for one of the formal factorial studies. Symbol orientations (initial static orientations) of 0 and 15 degrees counterclockwise from vertical; symbol definitions of 5 x 7, 8 x 11, 15 x 21 (horizontal x vertical), and stroke; and rotation rates of 0, 0.5, 5 and 10 degrees per second were investigated using a complete factorial design in which time to read alphanumeric and geometric symbols was the performance measure.

Symbol definition, static symbol orientation, and the interaction between symbol definition and static symbol orientation had statistically reliable and meaningful effects on symbol legibility. Figure 2 shows these results. With upright symbols, there was no appreciable difference in the time to read symbols for the four symbol definitions. With the 15 degree rotated symbols, the 5 x 7 symbol definition required significantly greater reading time than the 8 x 11 symbols; 8 x 11 symbols were slightly poorer than 15 x 21 symbols. The 15 x 21 and stroke written symbols were essentially equivalent in the time required to read them. Although rotation rate did not have a significant effect on symbol legibility, the general effect was for reading time to decrease as rotation rate increased. This was because with higher rotation rates, low definition symbols more quickly passed through an orientation that resulted in a legible symbol. For the 15 x 21 and stroke symbols, this effect did not occur as the symbols were legible at all orientations.

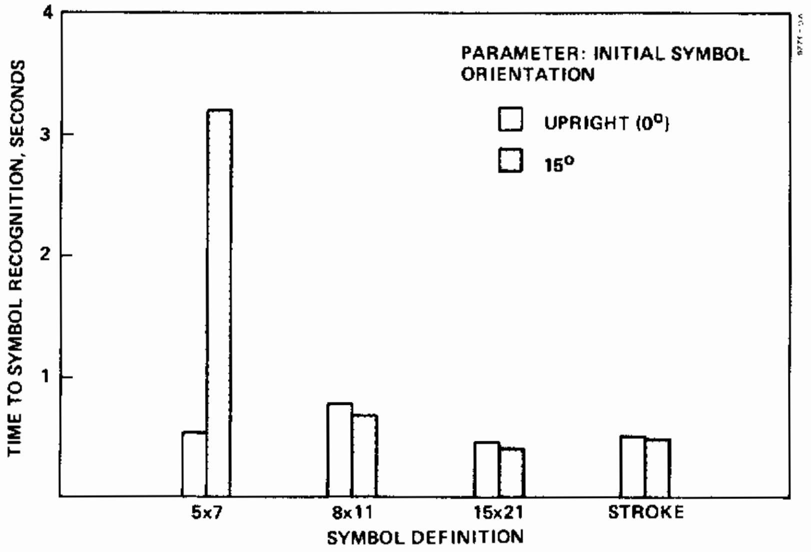


Figure 2. Average symbol recognition times as a function of symbol definition with symbol orientation as a parameter.

### 1.2.6 Symbol Luminance, Display Surround Luminance, and Active Area Study

Symbol luminance, surround luminance, and active area are psycho-physically related parameters and formed the basis for the next full factorial study. In this study, the luminance of the displayed symbols was adjusted until the subjects could correctly read them. Thus, threshold symbol luminance data were obtained by using luminance as the performance measure (dependent variable). Display surround luminances of 0.05, 5, 50, 500, and 2000 fL were investigated in combination with active areas of 4, 11, 25, 45, 64, 79, and 100 percent.

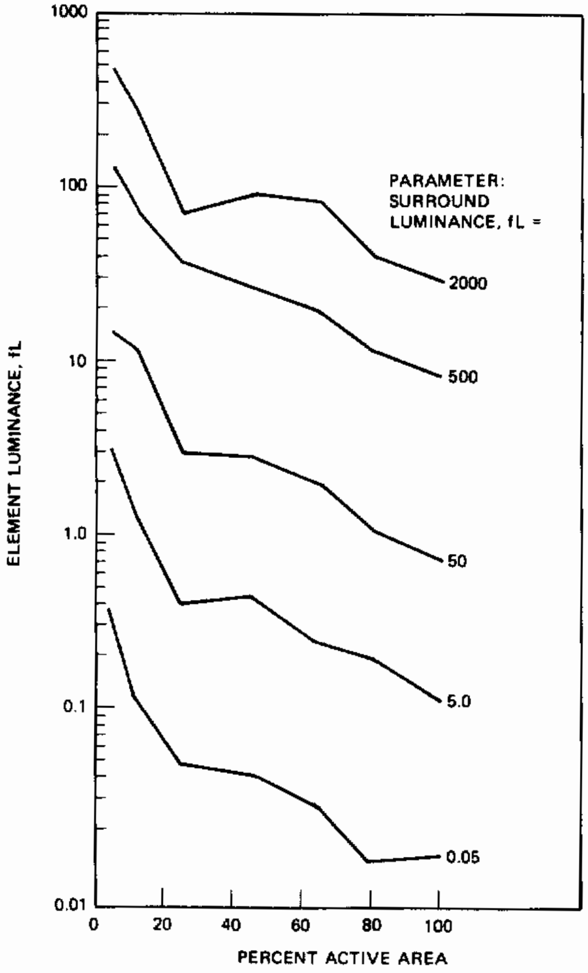


Figure 3. Threshold element luminance as a function of percent active area and surround luminance.

The results of the study are shown in Figure 3. It can be seen that for any surround luminance, required symbol element luminance decreases as active area increases. Thus, element luminance in a matrix display can be traded off with active area. The data shown in Figure 3 are for 100 percent threshold legibility. Although the symbols were legible at threshold, the luminance values would not be recommended for use in operating environments. To obtain data applicable to practical use of matrix displays, a substudy was conducted in which the subjects adjusted luminance to comfortable viewing levels for each of the surround luminance/active area conditions. From these data, element luminance field factors were derived as shown in Figure 4. With these field factors, practical levels of matrix display luminance can be obtained from threshold data.

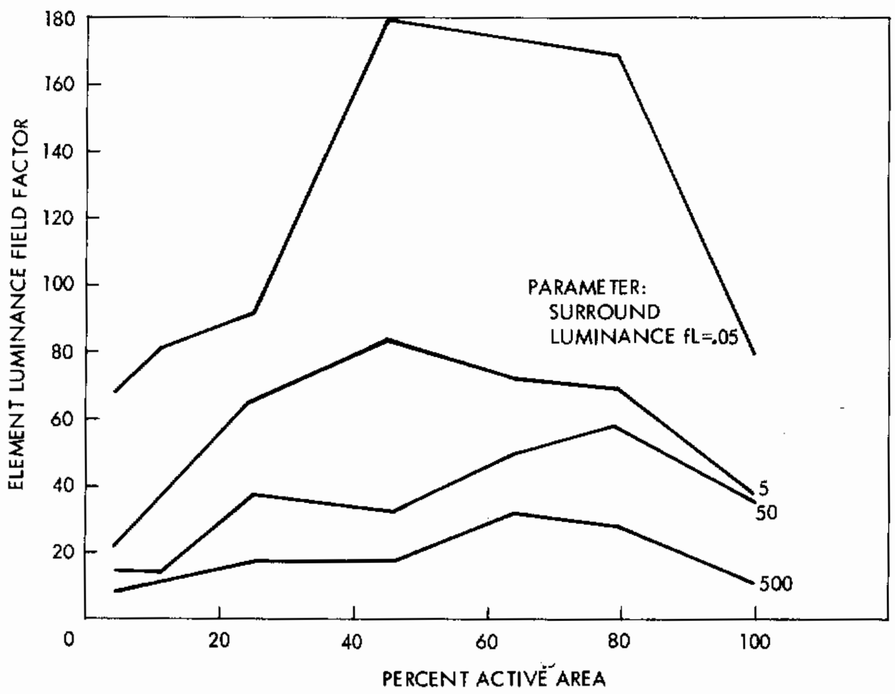


Figure 4. Field factors for converting threshold element luminance to a comfortable viewing level as a function of percent active area.

### 1.2.7 Modulation Sensitivity Study

Human modulation sensitivity function (MSF) data in conjunction with display modulation transfer function data have in recent years been used to specify display design requirements. Several MSF studies (e.g., Patel, 1966; Van Meeteren and Vos, 1972; Rogers and Carel, 1973) have been conducted, using sinusoidally modulated patterns. The new generation of flat panel displays are nearly square wave modulated. This study was conducted to obtain MSF data for near square wave modulated two-dimensional flat panel display applications and secondarily, to determine if existing MSF data obtained with sinusoidally modulated patterns are applicable to flat panel displays.

Two-dimensional, near square wave modulated dot patterns at spatial frequencies of 6, 12, and 24 cycles per degree and surround luminances (visual adaptation levels) of 0.1, 1.0, 10, and 100 fL were investigated in this study. Figure 5 is an example of the modulation pattern. The subjects adjusted element luminance, both ascending and descending trials, so

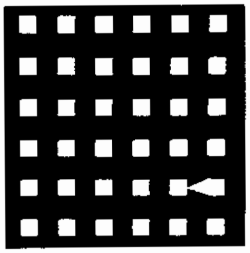


Figure 5. Example of two dimensional, square-wave modulated pattern.

that the pattern was just detectable. Threshold element luminance was converted to threshold modulation to plot the MSF results shown in Figure 6. In Figure 6, the data from this study are compared with the Rogers and Carel (1973) data. The data suggest that larger modulations are required to detect the square wave patterns. Because of differences in equipment and procedures between the present study and that of Rogers and Carel (1973), it cannot be definitively stated that square wave modulated patterns require greater modulation.

The results of this study provide a first set at MSF data for square wave modulated two-dimensional patterns. To compare square wave and sinusoidally modulated patterns, a single study with identical apparatus and procedure is required.

In the course of this research program, 17 parameters related to dot-matrix display symbol legibility were addressed in either the literature survey, the laboratory studies, or both. In Section 4. 0 of this report (Implications of the Research for Design and Use of Matrix Displays), the results of the research program are brought together and discussed in terms of matrix display design.

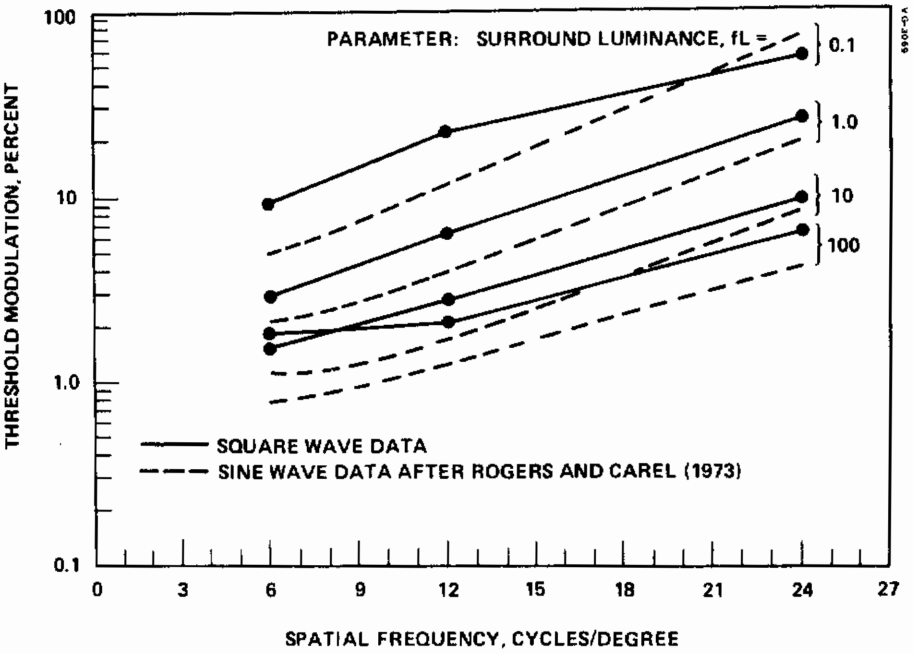


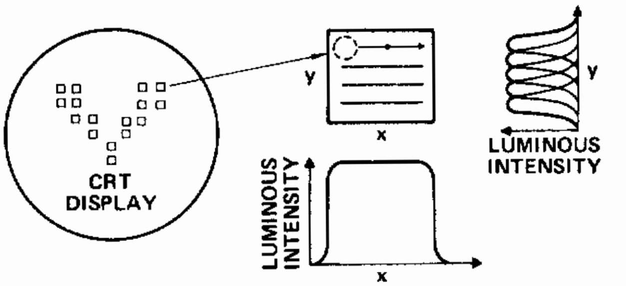
Figure 6. Modulation threshold for square and sine wave modulated patterns.

# 2.0 LABORATORY EQUIPMENT AND STUDY PROCEDURES

## 2.1 LABORATORY EQUIPMENT

The requirement for investigation of a large number of factors under controlled conditions placed severe demands on the laboratory equipment. The equipment had to be capable of exploring the full range of variables singly or in combination. This led to the selection of a digitally driven CRT to simulate a matrix display. The approach used existing computer facilities, symbol and dot generation equipment, and CRT deflection amplifiers. Additional equipment was fabricated to modify the spatial-intensity distribution of a Gaussian shaped CRT spot to approximate the more nearly uniform brightness distribution of matrix displays, e.g., a LED. This involved using a CRT with a small spot size relative to the smallest emitter to be tested and then deflecting the spot to cover the area of the individual emitters which make up the matrix. Figure 7 is an illustration of the matrix element structure. The CRT selected to meet these performance requirements was a Litton L-4248 tube. This tube has a P-4 phosphor and is capable of producing a 2-mil spot size with 500 foot-Lambert brightness. The simulation approach reproduced the physical constraints on the coordinates of each dot while the symbols were translated and rotated. This resulted in distortion of the symbol as would occur in an actual matrix display. This simulation allowed pre-programming of display parameters and the dynamic control of displayed material by the computer.

A block diagram of the simulation technique is shown in Figure 8. With this apparatus, the study parameters could be controlled and varied in a



- DISPLAY REFRESH RATE – 50 Hz
- ADJUSTABLE DISPLAY LUMINANCE – 0 TO 500 fL
- 0.002 INCH CRT SPOT SIZE
- DOTS ARE CREATED FROM MERGED RASTER SCAN

Figure 7. Detail illustration of matrix display structure.

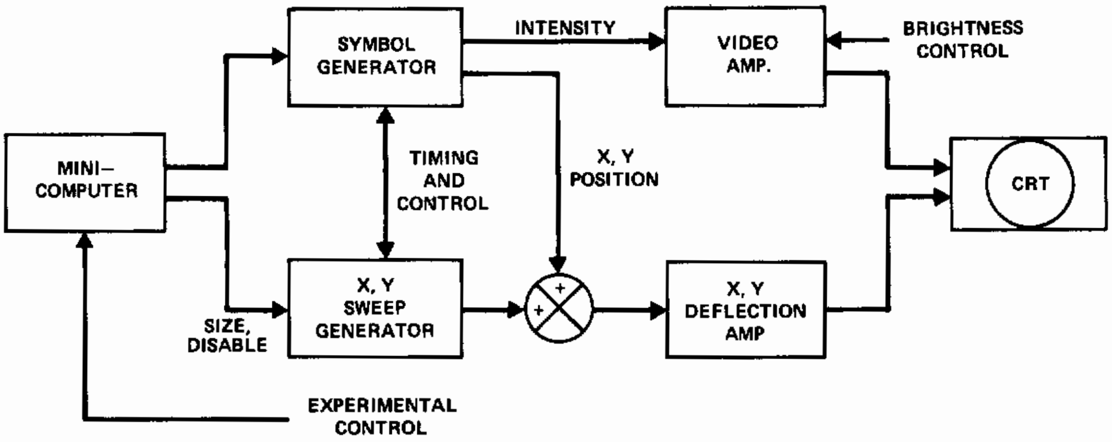


Figure 8. Matrix display simulation technique.

flexible way. The display brightness control shown is a 10-turn potentiometer. Experimental and parameter control was via paper tape input to a NOVA minicomputer. The display refresh rate was 50 Hz. Figures 9, 10 and 11 are composite photographs of the 10 symbols used in the studies, both upright and rotated, for matrix sizes of 5 x 7, 8 x 11, and 15 x 21 respectively. Apparent differences in element size and spacing reflect differences in photographic technique and are not a real effect. It is apparent in some of the photographs that there are "holes" in the matrix structure of the symbols and an explanation for this follows. The computer algorithm was such that the precise x, y position of each element was calculated and then rounded off to the nearest physical array position. Depending on the distance from the point of rotation, some of the dots have moved to a new matrix position whereas adjoining dots have not moved, thus creating "holes" and in some cases, an overwritten dot.

One of the experimental requirements was that normal stroke type symbology be used as a baseline comparison for the matrix symbols. Because the cathode ray tube used to simulate the matrix symbols required an extremely small spot size, the stroke width of symbols constructed with a single stroke was spidery and unacceptable. Consequently, four equally spaced parallel and slightly defocused strokes were used to construct the stroke symbols. The symbols were constructed to duplicate the same font used with the matrix symbols and are shown in the composite photograph of Figure 12.

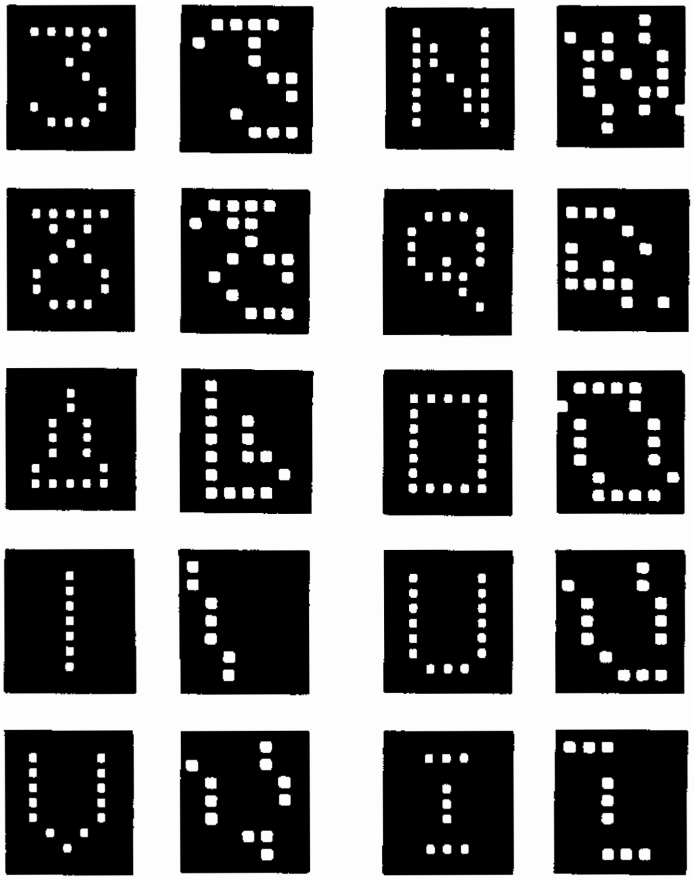


Figure 9. Upright and 15-degree off-axis 5 x 7 matrix symbols.

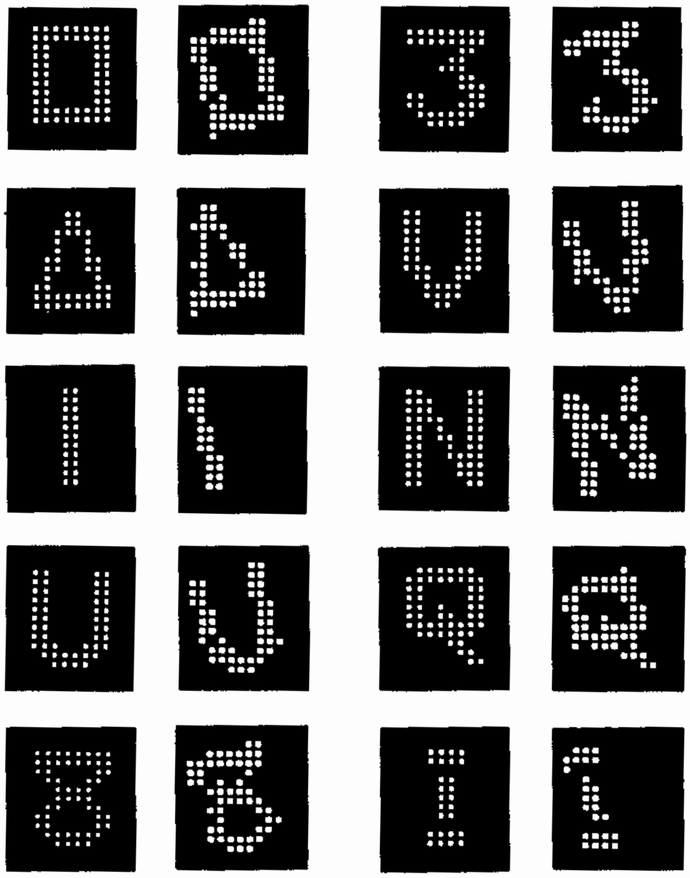


Figure 10. Upright and 15-degree off-axis 8 x 11 matrix symbols.

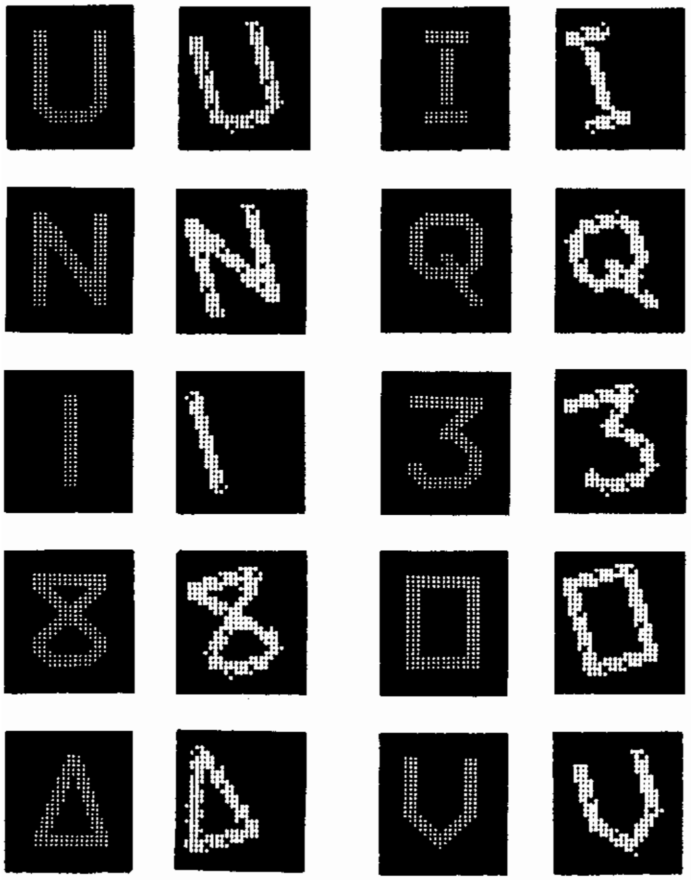


Figure 11. Upright and 15-degree off-axis 15 x 21 matrix symbols.

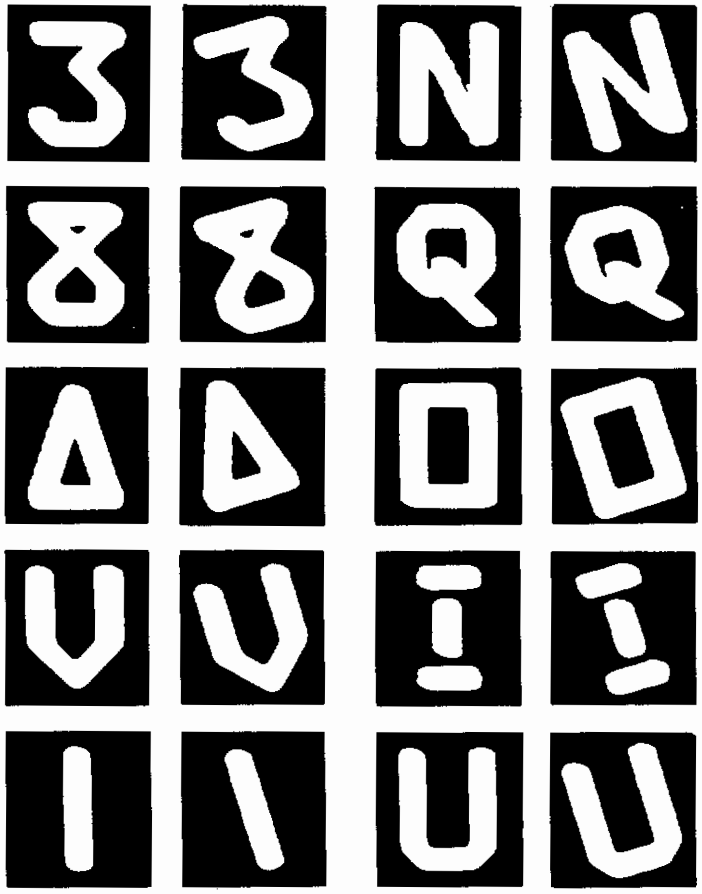


Figure 12. Upright and 15-degree off-axis stroke-written symbology.

Ambient illumination was provided by both fluorescent and incandescent sources. In all cases, color temperature was held qualitatively constant in the sense that the illumination appeared white to the eye. Surround luminance was measured as reflected from the display face and a 19-inch diameter uniformly illuminated cardboard mask surrounding the display (the reflected ambient illumination measured from both the display and the mask were nearly identical).

The viewing distance between the subject and the display face was adjusted where necessary to obtain the proper value of symbol subtense. Subjects were seated in a straight backed chair and for those conditions of 45 degrees off-axis viewing (right or left) the experimenter rotated the display rack 45 degrees with respect to the subject's line of sight. When subjects sat perpendicular to the display, they wore an "anti-reflection" black face mask and black velvet smock to prevent reflections of the subject from affecting the data.

All subjects were pretested for visual acuity at 30 inches. In addition, subjects in the screening study were also retested for visual acuity at 20 feet. Only subjects having 20/20 corrected vision or better were used for the experiments.

The order of presentation of experimental conditions was always prespecified for each subject by the experimental design and was preprogrammed by software input to the Nova minicomputer. A summary of the experimental variables and the method of control is shown in Table 2.

## 2.2 STUDY PROCEDURES

During the course of the pilot and screening studies, it was observed that the parameters under investigation formed a dichotomy. This observation was used to organize the final factorial evaluation into the several separate studies. Brightness related parameters of surround luminance, contrast, and percent active area had implications in terms of basic visual perception. Other parameters, such as symbol subtense, definition, rotation, and orientation were related to "higher" mental processes, involving information processing. As a result of this distinction, two separate

TABLE 2. PARAMETER SUMMARY AND METHOD OF CONTROL

| Parameter | Method of Control |
|---|---|
| Percent Active Area<br>Symbol Definition<br>Symbol Orientation<br>Symbol Motion | Computer control via software |
| Symbol Subtense | Viewing distance |
| Viewing Angle | Mechanical adjustment by experimenter |
| Display Background Luminance | Ambient illumination set by experimenter |
| Contrast | Display luminance and ambient illumination set by experimenter |

dependent measures were derived. For those studies investigating information-processing related variables, time was selected as the dependent measure. For the study of those variables of a more psychophysical nature, display luminance or its correlates (modulation and contrast) were chosen as being a more sensitive dependent measure.

In all the studies utilizing either time or luminance as a dependent measure, one of two sets of general procedures were followed. Consequently, to avoid needless repetition, descriptions of procedures from all of the studies have been drawn together and organized under their respective dependent measures.

The nature of the experimental studies were basic in the sense that for all studies the displayed information was a single alphanumeric or geometric symbol and the task was one of symbol identification.

### 2.2.1 Time Procedures

Symbol definition, rotation, and orientation are matrix display parameters which involve information-processing on the part of the subject. Subjects were required to make sense out of displayed symbols. Time required for correct symbol identification was an appropriate performance measure to gauge the effect of these variables.

The basic procedure followed in all studies utilizing time as a dependent measure was as follows. The experimenter established the proper levels of all variables for a given experimental trial and then handed the subject a pushbutton by which he activated the display. The subject pushed the pushbutton once, causing a symbol to appear on the display. As soon as he was able to identify the symbol, the subject pushed the button again to extinguish the symbol. Subject's time to symbol identification was automatically recorded by the Nova minicomputer which activated and deactivated the display. In those cases where the subject never recognized the symbol, the symbol was automatically removed from the display after 10 seconds, and 10 seconds was recorded as the subject's time score for that condition.

While extinguishing the symbol, subjects reported the symbol identity to the experimenter who made note of any misidentifications. In an attempt to reduce the number of misidentifications, accuracy was stressed as being of primary importance in all time related studies. Subjects were cautioned to make sure they knew the identity of the symbols before they pressed the button to extinguish the symbol.

### 2.2.1.1 Screening Study Procedures

The screening study was conducted to narrow the range of variables for later parametric examination by identifying those parameters which had a significant effect on matrix display legibility. Time served as the dependent measure in accordance with the basic procedures described above even though some of the variables did not fall into the category of variables dependent on information processing. The nature of the screening study required the use of one performance measure for all variables.

Subjects read a set of written instructions, a copy of which is included as Appendix B of this report. To familiarize the subjects with symbol geometry, they were shown all of the upright symbols as they appeared on the display.

Subjects were given two practice trials under actual experimental conditions so that they could become familiar with the procedures. All 10 symbols were seen under each experimental condition, and the order of presentation of symbols was randomized.

### 2.2.1.2 Orientation, Definition, Rotation Study Procedures

A parametric investigation of the effects of symbol definition, rate of rotation, and initial orientation angle was conducted using time as a dependent measure. The basic procedures employed were those described above.

Symbol distortion is minimal at angles which are multiples of 45 degrees. Thus, it was decided to select a static symbol orientation angle between zero and 45 degrees which would lead to considerable symbol distortion. Fifteen degrees was selected as a representative value. Regardless of how distorted a symbol might be, it is possible to train an individual to associate a particular selected name with that symbol; e.g., an individual may be trained to associate the symbol name O with quite meaningless shapes. During the definition-rotation-orientation study, subjects were purposely <u>not</u> pretrained to identify off-axis oriented or rotated symbols for this reason. If the subjects had been trained to associate given distorted images with their proper symbol names, this would not have provided information about the practical effects of distortion on symbol legibility. Consequently, subjects were shown photographs of only 5 x 7 upright symbols. Due to experimental design considerations, only eight of the ten symbols were actually utilized (N, Q, U, V, 3, 8, Δ, □). To keep from artificially restricting the range of possible responses, subjects were not informed as to the limited nature of the symbol set. The 5 x 7 character set they were shown prior to the experimental trials contained 37 symbols (the entire alphabet, the numerals 0 through 9, and a triangle). Subjects were informed that they might not see some of the symbols while others might appear more than once. A written set of instructions was given to each subject, and a copy of these is contained in Appendix C.

Subjects were tested on their knowledge of the upright 5 x 7 symbols by means of flash cards. After correctly identifying all the 5 x 7 upright symbols, subjects were given practice with the button-pushing task utilizing two symbols – I and 1. One symbol was presented with each trial or experimental condition, and the eight symbols were randomized and balanced over 32 trials for each subject.

### 2.2.2 Threshold Procedures

The effects of variables such as symbol subtense, contrast, active area, luminance and ambient illumination are not as sensitive to time as a dependent performance measure as to a measure more directly related to observer perception. The above variables were seen as influencing image visibility in such a way that they could be traded off against each other. Since display luminance could be readily and continuously varied, this parameter was chosen as the means to measure the effect of the other perceptual variables. The following studies were conducted in which threshold symbol luminance required for symbol identification was used as the dependent measure.

### 2.2.2.1 Symbol Subtense Study Procedure

A brief study was conducted to assess whether subtense differentially affected the legibility of matrix and stroke written symbology. During experimental trials, subjects were initially shown symbols below their brightness threshold. Symbol luminance was incremented step-wise by the experimenter who paused after each step to ask the subject if he could identify the symbol. Threshold level was recorded at that point where the subject first identified the symbol correctly with no subsequent corrections. The experimenter continued to increment symbol luminance after the subject had correctly identified the symbol to insure that the identification did not constitute a "lucky guess". When subjects subsequently changed their minds, their initial correct response was not taken as their visual threshold. It was the first correct response, of three successive correct responses, which was recorded as threshold.

To prevent subjects personalities from influencing their threshold levels (conservative subjects might be expected to wait until the symbols were brighter so they could be sure of what the symbols were before attempting an identification, while less conservative subjects might be more inclined to guess on the basis of less information), all subjects were instructed to guess as soon as they saw anything at all and were to continue making a verbal response at every step subsequent to this point.

Subjects were shown only one symbol under each condition and were informed that a given symbol could appear more than once. In this way, subjects were effectively prevented from guessing symbol identities on the basis of information gained from previous trials.

All subjects read a set of written instructions which are contained in Appendix D. To familiarize the subjects with the symbols, subjects were shown the eight matrix symbols and the eight stroke-written symbols on the display. All the subjects used in the subtense study had previously participated in the screening study, all were familiar with the symbol font. Subjects were given two training trials under actual experimental conditions to familiarize them with experimental procedures.

### 2.2.2.2 Active Area-Surround Luminance Study Procedures

A parametric investigation of percent active area and surround luminance was conducted utilizing threshold symbol luminance as the dependent measure. The basic experimental procedures were the same as those discussed above for the Symbol Subtense Study.

Subjects were given written instructions which are reproduced in Appendix E. They were also given three training trials under actual experimental conditions to familiarize themselves with the experimental procedures.

In addition to the parametric data gathered for threshold symbol luminance, a small substudy using two subjects was conducted to determine the symbol luminances required for comfort level viewing. Here subjects were given control over the symbol luminance potentiometer and were instructed to set symbol luminance to that level they considered to be comfortable for viewing under the various experimental conditions. In other words, they were instructed to set the display where they normally would for an operational display.

### 2.2.2.3 Modulation Sensitivity Function Study Procedures

A modulation sensitivity study was conducted to determine the discriminability of square wave modulated patterns as compared to sine wave modulated patterns. This study differed from the previous studies in that a square field of square wave modulated dots was displayed instead of a symbol. The intent was to relate the results of this study to those obtained in previous modulation sensitivity function studies, e.g., Rogers and Carel (1973) and Patel (1966) which used sinusoidally modulated patterns, and Campbell and Robson (1968) which used square-wave modulated patterns in one dimension, and thereby determine how past research of this nature should be applied to matrix display design. A photograph of typical patterns of different field size is shown in Figure 13. Threshold modulation was utilized as the dependent variable, and the subject was given control of the 10-turn display luminance potentiometer. Subjects were instructed to set their "minimum detectable threshold" or that point at which the pattern was just barely visible. A further description of minimum detectable threshold is given in the written instructions to subjects included as Appendix F.

The specific procedures followed in the modulation sensitivity study were as follows. The experimenter adjusted the pattern luminance knob so that the pattern was visible to the subject on the first trial of any condition.

Figure 13. Two-dimensional, square-wave modulated patterns for two field sizes.

The subject was then handed the display luminance control and requested to set his descending minimum detectable threshold. Subjects were allowed to overshoot and use the control knob to bracket their threshold region. After completing the setting, the experimenter measured the element luminance with a photometer and then adjusted the pattern brightness downward until it was no longer visible on the display. The subject was then instructed to set his second (ascending) minimum detectable level. The two measures were averaged for each trial.

# 3.0 LABORATORY STUDIES

## 3.1 PILOT STUDY

### 3.1.1 Introduction and Purpose

During the initial phases of the program, there was considerable debate as to the relative propriety of various ways of combining or grouping several display geometry parameters. The parameters in question were dot size, dot spacing, symbol definition, percent active area, symbol subtense, symbol height, and viewing distance. These parameters are not all independent, and it was not necessarily desirable to quantitatively examine all of them. As used here, dot size is the length of the sides of the square active elements and dot spacing is the center to center spacing of the elements.

The purpose of this informal pilot study was to resolve the foregoing issues and to determine which parameters should be examined in the formal screening study. Actually, two pilot studies were conducted, in which the parameters were dot size, dot spacing, and symbol definition. The resulting data were also plotted in terms of percent active area defined as:

$$\text{Percent Active Area} = \left(\frac{\text{Dot Size}}{\text{Dot Spacing}}\right)^2 \times 100 \ .$$

The levels of each parameter that were used were:

Dot Size: 0.005 and 0.020 inch
Dot Spacing: 0.010, 0.025, and 0.040 inch
Symbol Definition: 7 and 21 dots per symbol height

Once dot size, dot spacing, and symbol definition are selected, symbol height is directly determined. In the first study, viewing distance was held constant at 30 inches which in turn forced symbol subtense to float. In the second study, symbol subtense was held constant at 15 arc-minutes and viewing distance floated. In each study, data were collected for two subjects. Display surround luminance was held constant at 11 foot-Lamberts. Displayed symbols were upright, stationary, and had a contrast of 4.

The subject's task was to activate the display with a hand-held pushbutton and report the displayed character as rapidly as possible while at the same time deactivating the display again with the pushbutton. The performance measure was the time required to recognize the displayed symbol.

### 3.1.2 Results and Discussion

The results of the first study are presented in Table 3. It is apparent that the subjects become limited by their reaction time as the symbol subtense increased beyond about 30 arc-minutes. Thus it appeared inappropriate to hold a fixed viewing distance and allow subtense to float. For this task and performance measure, the effect of an uncontrolled subtense

TABLE 3. RESULTS OF PILOT STUDY 1

Fixed Conditions:

Surround Luminance = 11 fL
Contrast = 4.0
Viewing Angle = 0 Degrees
Viewing Distance = 30 Inches

| Symbol Definition | Dot Size, Inches x $10^{-3}$ | Dot Spacing, Inches x $10^{-3}$ | Percent Active Area | Symbol Subtense, Arc-Min | Average Response Time, Millisecs |
|---|---|---|---|---|---|
| 7 | 5 | 10 | 25 | 8 | 1,530 |
| 7 | 5 | 25 | 4 | 18 | 1,020 |
| 7 | 20 | 25 | 64 | 20 | 336 |
| 7 | 20 | 40 | 25 | 30 | 306 |
| 21 | 5 | 10 | 25 | 24 | 256* |
| 21 | 5 | 25 | 4 | 58 | 234* |
| 21 | 20 | 25 | 64 | 60 | 240* |
| 21 | 20 | 40 | 25 | 94 | 225* |

*Reaction Time Limited

predominated and obscured the effect of other variables. No other conclusions are drawn from the data presented in Table 3.

The results of the second study are summarized in Table 4 and Figure 14. It is evident that dot size, dot spacing, and percent active area all show an effect; however, the means in the graphs for dot size and dot spacing have very high variances associated with them while the means for percent active area have rather small variances. Table 4 presents response times averaged across 10 symbols and illustrates this fact. This suggests that the variable of percent active area has a greater and more reliable effect on performance that dot size and dot spacing. It is the judgment of the authors that the effect of active area is even more dramatic than evidenced in the data.

TABLE 4. RESULTS OF PILOT STUDY 2

Fixed Conditions:

Surround Luminance = 11 fL
Contrast = 4.0
Viewing Angle = 0 Degrees
Symbol Subtense = 15 Arc-Min

| Symbol Definition | Dot Size, Inches x $10^{-3}$ | Dot Spacing, Inches x $10^{-3}$ | Percent Active Area | Average Response Time, Millisecs | |
|---|---|---|---|---|---|
| | | | | Subject 1 | Subject 2 |
| 7 | 5 | 10 | 25 | 460 | 617 |
| 7 | 5 | 25 | 4 | 1,420 | 1,165 |
| 7 | 20 | 25 | 64 | 405 | 531 |
| 7 | 20 | 40 | 25 | 374 | 509 |
| 21 | 5 | 10 | 25 | 332 | 791 |
| 21 | 5 | 25 | 4 | 2,490 | 1,759 |
| 21 | 20 | 25 | 64 | 339 | 412 |
| 21 | 20 | 40 | 25 | 332 | 376 |

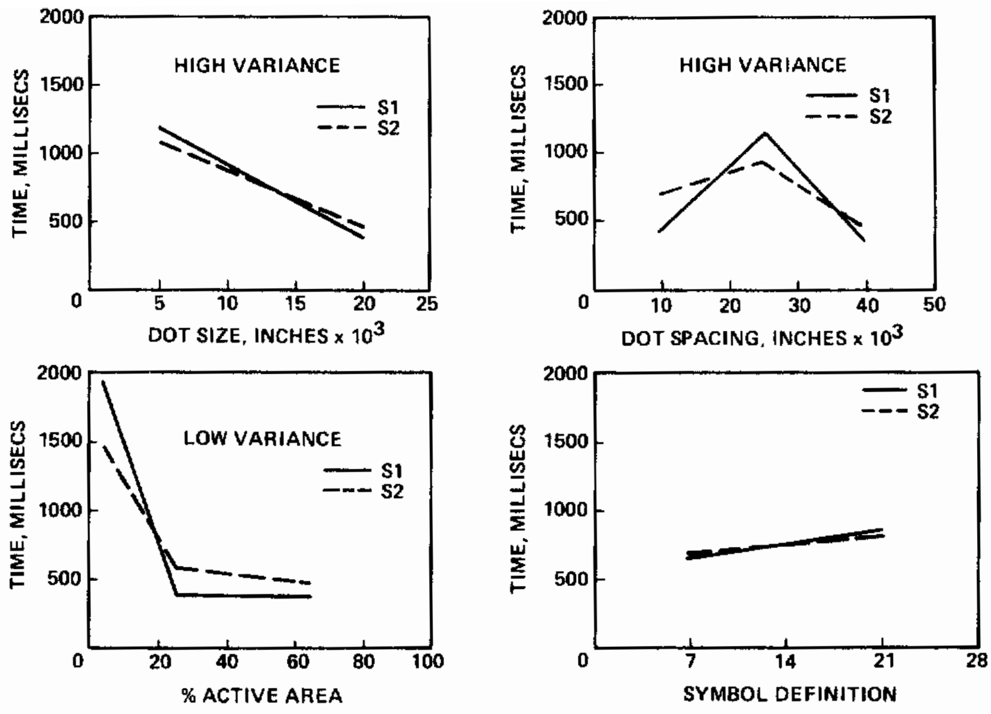


Figure 14. Results of pilot study 2.

Although the effect of symbol definition is not strong in the data, it will be seen that this parameter has a strong interaction with symbol orientation. Examination in the laboratory has shown that 5 x 7 dot-matrix symbols become distorted when in a non-upright orientation whereas the 15 x 21 dot-matrix symbols do not distort appreciably. The slight trend toward slower response times as symbol definition increases that is evident from Figure 14 is the reverse of that which would be expected. The cause of this effect will be discussed with the results of the screening study.

The conclusion drawn from these data is that percent active area, symbol definition, and symbol subtense are the critical parameters which best describe basic dot-matrix display geometry, and it was these parameter that should be examined in the formal screening study.

## 3.2 SCREENING STUDY

### 3.2.1 Purpose

Because of the large number of variables identified as potentially contributing to matrix symbol legibility and the fact that little a priori knowledge was available as to how these variables interacted, the research strategy was to narrow the number of parameter combinations by means of a screening study prior to conducting formal parametric research.

A formal factorial experiment using a complete range of values for all the variables of interest was neither an intelligent nor parsimonious way of gathering the required information. A single factorial replication would have required millions of trials. A formal experiment of this magnitude would have been very expensive and included variables that were non-contributory.

The purpose of the screening study was to determine which of the large number of parameters had a significant effect on matrix display legibility. By selecting only those parameters so identified, reasonably sized factorial parametric studies could then be designed.

### 3.2.2 Experimental Parameters

The experimental parameters that were examined in the screening study are summarized in Table 5. These are the parameters identified in the literature survey as lacking information applicable to the design of matrix displays and by the pilot study as being critical parameters that affect matrix display legibility.

### 3.2.3 Experimental Design

The screening study utilized two levels of each parameter as noted in Table 5. The experimental design utilized a $2^{10}$ fractional factorial design, i.e., 10 factors at two levels each. A one-eighth replication was conducted; thus, 128 data points were examined out of the total 1,024 possible. These data points were blocked into eight blocks (subjects) with 16 experimental conditions within each block. This design allowed all main effects and two

TABLE 5. SCREENING STUDY PARAMETERS

| Study Parameter | Levels |
|---|---|
| Percent Active Area | 11 and 64 percent |
| Symbol Definition | 7 and 21 dots/symbol height |
| Symbol Subtense | 15 and 30 arc-minutes |
| Viewing Angle | 0 and 45 degrees |
| Symbol Orientation (Static) | 0 and 15 degrees |
| Surround Luminance | 0.05 and 100 foot-Lamberts |
| Contrast | 0.5 and 3 |
| X Translation | 0 and 0.1 inch/sec |
| Y Translation | 0 and 0.1 inch/sec |
| Rotation (Dynamic) | 0 and 10 degrees/sec |

factor interactions to be measured under the assumption that higher interactions were negligible. For more detailed information on the particular experimental design used, the reader is referred to Plan 8.10.16 in Fractional Factorial Experimental Designs for Factors at Two Levels, National Bureau of Standards, Applied Mathematics Series Number 48.

The factors in Table 5 were represented as A, B, C, D, E, F, G, H, J, and K respectively. In Table 6, the combinations of factors that were applied to the individual experimental units are denoted by lower-case letters. The presence of a letter indicates the high level of that factor; its absence denotes the the low level. The symbol (1) is used to indicate that treatment where all factors are at the low level.

Procedures used during this study were similar to those utilized in the pilot study wherein the subject utilized a hand-held pushbutton to activate and deactivate the display with time to correct identification being the performance measure. A detailed description of the procedures is presented in Section 2.2.1.1.

### 3.2.4 Results and Discussion

The subjects were presented 10 symbols under each experimental condition. For purposes of analysis, the time-to-identification scores for the correctly identified symbols within a given condition were averaged to

## TABLE 6. SUBJECT TREATMENT CONDITIONS FOR LABORATORY SCREENING STUDY

Subjects

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| (1) | bcdegjk | abdfhjk | acefgh | aegjk | abcd | bdefgh | cfhjk |
| bdfj | cefgk | ahk | abcdeghj | abdefgk | acfj | eghj | bcdhk |
| beghk | cdhj | adefgj | abcfk | abhj | acdeghk | dfk | bcefgj |
| defghjk | bcfh | abeg | acdjk | adfh | abcefghjk | bjk | cdeg |
| abchjk | adegh | cdf | befgjk | bcegh | dhjk | acdefgjk | abf |
| acdfhk | abefghj | bcj | degk | cdefghj | bfhk | abcegk | adj |
| acegj | abdk | bcdefhk | fhj | ck | bdegj | abcdfhj | aefghk |
| abcdefg | afjk | ceghjk | bdh | bcdfjk | efg | ach | abdeghjk |
| bcfghj | defhk | acdgk | abej | abcefhk | adfghj | cdej | bgk |
| cdgh | behjk | abcfgjk | adef | acdehjk | abgh | bcef | dfgjk |
| cefjk | bdfg | abcdeh | aghjk | acfg | abdefjk | bcdghjk | eh |
| bcdek | gj | acefhj | abdfghk | abcdgj | aek | cfghk | bdefhj |
| afgk | abcdefj | bdghj | cehk | efj | bcdfgk | abdehk | acghj |
| abdgjk | ace | fgh | bcdefhjk | bde | cgjk | aefhjk | abcdfgh |
| abefh | acdfghjk | dejk | bcg | bfghjk | cdefh | adg | abcejk |
| adehj | abcghk | befk | cdfgj | dghk | bcehj | abfgj | acdefk |

provide a single time score for that condition. As the importance of accuracy was stressed in the instructions to subjects, misidentifications were few in number and were excluded from the numerical analysis. However, these incorrect identifications were entered into a confusion matrix to provide an index of the most easily confusable symbols (see Figure 15). In this matrix, the numbers in the vertical column below each symbol represent the number of times that symbol was erroneously identified as the symbol at the left-hand side of the matrix. As can be seen from the confusion matrix, the two most easily confused sets of symbols were the U and V and the 8 and 3. This result, as well as the other symbol confusions, were to be anticipated as the symbol set was originally selected so as to contain pairs of easily confused symbols.

An analysis of variance was performed on the average time-to-identification scores. The results of this analysis are presented in Table 7. The results for each parameter will be discussed, followed by a discussion of two factor interactions that were statistically significant ($p < 0.05$) in the analysis of variance. The statistic Eta$^2$ was calculated for all main effects and two factor interactions to establish the percent of variance accounted for by that factor.

### 3.2.4.1 Percent Active Area

The main effect of percent active area is shown in Figure 16 and was significant at $p < 0.001$. Average time to symbol recognition was 4.3 seconds for 11 percent active area symbols compared to 1.48 seconds for 64 percent active area symbols. The main effect of percent active area accounted for 18.1 percent of the experimental variance. To interpret these results, it is necessary to consider the relationship between dot luminance from which the measure of contrast is derived and percent active area. Although these parameters were orthogonal in the study, they both affect the perceived symbol brightness which is largely what the observer

TRUE IDENTITY

| RESPONSE | I | N | Q | U | V | 1 | 3 | 8 | △ | □ |
|---|---|---|---|---|---|---|---|---|---|---|
| I | | | | | | | | | | |
| N | 1 | | | | | | | | | |
| Q | | | | | | | | | | 1 |
| U | | | | | 3 | | | | 1 | 2 |
| V | | 2 | | 2 | | | | | | |
| 1 | 2 | | | | | | | | | |
| 3 | | | | | | | | 4 | | |
| 8 | | | | | | | | | | |
| △ | | | | 1 | | | | | | |
| □ | | | | | | | | | | |

Figure 15. Confusion matrix of symbols for screening study.

# TABLE 7. ANALYSIS OF VARIANCE SUMMARY FOR SCREENING STUDY

A — Static Symbol Orientation
B — X Translation
C — Y Translation
D — Rotation (Dynamic)
E — Percent Active Area
F — Symbol Definition
G — Symbol Subtense
H — Viewing Angle
J — Surround Luminance
K — Contrast

| Source | df | SS | MS | F | P | $Eta^2$ |
|---|---|---|---|---|---|---|
| A | 1 | 0.39250 | Same as SS with 1 df | 0.159 | | |
| B | 1 | 0.90350 | | 0.366 | | |
| C | 1 | 0.05986 | | 0.024 | | |
| D | 1 | 1.553 | | 0.629 | | |
| E | 1 | 255.893 | | 103.602 | 0.001 | 18.08 |
| F | 1 | 5.458 | | 2.210 | | |
| G | 1 | 105.142 | | 42.568 | 0.001 | 7.43 |
| H | 1 | 5.179 | | 2.097 | | |
| J | 1 | 226.568 | | 91.728 | 0.001 | 16.01 |
| K | 1 | 180.657 | | 73.140 | 0.001 | 12.77 |
| AB | 1 | 0.044 | | 0.018 | | |
| AC | 1 | 0.118 | | 0.048 | | |
| AD | 1 | 0.020 | | 0.008 | | |
| AE | 1 | 5.010 | | 2.029 | | |
| AF | 1 | 29.055 | | 11.763 | 0.005 | 2.05 |
| AG | 1 | 8.104 | | 3.281 | | |
| AH | 1 | 2.384 | | 0.965 | | |
| AJ | 1 | 1.970 | | 0.797 | | |
| AK | 1 | 14.288 | | 5.785 | 0.025 | 1.01 |
| BC | 1 | 1.602 | | 0.649 | | |
| BD | 1 | 0.0003 | | 0.001 | | |

(Continued next page)

(Table 7, continued)

| Source | df | SS | MS | F | P | Eta$^2$ |
|---|---|---|---|---|---|---|
| BE | 1 | 4.401 | | 1.782 | | |
| BF | 1 | 0.751 | | 0.304 | | |
| BG | 1 | 0.567 | | 0.229 | | |
| BH | 1 | 4.305 | | 1.743 | | |
| BJ | 1 | 1.334 | | 0.540 | | |
| BK | 1 | 1.342 | | 0.543 | | |
| CD | 1 | 0.014 | | 0.006 | | |
| CE | 1 | 7.666 | | 3.104 | | |
| CF | 1 | 0.858 | | 0.347 | | |
| CG | 1 | 8.376 | | 3.391 | | |
| CH | 1 | 0.010 | | 0.004 | | |
| CJ | 1 | 4.157 | | 1.683 | | |
| CK | 1 | 10.572 | | 4.280 | 0.05 | 0.75 |
| DE | 1 | 0.001 | | 0.0004 | | |
| DF | 1 | 0.051 | | 0.021 | | |
| DG | 1 | 1.366 | | 0.553 | | |
| DH | 1 | 0.054 | | 0.022 | | |
| DJ | 1 | 2.072 | | 0.839 | | |
| DK | 1 | 0.139 | | 0.056 | | |
| EF | 1 | 2.198 | | 0.890 | | |
| EG | 1 | 22.411 | | 4.073 | 0.005 | 1.58 |
| EH | 1 | 4.810 | | 1.947 | | |
| EJ | 1 | 60.588 | | 24.530 | 0.001 | 4.28 |
| EK | 1 | 70.036 | | 28.355 | 0.001 | 4.95 |
| FG | 1 | 2.119 | | 0.858 | | |
| FH | 1 | 0.960 | | 0.388 | | |
| FJ | 1 | 4.819 | | 1.951 | | |
| FK | 1 | 0.157 | | 0.064 | | |

(Continued next page)

(Table 7, concluded)

| Source | df | SS | MS | F | P | Eta$^2$ |
|---|---|---|---|---|---|---|
| GH | 1 | 1.849 | | 0.748 | | |
| GJ | 1 | 25.904 | | 10.487 | 0.005 | 1.83 |
| GK | 1 | 2.751 | | 1.114 | | |
| HJ | 1 | 2.375 | | 0.962 | | |
| HK | 1 | 5.615 | | 2.273 | | |
| JK | 1 | 30.778 | | 12.461 | 0.001 | 2.18 |
| Blocks | 7 | 124.85 | 17.835 | 7.22 | 0.001 | 8.82 |
| Error | 65 | 160.40 | 2.47 | | | |
| Total | | 1415.033 | | | | 81.74 |

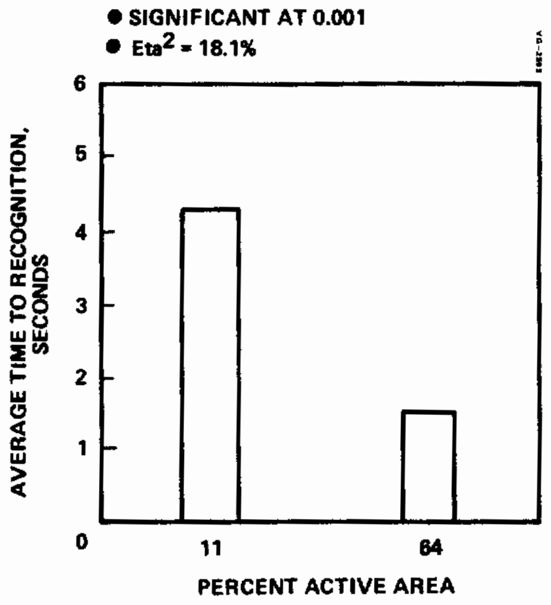


Figure 16. Effect of percent active area on symbol legibility.

responds to. With emitter luminance held constant, perceived symbol brightness increases with increased active area due to the larger emitting area which results in a greater total luminous flux per symbol. Hence, the effect of percent active area can be interpreted as primarily an effect due to increased perceived symbol brightness with increased percent active area.

### 3.2.4.2 Display Surround Luminance

The main effect of display surround luminance (adaptation level) is shown in Figure 17. This effect was statistically significant at $p < 0.001$ and accounted for 16 percent of the experimental variance. As seen in Figure 17, faster time scores were obtained for symbols displayed with the 100-fL surround than for symbols displayed under the 0.05-fL surround. Symbol identification times for the 100-fL surround were 1.56 seconds compared with the 4.23 seconds required for symbols presented under 0.05-fL surround.

It must be stated that throughout these experiments surround luminance is equal to the observer's adaptation level. There was no mismatch between the inactive display luminance and the surround luminance. Perceptually, the observer is probably reacting to the total symbol brightness of which the surround luminance is but one component; i.e., $B_{\text{symbol}} = B_{\text{surround}} + B_{\text{active element}}$. This effect has been observed in numerous experiments to date.

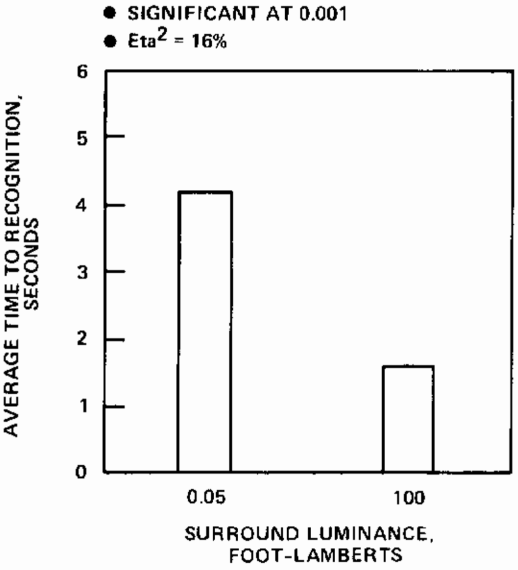


Figure 17. Effect of surround luminance on symbol legibility.

### 3.2.4.3 Contrast

In this study, contrast was defined as

$$C = \frac{B\ \text{max} - B\ \text{min}}{B\ \text{min}},$$

where B max = emitted dot luminance plus the reflected luminance of the ambient illumination and B min = the reflected luminance of the ambient. Two levels of contrast were investigated: 0.5 and 3.0. As seen in Figure 18, significantly faster times ($p < 0.001$) were obtained under high contrast conditions than under low contrast. An average of 1.71 seconds was required for symbol identification at a contrast of 3.0 compared with 4.08 seconds for the 0.5 contrast. The main effect of contrast accounted for 12.77 percent of the experimental variance.

### 3.2.4.4 Symbol Subtense

Symbol subtenses of 15 and 30 minutes of arc were investigated. As seen in Figure 19, the main effect of symbol subtense was highly significant ($p < 0.001$), with faster time scores for the larger subtense. Required time decreased from 3.8 seconds to 1.99 seconds as subtense increased from 15 to 30 minutes of arc. This effect accounted for 7.4 percent of the experimental variance.

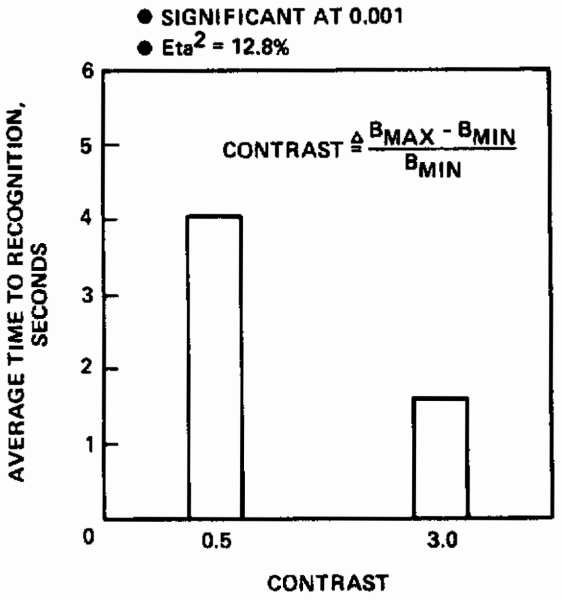


Figure 18. Effect of contrast on symbol legibility.

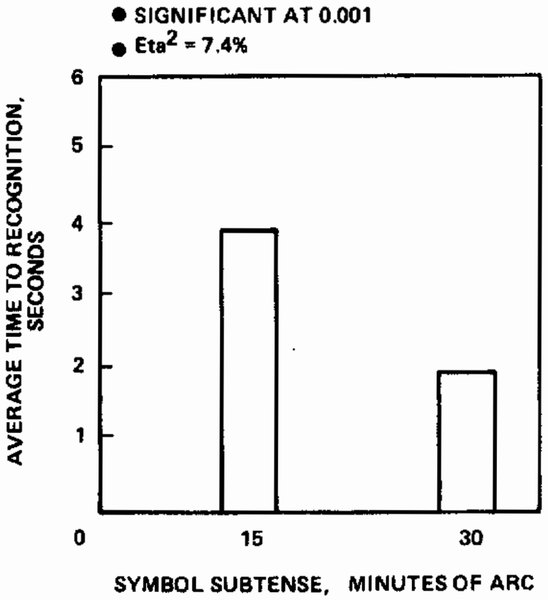


Figure 19. Effect of symbol subtense on symbol legibility.

### 3.2.4.5 Symbol Definition

The parameter symbol definition was defined as the number of dots in the vertical dimension available for the construction of a symbol. The two levels investigated were 7 and 21 dots per symbol height. Since each vertical definition was associated with a particular horizontal definition (7 with 5, 21 with 15), symbol definition was synonymous with matrix size. As seen in Figure 20, time required for symbol identification was lower for the 15 x 21 matrix symbols (2.69 seconds compared with 3.10 seconds required for 5 x 7 matrix symbols); this effect was not statistically reliable ($p > 0.2$). In addition, the $\text{Eta}^2$ value showed that this effect accounted for only 0.4 percent of the experimental variance. While the main effect of symbol definition was small when averaged over all viewing conditions, there was a significant interaction observed between static symbol orientation and symbol definition. A discussion of this interaction will follow.

### 3.2.4.6 Static Symbol Orientation

The two levels of symbol orientation that were investigated were upright symbols and symbols rotated 15 degrees counterclockwise. Pre-experimental evaluation showed that the 5 x 7 symbols appeared distorted when slanted with respect to the physical matrix and that the 15 x 21 symbols did not appreciably distort. Figure 21 illustrates this effect. Thus it was anticipated that any effect of static symbol orientation, if it occurred, would be most pronounced for the 5 x 7 matrix symbols. Indeed, while Figure 22 showed no effect due to static-symbol orientation, a significant interaction ($p < 0.005$) was obtained between static symbol

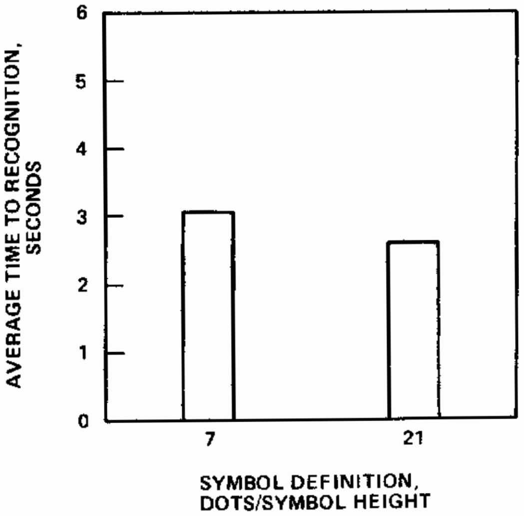


Figure 20. Effect of symbol definition on symbol legibility (not statistically significant).

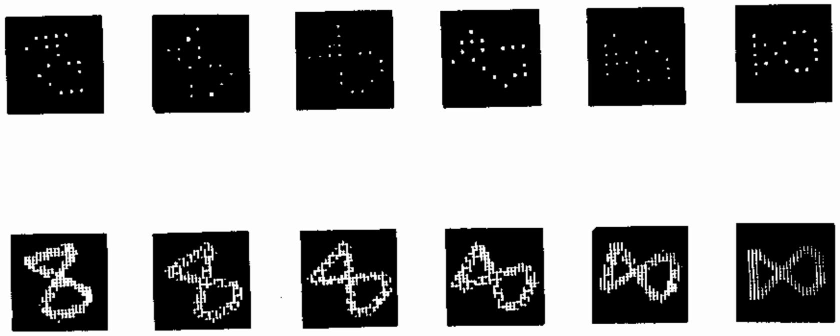


Figure 21. Illustrated effect of symbol orientation for 5 x 7 and 15 x 21 matrix symbology.

orientation and symbol definition. This interaction will be discussed later.

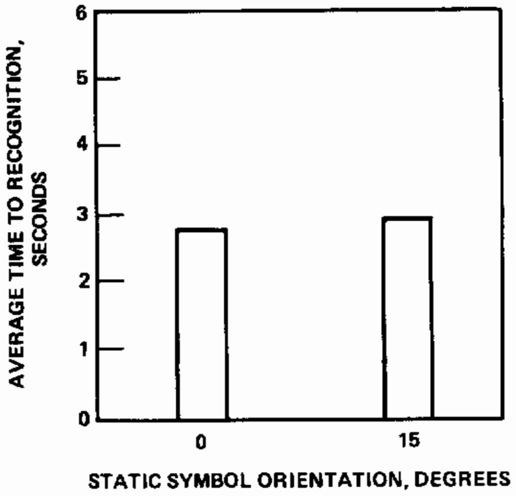


Figure 22. Effect of symbol orientation on symbol legibility (not statistically significant).

### 3.2.4.7 Viewing Angle

The two levels of viewing angle investigated were 0 and 45 degrees off-axis. To achieve the off-axis angle, the display was rotated relative to the subject's line of sight. For each subject, the display was rotated both 45 degrees to the right and 45 degrees to the left an equal number of times. While there was a tendency for off-axis presented symbols to require longer times for identification, as shown in Figure 23 (3.1 seconds for off axis symbols compared with 2.69 seconds for straight-on symbols), the difference was not significant ($p > 0.10$) and accounted for only 0.4 percent of the experimental variance. Viewing angle was not found to reliably interact with any other variables. Although many studies have shown viewing angle to directly affect legibility, the nature of this task and performance measure did not show it to have a strong effect. Further, there is no reason to suspect that viewing angle affects matrix symbology as opposed to stroke written symbology in a differential manner. However, due to the unique characteristics of some physical display media, i.e., directional emitters and reflectance properties, there is reason to suspect specific variations across display devices.

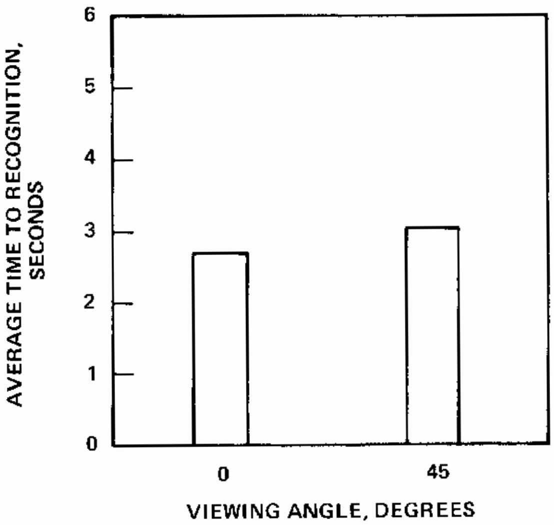


Figure 23. Effect of viewing angle on symbol legibility (not statistically significant).

### 3.2.4.8 X Translation, Y Translation, and Rotation

Three factors involving symbol motion were investigated: X-axis translation, Y-axis translation, and symbol rotation. The levels of the factors investigated were as follows: X and Y translation — 0 and 0.1 inch/sec; symbol rotation 0 and 10 degrees/sec. As seen in Figures 24, 25 and 26, no appreciable effects were observed for any of the motion factors. It must be pointed out, however, that motion of a greater magnitude probably would be a significant factor. It happened that with the simulation technique utilized in this experiment, greater magnitudes of motion were not feasible. It may also be that effects of rotation would show up at lower rates, and for this reason rotation was examined further in the parametric studies (see Section 3.4).

### 3.2.4.9 Interaction of Symbol Definition and Symbol Orientation

As seen in Figure 27, the effect of 15 degrees of off vertical orientation was more detrimental for 5 x 7 dot symbols than for 15 x 21 dot symbols. Time to identification was 3.63 seconds for slanted 5 x 7 symbols compared to 2.27 seconds for slanted 15 x 21 dot symbols. This static symbol orientation by definition interaction was significant at the $p < 0.005$ level, and

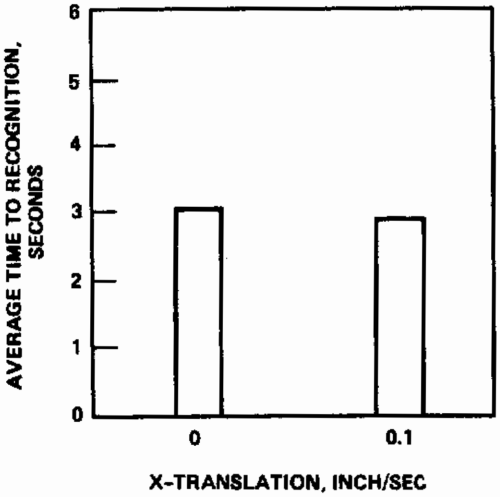


Figure 24. Effect of X translation on symbol legibility (not statistically significant).

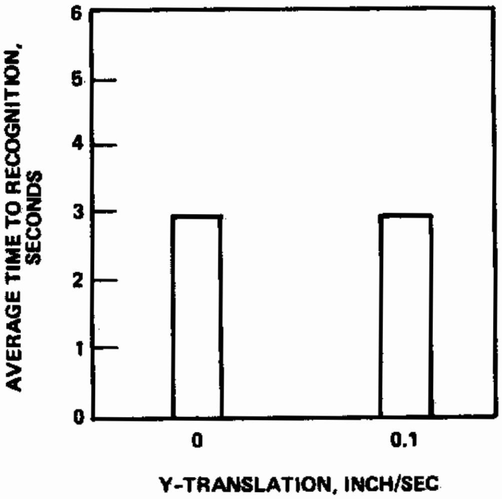


Figure 25. Effect of Y translation on symbol legibility (not statistically significant).

calculation of the statistic Eta$^2$ showed that this interaction accounted for 2.1 percent of the experimental variance.

From Figure 27, it appears that upright 15 x 21 dot symbols required longer time for recognition than upright 5 x 7 dot symbols. This result is most likely an artifact resulting from a confounding of symbol definition and illuminated area due to constraints placed on the construction of the 15 x 21 dot symbols to maintain symbol stroke width. Because it was deemed desirable to maintain stroke width in the construction of 5 x 7 and 15 x 21 dot symbols, the

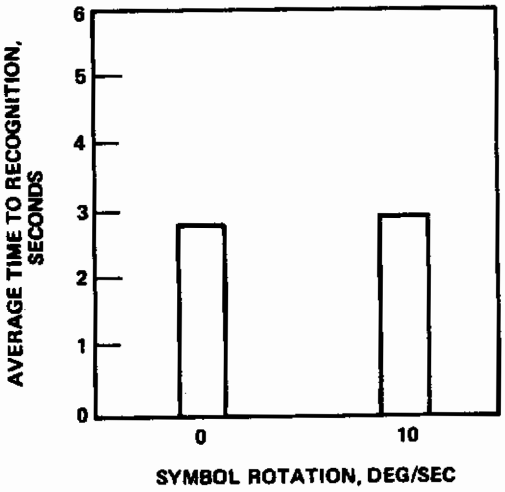


Figure 26. Effect of rotation on symbol legibility (not statistically significant).

15 x 21 dot symbols were physically constructed by making the symbol strokes three dots wide (see Figure 21). This resulted in a smaller illuminated area for the 15 x 21 symbols than for the 5 x 7 symbols. The effect of percent active area as previously defined (see paragraph 3. 1. 1) is being seen in only one dimension with the 5 x 7 single stroke symbol set. Another way of viewing this is that there is an added dead space between rows of dots in the 15 x 21 symbols which is not present in the 5 x 7 symbols. Thus the apparent inferiority of the 15 x 21 upright symbols as shown in Figure 27 is probably a reflection of the lower perceived brightness of the 15 x 21 dot symbols.

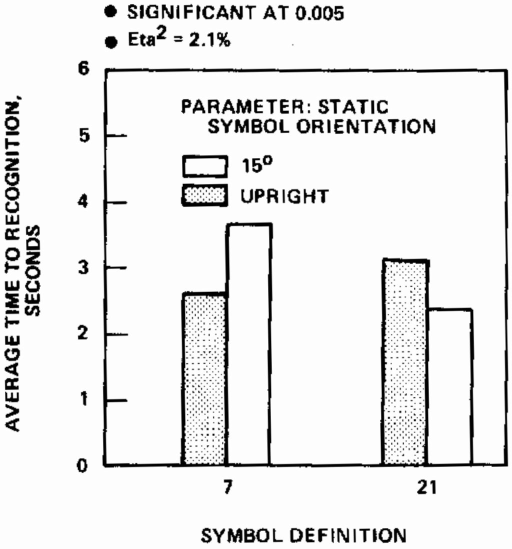


Figure 27. Interaction of symbol definition and symbol orientation.

3. 2. 4. 10 Five Interactions of a Common Nature

The following two-factor interactions will be discussed as a group, since they all reflect and reinforce the observation that when perception is operating at a marginal level due to one or several critical parameters, then the effect of any other parameter is greatly amplified. Figures 28 through 32 all illustrate this phenomenon. The interactions of this type were percent active area by surround luminance, percent active area by contrast, percent active area by symbol subtense, contrast by surround luminance, and symbol subtense by surround luminance. For the first three interactions listed, an increase in percent active area was associated with a decrease in time scores, and in each case the increase in percent active area was proportionately more beneficial for the symbols displayed at the low levels of the other variables than at the high levels. The significant interaction ($p < 0.001$) between percent active area and surround luminance is shown in Figure 28. The decrease in recognition time for an increase in surround luminance was

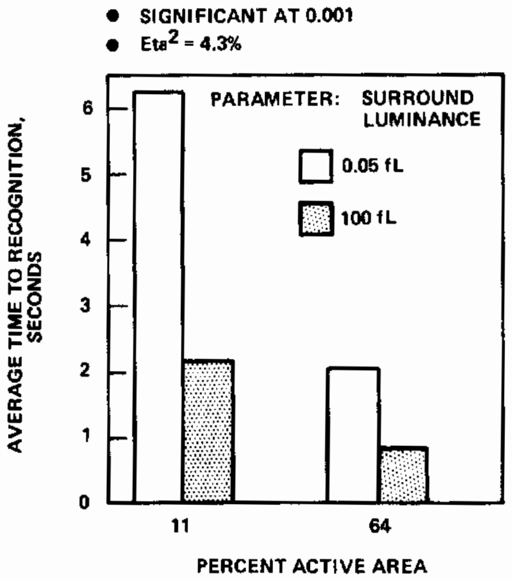


Figure 28. Interaction of percent active area and display surround luminance.

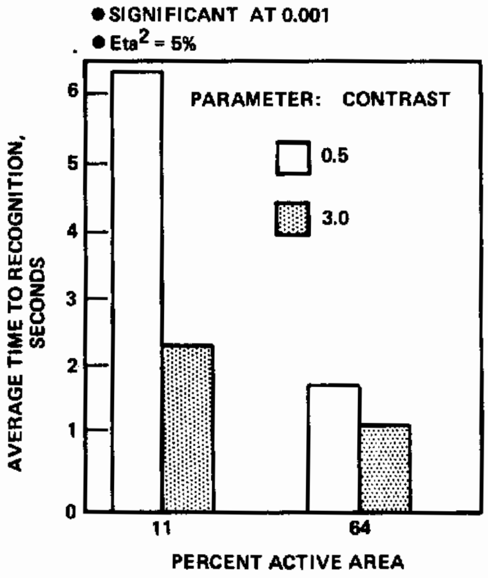


Figure 29. Interaction of percent active area and display contrast.

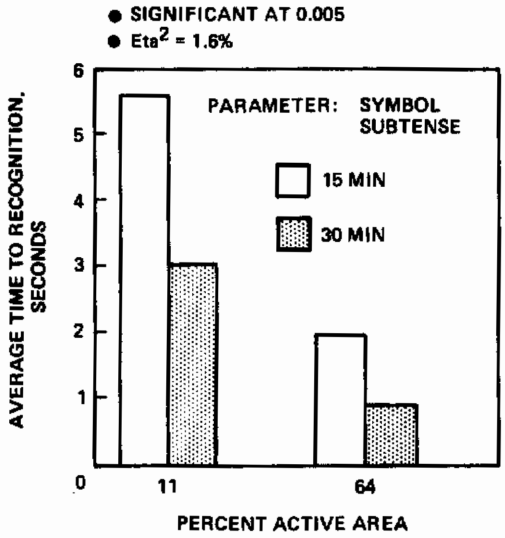


Figure 30. Interaction of percent active area and symbol subtense.

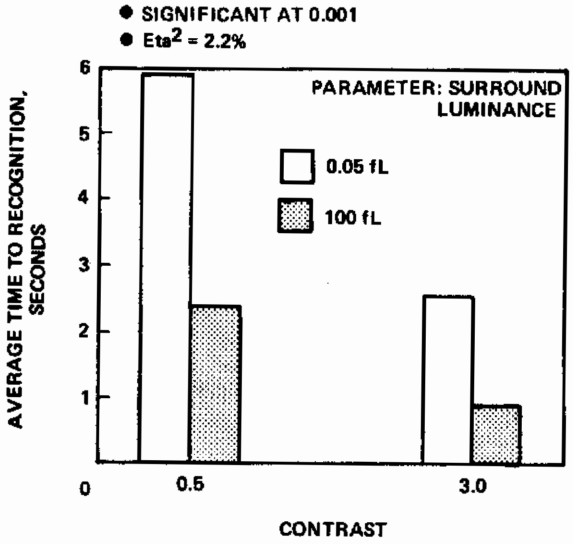


Figure 31. Interaction of display contrast and surround luminance.

more pronounced for the low levels of percent active area. Required time to symbol recognition decreased from 6.33 to 2.29 seconds for symbols displayed at the 11 percent active area while the corresponding decrease for symbols at 64 percent active area was from 2.13 to 0.83 seconds. This interaction accounted for 4.3 percent of the experimental variance.

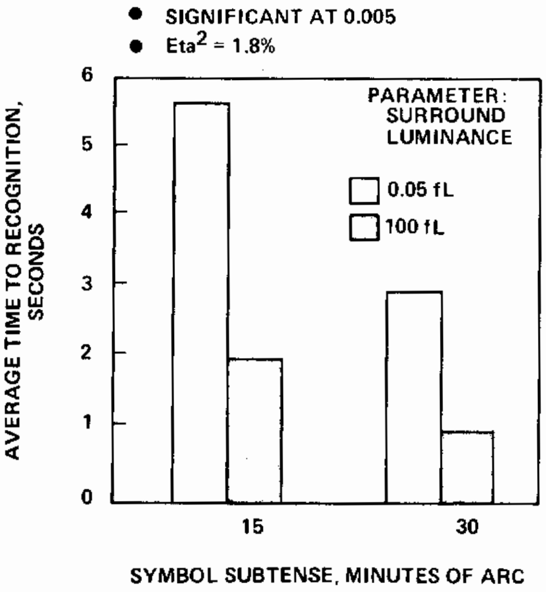


Figure 32. Interaction of symbol subtense and surround luminance.

As seen in Figure 29, there was an interaction ($p < 0.001$) between percent active area and contrast. The decrease in time scores at 11 percent active area was proportionately larger than at 64 percent active area when compared at 0.5 and 3.0 contrast values. Time scores decreased at 11 percent active area from 6.24 to 2.38 seconds compared to a decrease from 1.92 to 1.04 seconds at 64 percent active area. This interaction accounted for 5.0 percent of the experimental variance.

As seen in Figure 30, there was an interaction ($p < 0.005$) between percent active area and symbol subtense. The decrease in time to recognition for a corresponding increase in symbol subtense was greater at 11 percent active area (decrease from 5.63 to 2.99 seconds) than at 64 percent active area (decrease from 1.97 to 0.99 seconds). This interaction accounted for 1.6 percent of the experimental variance.

Figure 31 shows the significant interaction ($p < 0.001$) obtained between surround luminance and contrast. An increase in surround luminance resulted in proportionately lower required times for symbols with a contrast of 0.5 than for symbols with a contrast of 3.0. Time required for symbol identification decreased with increased surround luminance from 5.90 to 2.26 seconds for a 0.5 contrast, compared with a decrease from 2.56 to

0.86 second for a 3.0 contrast. This interaction accounted for 2.2 percent of the total experimental variance.

Figure 32 shows the significant interaction obtained between symbol subtense and surround luminance where an increase in surround luminance resulted in proportionately lower time scores for symbols displayed at 15 minutes subtense than for symbols displayed at a 30 minutes subtense. Time decreased with increased surround luminance from 5.58 to 2.02 seconds for symbols of 15 minutes subtense, compared to a decrease from 2.88 to 1.1 seconds for symbols of 30 minutes subtense. This interaction accounted for 1.8 percent of the experimental variance.

### 3.2.4.11 Other Interactions

There were two interactions of a statistically significant nature that must be mentioned. They are Y translation by contrast ($p < 0.05$) and symbol orientation by contrast ($p < 0.025$). Together, they account for less than 2 percent of the experimental variance. These interactions are difficult to reconcile in any logical manner and are attributed to one of two causes. The first and perhaps most likely is that they were a chance occurrence, since it is not unlikely that from a total of 55 main effects and interactions tested at $p = 0.05$, one will find two chance occurrences. The other possible explanation is due to each main effect and two-factor interaction being aliased by nature of the fractional factorial design with seven other higher-order interactions that were assumed to be negligible. It is possible that in these two cases, this assumption was poor and that the higher order interactions are obscuring the results.

### 3.2.5 Conclusions

The principal conclusions drawn from the screening study are:

1. Parameters having a major effect on matrix display legibility are percent active area, display surround luminance (adaptation level), contrast, and symbol subtense.
2. Parameters having an important two-factor interaction are symbol definition and symbol orientation.

## 3.3 SYMBOL SUBTENSE STUDY

### 3.3.1 Purpose

The effect of symbol subtense (15 and 30 minutes of arc) on subject time-to-symbol-recognition was found to be highly significant ($p = 0.001$) in the screening study. As a consequence, a brief study was designed to assess whether the effect of subtense measured for matrix symbols was similar to the effect measured for stroke-written symbols. It was reasoned that if no differential effects of subtense for matrix versus stroke symbols could be demonstrated, then the extensive subtense data now available for stroke symbols would be directly applicable to a matrix display format.

As previously noted (Section 2.2.2.1), threshold display luminance (contrast) was used as the performance measure in this study, and the subject's task was to identify the symbol as display luminance was incremented by the experimenter. Surround luminance (adaptation level) was included as a parameter to increase the data base and verify that higher order interactions with symbol subtense did not exist as well as the first order interaction with stroke writing mode.

### 3.3.2 Experimental Design and Parameters

The variables and the levels of the variables investigated in the subtense study were as follows:

1. Subtense: 15 and 30 minutes of arc
2. Symbol Writing Mode: dot and stroke
3. Surround Luminance: 0.05 and 100 fL.

Stroke symbols were constructed to duplicate the same font being used with the matrix symbols.

The experimental design employed was an eight by eight Latin square (with each subject seeing only one of eight symbols in each experimental condition). Eight symbols were utilized (1, 3, 8, I, Q, U, V, Δ), and eight subjects participated. All subjects were pretested for visual acuity (with a Snellen chart) both at 20 feet and 30 inches. Only subjects with 20/20 corrected vision or better at both distances were used.

### 3.3.3 Results and Discussion

An analysis of variance was performed on the symbol luminance required for threshold symbol identification. This analysis showed the two-factor interaction of subtense and symbol writing mode, as well as the three factor interaction between subtense, mode, and surround luminance to be nonsignificant. In addition, the values of Eta$^2$ for these interactions were negligible. Thus, on a practical basis it is concluded there was no differential effect of subtense on matrix as opposed to stroke-written symbology. These results for matrix versus stroke symbols are shown in Figure 33 which shows that there was no differential effect of symbol subtense on matrix and stroke symbology. The ordinate of Figure 33 is the ratio of symbol luminance thresholds for 15 and 30 arc minute symbols. It can be seen that the ratios do not vary as a function of symbol writing mode. The data are presented in this manner because the main effect of subtense, although statistically reliable, was confounded with percent active area. Because of the inherent nature of the symbology, this was unavoidable and unfortunately no inferences can be drawn from the absolute magnitudes of the response data from matrix versus stroke symbology. However, the interactions of symbol writing mode with symbol subtense and surround luminance are clear of any confounding and the data are averaged across the values of surround luminance and presented as a response ratio for the two values of symbol subtense.

As a consequence of the above results, it is concluded that the data presently available concerning the effects of subtense on stroke-written symbology are applicable to a matrix format. Consequently, symbol subtense will not be a parameter in subsequent parametric studies.

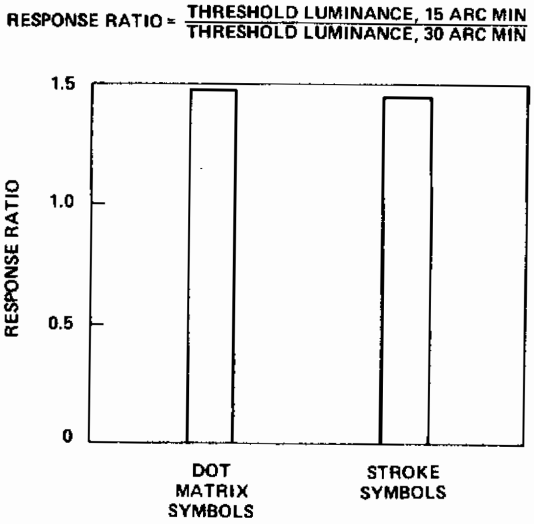


Figure 33. Ratio of threshold luminances for matrix and stroke symbology for symbol subtenses of 15 and 30 arc min.

## 3.4 SYMBOL ORIENTATION, SYMBOL DEFINITION, AND SYMBOL ROTATION STUDY

### 3.4.1 Introduction and Purpose

The parameters in this study represent one of the dichotomous groups that were identified as operationally and statistically significant factors in the legibility of symbols on matrix displays (see Section 3.2). This group of parameters was selected as one in which performance, given the fact that he can see the symbols, was limited primarily by the observer's ability to cognitively process information. The distorted symbology depicted in Figures 9 and 21 illustrates the problem faced by the observer with mis-oriented symbols of limited definition. It is clear that "time-to-recognition" is an appropriate performance measure to examine the effects of these parameters.

Rotating the symbol at 10 degrees per second did not show an effect on legibility in the screening study but because the subject may have been able to effectively integrate information over time at the faster rotation rates it was felt that very slow rotation rates might have a more detrimental effect. As a result, symbol rotation was retained as a parameter in this study.

Procedures used in this study (see Section 2.2.1.2) allowed the subject to control the time the display was activated, and the "time activated" was the performance measure.

### 3.4.2 Experimental Design and Parameters

Six replications (subjects) of a complete factorial experimental design were conducted on the following parameters and levels.

| | | |
|---|---|---|
| 1. | Symbol Rotation Rate | 0, 0.5, 5, and 10 degrees/sec |
| 2. | Symbol Definition | 5 x 7, 8 x 11, 15 x 21, and stroke |
| 3. | Static Symbol Orientation | 0 and 15 degrees counter-clockwise from vertical |
| 4. | Active Area | Fixed for matrix symbols at 25 percent |

| | | |
|---|---|---|
| 5. | Symbol Subtense | Fixed at 30 minutes of arc |
| 6. | Surround Luminance | Fixed at 5 foot-Lamberts |
| 7. | Contrast | Fixed at 5.0 |

### 3.4.3 Results and Discussion

The effect of symbol definition for the various rotation rates is illustrated in Figure 34. These data are averaged over the two initial orientations of 0 and 15 degrees off-axis and should be evaluated in conjunction with the data of Figure 35 which illustrates the effect of symbol definition for the two orientations averaged over the four rotation rates.

The analysis of variance results are summarized in the first part of Table 8 for the raw data and in the second part after subtracting 200 milliseconds and taking the logarithm of the raw data. The rationale for this manipulation was to correct for a skewed distribution which was bounded on the low side by the observer's reaction time of about 200 milliseconds. The result of the transformation yields an approximately normal distribution which satisfies basic assumptions for the analysis of variance.

Examination of Figure 34 reveals that a primary result of this study is that 5 x 7 symbols are considerably less legible than 8 x 11 and larger symbol definitions (these results are averaged over 0 and 15 degree off-axis

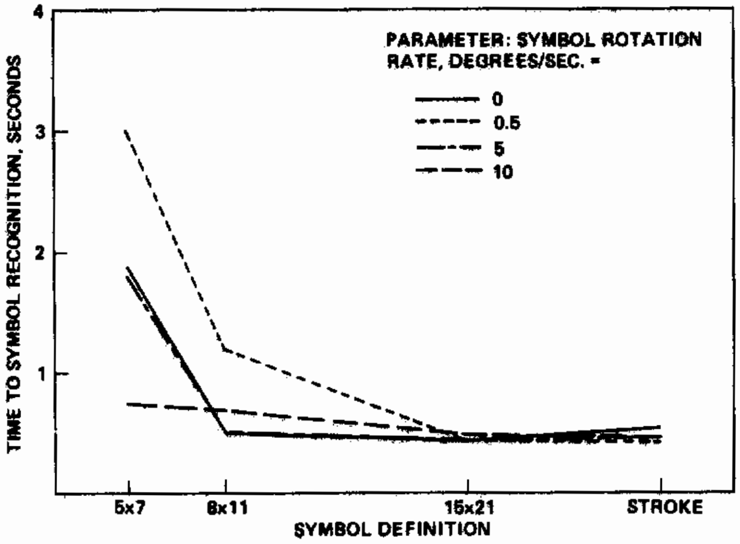


Figure 34. Average symbol recognition times as a function of symbol definition with rotation rate as a parameter.

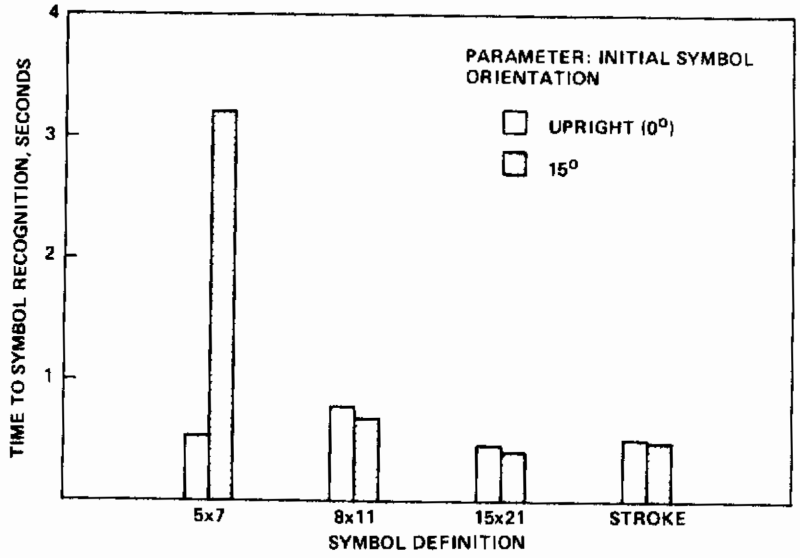


Figure 35. Average symbol recognition times as a function of symbol definition with symbol orientation as a parameter.

orientations). This main effect of symbol definition was statistically significant at $p < 0.005$. Figure 35, however, shows that if the 5 x 7 symbols are viewed under only upright conditions they are just as legible as any other value of symbol definition. This result implies a strong interaction between symbol orientation and symbol definition, and indeed this interaction was significant at $p < 0.001$. The main effect of symbol orientation was statistically significant at the $p < 0.025$ level. It should be noted that when the symbol was initially upright, the observer was always able to identify it prior to any movement for the rotation rates examined in this experiment. In general, the interaction between symbol definition and orientation is of a very specific nature, i.e., all symbols are very legible at unique orientations such as 0, ±45 degrees, ±90 degrees, etc., and this is not really of much practical interest for dynamically moving displays.

## TABLE 8. ANALYSIS OF VARIANCE TABLE FOR ORIENTATION-DEFINITION-ROTATION STUDY

| Source | SS | df | MS | Error Term | Error df | F | P | $Eta^2$ |
|---|---|---|---|---|---|---|---|---|
| I. Analysis Performed on Raw Data $X_i$ | | | | | | | | |
| D | 84 | 3 | 28. | DS | 21 | 5.4 | 0.01 | 10.28 |
| R | 16. | 3 | 5. | RS | 21 | 4.6 | 0.025 | 1.90 |
| O | 24. | 1 | 24. | OS | 7 | 4.8 | 0.1 | 3.00 |
| DR | 30. | 9 | 3. | DRS | 63 | 2.3 | 0.05 | 3.72 |
| DO | 88. | 3 | 29. | DOS | 21 | 6.7 | 0.005 | 10.74 |
| RO | 8. | 3 | 3. | ROS | 21 | 1.5 | NS | 1.00 |
| DRO | 50 | 9 | 6. | DROS | 63 | 3.9 | 0.005 | 6.10 |
| II. Analysis Performed on Log $(X_i - 0.2)$ | | | | | | | | |
| D | 4.215 | 3 | 1.405 | DS | 21 | 6.50 | 0.005 | 9.1 |
| R | 0.355 | 3 | 0.118 | RS | 21 | 1.21 | NS | 0.8 |
| O | 1.415 | 1 | 1.415 | OS | 7 | 8.47 | 0.025 | 3.1 |
| DR | 0.803 | 9 | 0.089 | DRS | 63 | 1.27 | NS | 1.7 |
| DO | 3.639 | 3 | 1.213 | DOS | 21 | 10.03 | 0.001 | 7.9 |
| RO | 0.473 | 3 | 0.158 | ROS | 21 | 2.25 | NS | 1.0 |
| DRO | 2.170 | 9 | 0.241 | DROS | 63 | 2.77 | 0.01 | 4.7 |

D = Definition
R = Rotation
O = Orientation
S = Subjects

The effect of rotation rate in the study was not pronounced and was only in evidence for off-axis 5 x 7 symbols thus giving rise to the third order interaction between the three parameters which was statistically significant at the $p < 0.01$ level. The effect on legibility was that off-axis symbols took several seconds to recognize, and the very low rotation rate (0.5 deg/sec) was a disrupting factor, whereas the much faster rotation rate (10 deg/sec) actually aided recognition by allowing the observer to integrate displayed information over time. The main effect and second order interactions of rotation rate were not statistically significant at the $p < 0.05$ level. The slightly elevated recognition time for 8 x 11 symbols rotating at 0.5 degree/second seen in Figure 34 is due to one errant subject and the 10-second time penalty for a response error. Little can be concluded from that alone; although, off-axis 8 x 11 symbols were subjectively annoying.

### 3.4.4 Conclusions

The primary conclusions to be drawn from this study are:

1. For static upright symbology, there is no performance difference for symbol definitions of 5 x 7 or greater.
2. For non-upright symbology (presented in a rigid x-y matrix) 5 x 7 symbology is illegible. Objective performance differences for 8 x 11 symbology as a function of orientation were small but from observation, it is subjectively annoying.
3. Rotation rate for the range examined had no primary effect on legibility except for low values of symbol definition that are unacceptable for a practical display. Given grossly distorted symbology, a secondary effect was that higher rotation rates allow integration of information over time and allow somewhat improved performance — an effect of questionable practical value.

## 3.5 ACTIVE AREA AND SURROUND LUMINANCE STUDY

### 3.5.1 Purpose

This study was the second of two parametric studies that evolved from observations during the screening study as a result of the apparent dichotomy of parameters affecting symbol legibility. It was felt that the parameters percent active area, surround luminance, and contrast affected legibility through the observer's ability to perceive the symbols as opposed to a higher level processing of information. In addition, it was hypothesized that these parameters could be directly traded off against each other. The purpose of this experiment was to examine the interrelationship of the visibility parameters; percent active area, surround luminance, and contrast; and obtain tradeoff criteria on which to base intelligent design. Surround luminance in this study is the same as adaptation level.

### 3.5.2 Experimental Design and Parameters

Based on the hypothesis that all three parameters affect perception and can be traded off against each other, it was reasoned that one could be selected as the dependent measure while parametrically varying the other two. Since display luminance could be continuously and conveniently controlled and is directly related to contrast, this was chosen as the dependent measure. It is equivalent to measuring contrast and the results are expressed directly in terms of emitted display luminance which is equal to $B_{max} - B_{min}$ or $\Delta B$. Percent active area and surround luminance were the independent parameters with levels of 4, 11, 25, 45, 64, 79, and 100 percent and 0.05, 5, 50, 500, and 2,000 fL, respectively. Six replications (subjects) of a full factorial design were run with the 10 symbols balanced over replications.

The subject's task (see Section 2.2.2.2) was to identify the displayed symbol as the display luminance (contrast) was increased by the experimenter.

Since practical displays are not designed for threshold visibility, it was necessary to derive field factors which can be used to convert threshold data to levels that provide comfortable viewing. Comfortable viewing levels were obtained from a limited size study using two subjects under similar conditions to those used to collect the threshold data.

### 3.5.3 Results and Discussion

Threshold data are summarized in Figure 36. Data points averaged over six subjects are represented by the solid segmented curves. The ordinate is actual element (dot) luminance as measured in a dark surround and is $B_{max} - B_{min}$ of $\Delta B$. Contrast is $\Delta B/B_{min}$. The dashed curves represent the relationship $\Delta B$ x Percent Active Area = Constant, and can be seen to approximate the actual data very closely. Each dashed curve was positioned on the vertical scale at the 100 percent active area point by adapting the data of Blackwell (1946). The target size used for the purpose of obtaining a value of threshold contrast from Blackwell's (1946) data was a circular disk subtending the same area as the 30 x 21 arc minute symbol used in this experiment; i.e., a disk subtending 28 arc minutes. The resulting contrast threshold was multiplied by the field factor of 2.5 to convert from a 50 percent probability of detection to one of near 100 percent. The resulting value of contrast was multiplied by the surround luminance to obtain the display luminance ($\Delta B$). This value of $\Delta B$ was divided by the average portion of the 5 x 7 matrix that was illuminated for the symbols used; i.e., it was evident from the data that $\Delta B$ was proportional to 1/Area. The resulting value

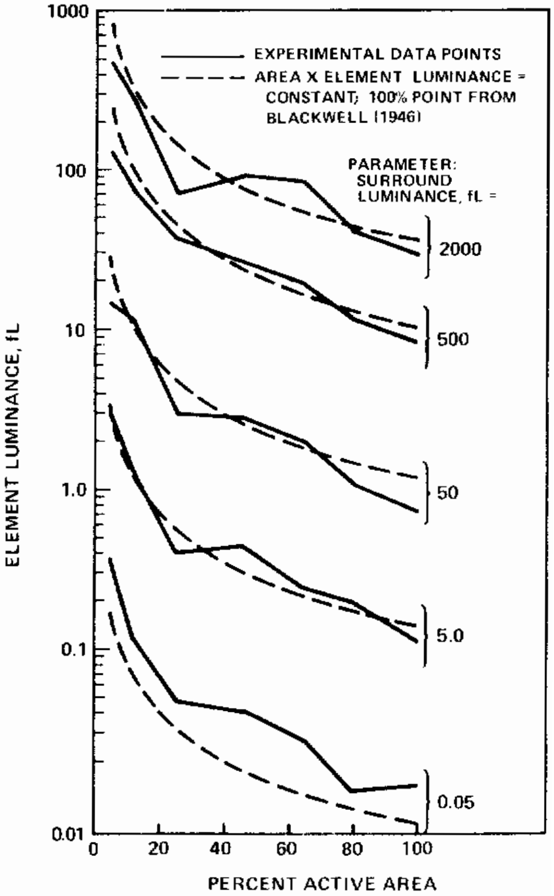


Figure 36. Threshold element luminance as a function of percent active area and surround luminance.

of $\Delta B$ was used to establish the 100 percent points on the dashed curves of Figure 36. The above procedure is further illustrated in Section 4.6.

The results of the analysis of variance are presented in Table 9. In the first part of Table 9, the analysis was performed on the raw data and is presented here only in the interests of completeness. A wide range of data values make up the data for this experiment (five log units as evidenced in Figure 36), and moreover all data values by the nature of the performance measure are bounded below at zero. The resulting distribution is extremely skewed and violates an important assumption underlying the analysis of variance; namely that the data be normally distributed. This problem is readily handled by performing a logarithmic transformation on the data prior to the analysis of variance. This in effect maps the range of 0 to $\infty$ into the new range of $-\infty$ to $\infty$ and deskews the data into an approximately normal distribution. The results of the analysis of variance on the transformed data are presented in the second part of Table 9, and it is seen that the main effects of percent active area and surround luminance remain highly significant ($p < 0.001$) whereas the interaction previously apparent has become insignificant. Graphically, the interaction is not obvious from Figure 36, since the data are presented on a semi-log scale. If plotted on linear scales, the effect just described would be readily visible.

The data collected for comfortable viewing levels (the level at which observers set the display luminance to comfortably view the pattern) is presented in Figure 37 in the form of field factors by which to multiply threshold element luminances. A good fit to the field factor curves is given by the equation:

$$F = \frac{50 + 2A - 0.02A^2}{L^{0.2}} ,$$

where

F is the element luminance field factor

A is the active area in percent

L is the surround luminance.

## TABLE 9. ANALYSIS OF VARIANCE FOR ACTIVE AREA-SURROUND LUMINANCE STUDY

| Source | SS | df | MS | Error Term | Error df | F | <P | $Eta^2$ |
|---|---|---|---|---|---|---|---|---|
| I. Element Luminance Data | | | | | | | | |
| A | 342855. | 6 | 57143. | AR | 30 | 51.7 | 0.001 | 17.12 |
| S | 739942. | 4 | 184985. | SR | 20 | 120.9 | 0.001 | 36.94 |
| AS | 732389. | 24 | 30516. | ASR | 120 | 32.4 | 0.001 | 36.55 |
| II. Log Element Luminance Data | | | | | | | | |
| A | 39.658 | 6 | 6.610 | AR | 30 | 174 | 0.001 | 11.3 |
| S | 306.233 | 4 | 76.558 | SR | 20 | 822 | 0.001 | 86.9 |
| AS | 0.922 | 24 | 0.038 | ASR | 120 | 1.46 | NS | 0.3 |

A = Percent Active Area

S = Surround Luminance

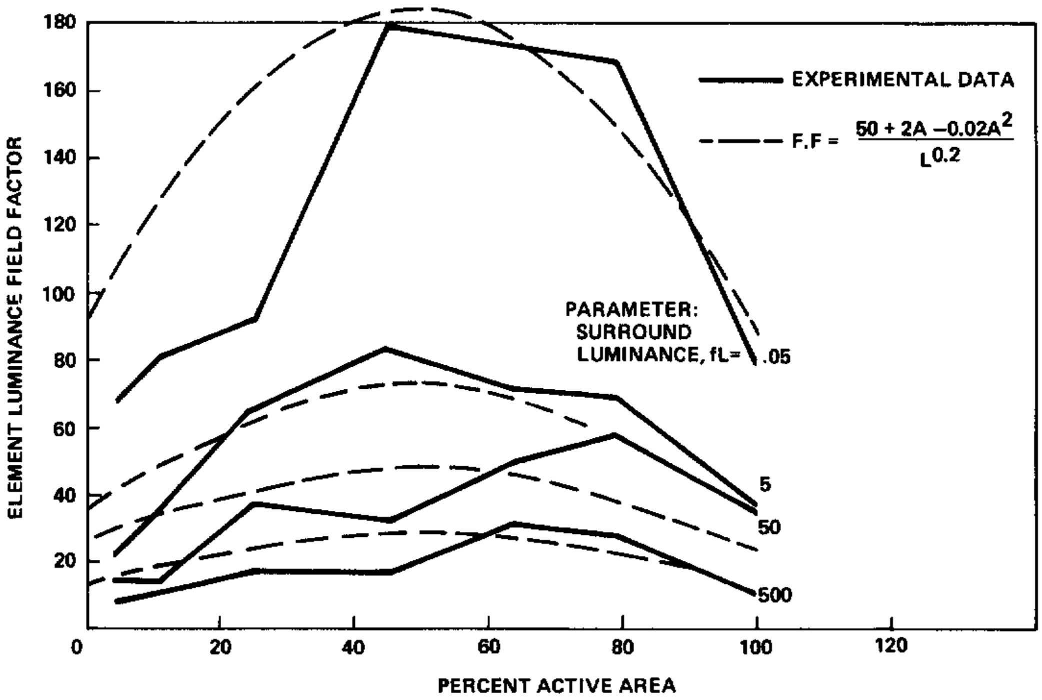


Figure 37. Field factors for converting threshold element luminance to a comfortable viewing level as a function of percent active area and surround luminance.

In summary, the results of this experiment indicate that Blackwell's (1946) data can be used directly with appropriate field factors and adjustment for illuminated area within the target symbol to predict matrix display luminance and active area requirements for various surround luminances and make tradeoffs between them directly. The good correlation with Blackwell's data allows the designer to have greater confidence when forced to extrapolate to adaptation levels not examined in this study.

The design tradeoff between active area and display brightness is indicated by the relationship Area x Emitter Luminace = constant.

## 3.6 MODULATION SENSITIVITY FUNCTIONS FOR MATRIX DISPLAYS

Analysis of human visual performance and display system quality has been greatly facilitated in recent years by the use of Fourier analysis which allows the designer to use classical methodology applicable to linear systems The human visual system as with most real-world systems is non-linear but can be approximated over a rather narrow output range by a linear system with reasonable success. The output range to be dealt with in this study is the region of "threshold" detectability. Threshold as used here refers to an observer decision criterion and does not presume that such a phenomenon exists at the sensory level.

In the development of visual analysis in the spatial frequency domain, a counterpart to the modulation transfer function (MTF) of the electro-optical imaging system has been derived. This counterpart is the modulation sensitivity function (MSF), and a number of authors have published modulation sensitivity data for sinusoidally modulated spatial patterns in one dimension. Representative of these are the data of Patel (1966) and Van Meeteren and Vos (1972) shown in Figure 38. These and other data also indicated that visual response depends on size of the visual field as well as average luminance. However, data were absent for fields subtending less than two degrees which is the area of most importance for alphanumerics and typical target sizes on sensor displays. Subsequently, Rogers and Carel (1973) collected MSF data for small fields modulated in two dimensions. Their results indicated that there were no observer performance differences getween one- and two-dimensional sinusoidal modulation patterns, thus validating the use of the data of Patel and others to predict observer performance in two-dimensional image recognition tasks.

### 3.6.1 Purpose

The objective of the present study was to obtain comparable data to that of Rogers and Carel, but for modulation patterns having the sharp on-off spatial characteristics and uniform luminance distribution across active elements, such as typically found in LED and other matrix displays. Campbell and Robson (1968) conducted a study of sine versus square wave modulation but for one-dimensional patterns. Linear system theory applied to the visual sensory system predicts little difference between the results of this experiment using two-dimensional square wave patterns and those of the aforementioned studies.

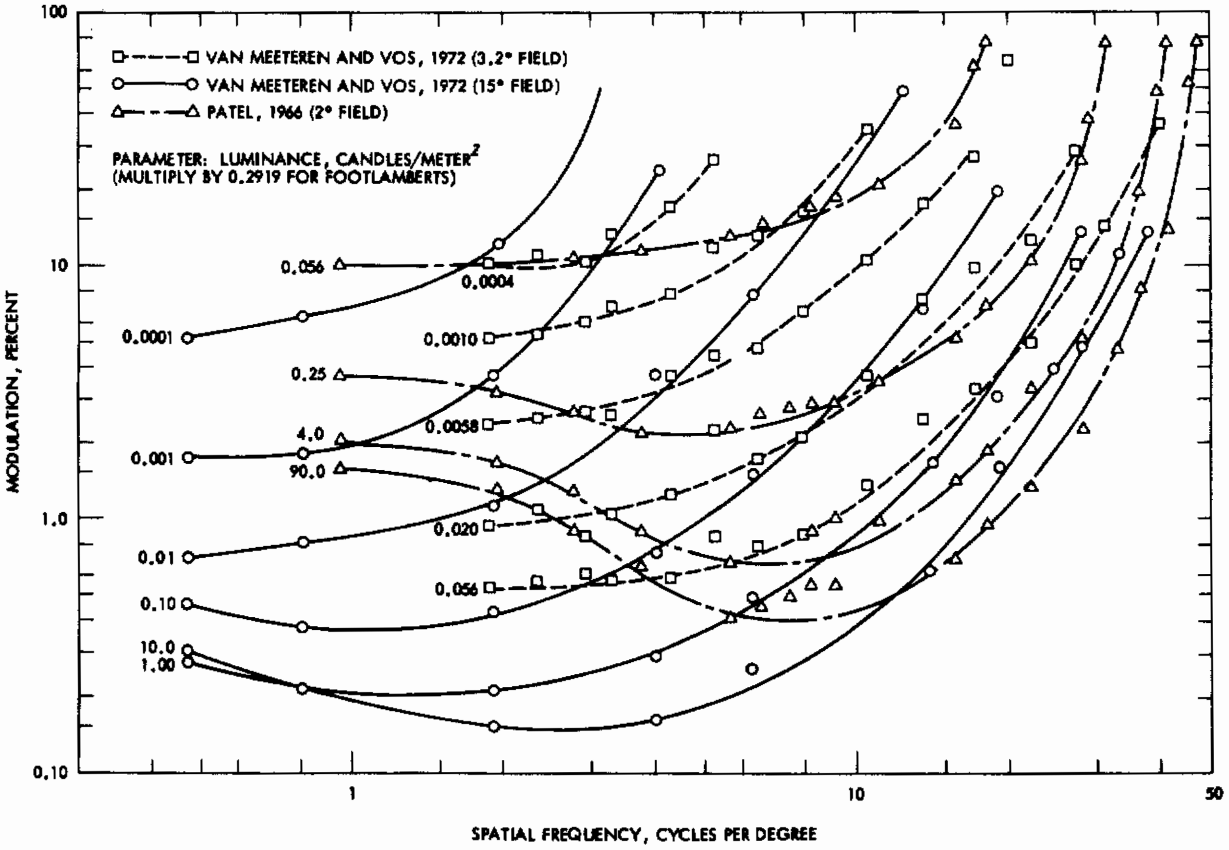


Figure 38. Three versions of the modulation sensitivity function, from Rogers and Carel (1973).

For a more thorough and pragmatic discussion of the underlying theory, the reader is referred to chapter XII of Cornsweet (1970). An abbreviated summary of the reasoning for the aformentioned hypothesis follows. It is widely accepted that the visual system is in general nonlinear. However, it will be argued that under the conditions existing in this experiment, a quasilinear describing function model of the visual system is appropriate.

A quasilinear describing function is a linear approximation of a nonlinear system. There are two effects of nonlinearities that will be discussed. The first is that a given change in the luminous intensity at the input to the system does not produce a proportional change at the output which is measured as perceived brightness. The second effect gives rise to frequencies at the output of the system which are not present at the input.

To deal with the first effect of nonlinearity, it is pointed out that in the model of this class of experiment, the subject is observing threshold signal levels. The assumption is made that the observer decision criterion in terms of sensory system output level does not vary across the spatial frequency spectrum except for small statistical variations. Thus, even though the relationship between input and output amplitude is nonlinear, the experiment is conducted in a very small region of the curve, i.e., at the threshold output level, and the visual system is approximated quite well by a piece-wise linear segment of this curve.

Considering the second effect of nonlinearity, the added frequencies generated by the nonlinearity are all higher multiple harmonics of the input frequencies. In addition, for the case of a square wave input, the input spectrum is made up wholly of odd harmonics of the sinusoidal signal having the same period as the square wave. Thus, the lowest spatial frequency present in the output signal is identified as the lowest square wave frequency used in the experiment which is 6 cycles per degree. It has been established in previous studies that the modulation sensitivity function (MSF) of the visual system falls off at 12 dB/octave above 6 cycles/degree. Thus, any of the higher harmonics either in the square wave input signal or generated by the nonlinearity will be attenuated greatly before they get through the visual system, and in fact even the first harmonic will be attenuated by 12 dB. As a result, an input square wave signal that reaches the perceptual threshold (decision criteria) at the output will be primarily due to the fundamental and will be little affected by the higher harmonics.

Campbell and Robson (1968) with similar reasoning established that the visual system could be modeled by a quasilinear describing function for a simple detection task of one-dimensional patterns. Further discrimination of the nature of the pattern required that higher harmonics of the input reach their individual thresholds indpendently of each other.

It is the purpose of this experiment to bridge the results of Rogers and Carel (1973) with those of Campbell and Robson (1968) and establish that basic perceptual processes operate in a quasi-linear fashion in the perception of two-dimensional dot-matrix (square-wave modulated) patterns. If such is the case, existing threshold data could be adapted and applied to matrix displays.

### 3.6.2 Experimental Design and Parameters

The experiment was a within-subjects design and was a complete factorial with six replications (subjects). The experimental parameters were surround luminance, field size, and spatial frequency in two dimensions. The levels of surround luminance, adaptation level, and average display luminance were identical for this study with the values being 0.1, 1.0, 10, and 100 foot-Lamberts. The values of 0.5 and 1.0 degree subtended angles were selected for field size, and spatial frequencies used were 6, 12, and 24 cycles per degree of subtended angle. The performance measure was display modulation for threshold detection. Modulation is defined as:

$$M = \frac{B_{max} - B_{min}}{B_{max} + B_{min}},$$

where $B_{min}$ is the minimum luminance on the modulation pattern which in this case is the ambient illumination multiplied by the reflectance of the display. $B_{max}$ is equal to $B_{min}$ plus the active emitted display luminance. A detailed description of the procedures used in this study is presented in Section 2.2.2.3.

### 3.6.3 Results and Discussion

Data for the two field sizes of 0.5 and 1.0 degrees showed no statistical differences and indeed, the individual means were nearly identical. It is apparent that field size within this range is not an important variable which is in agreement with the data of Rogers and Carel (1973). As a result, the data for the two field sizes were pooled and are summarized in Figure 39 along with comparable results from the Rogers and Carel (1973) study shown

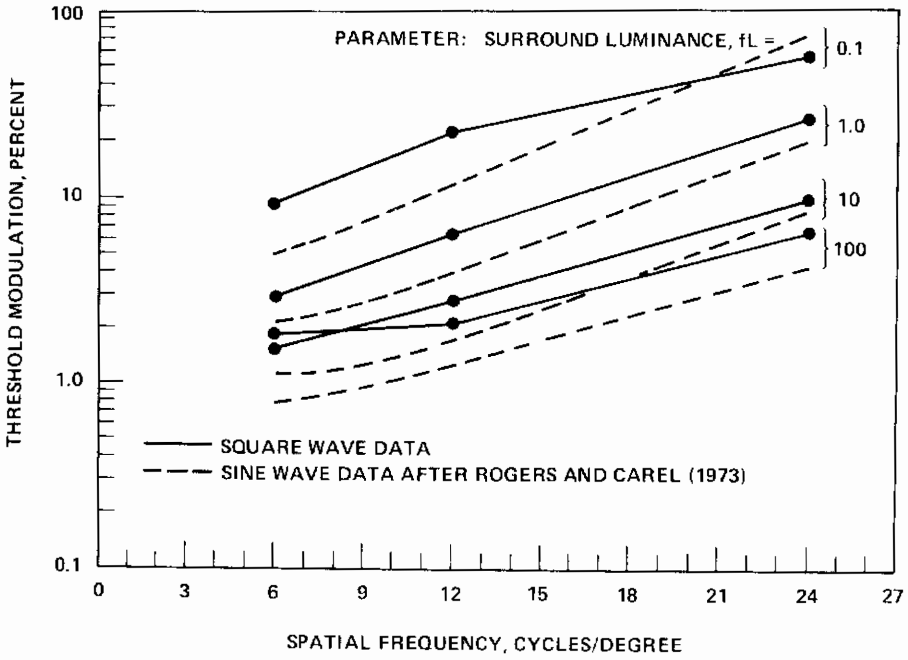


Figure 39. Modulation thresholds averaged over field sizes sizes of 0.5 and 1.0 degrees.

in the dashed curves. Although the differences in mean values between Rogers and Carel (1973) and the present study are statistically significant, the operational meaning of these differences is uncertain. Typically threshold modulation data are multiplied by field factors varying from 2 to 30 to obtain useful design values for practical applications. The actual differences as seen from Figure 39 are all less than a factor of two. The results of t-tests run on the data from this experiment to test the means against those of the Rogers and Carel (1973) experiment all indicated statistical significance at $p < 0.02$ level.

Whether actual differences exist that have meaningful implications with regard to a model of the human visual system is uncertain due to several effects. The first of these, and probably most important, is that basic differences existed in the form of the two-dimensional modulation patterns between the two experiments other than that of sine wave opposed to square wave modulation. Indeed, the modulation pattern in the Rogers and Carel (1973) study is best described by the rule:

$$\text{Display Luminance} = \text{Max}\,[f(X),\ f(Y)]\ ,$$

where f(X) and f(Y) are sine waves; whereas in this study, the modulation could be described by the rule:

$$\text{Display Luminance} = \text{Min}\,[f(X), f(Y)]\ ,$$

where f(X) and f(Y) are square waves. In effect, the two patterns were the negative of each other.

Another study conducted by Watanabe et al. (1968) showed that visual thresholds are affected by a number of factors such as pattern orientation, observation distance, and temporal effects. Observation distance differed between this experiment and the prior experiments.

Subject instructions and experimental technique have a large effect on measured thresholds. For example, thresholds measured by Rogers and Carel (1973) differed from those of Campbell and Robson by 50 percent for field sizes of 2 degrees. In this case, binocular versus monocular viewing may have been a factor.

During the course of this experiment, it became obvious that accurate brightness measurements are extemely difficult and tedious to make on a CRT, and seemingly small differences in calibration technique could have a major effect on comparisons of data for different experiments.

In summary, it must be concluded that a single experiment with identical apparatus and technique is required for the direct comparison of any experimental parameter such as one- versus two-dimensional patterns and sine wave versus square wave modulation. In that sense, the results of this experiment are inconclusive.

# 4.0 IMPLICATIONS OF THE RESEARCH FOR DESIGN AND USE OF MATRIX DISPLAYS

During the course of the program, 17 prameters related to matrix display symbol legibility were addressed in either the literature survey, the laboratory research, or both. In Section 3.0 where the research studies were described, the results of the research were presented and major conclusions were drawn. In this section, the findings of the research program are briefly discussed in terms of the design and use of matrix displays.

## 4.1 ALPHANUMERIC FONT

Non-electronic, electronic, and matrix display research on the legibility of various alphanumeric fonts, where font is defined as the fundamental geometry or style of the alphanumerics, was reviewed in the literature survey. Over the years, several fonts have evolved for use in electronic displays that are equally good. Included among these fonts are the Leroy, Lincoln/Mitre, and NAMEL fonts, shown in Figure 40. Since symbols are formed by discrete elements in matrix displays and hence are not continuous as in stroke or calligraphic written symbology, font must be translated into a matrix form. A comparison of stroke and 5 x 7 matrix formed Lincoln/Mitre alphanumeric symbols is shown in Figure 41.

The legibility of a matrix font is therefore dependent upon how the stroke written form of the font was translated into matrix form. One laboratory study has been done in which Lincoln/Mitre, IBM 029, modified Hazeltine, and Diamond Ordnance Fuse Laboratory fonts were compared, using a 5 x 7 matrix (Shurtleff, 1970). The four fonts were found to be equally good. Other researchers have used the Lincoln/Mitre font and obtained good results (Anderson, 1970; Shurtleff, 1970b). Semple (1971) concluded from his review of the literature that the Lincoln/Mitre font is highly legible even for small symbols. The Lincoln/Mitre font was therefore selected as the font to be used in the research studies.

The legibility of a given font depends on the matrix size and the shape and arrangement of the matrix emitters. The larger the matrix size or

A B C D E F G H I J K L M N O P Q R S T

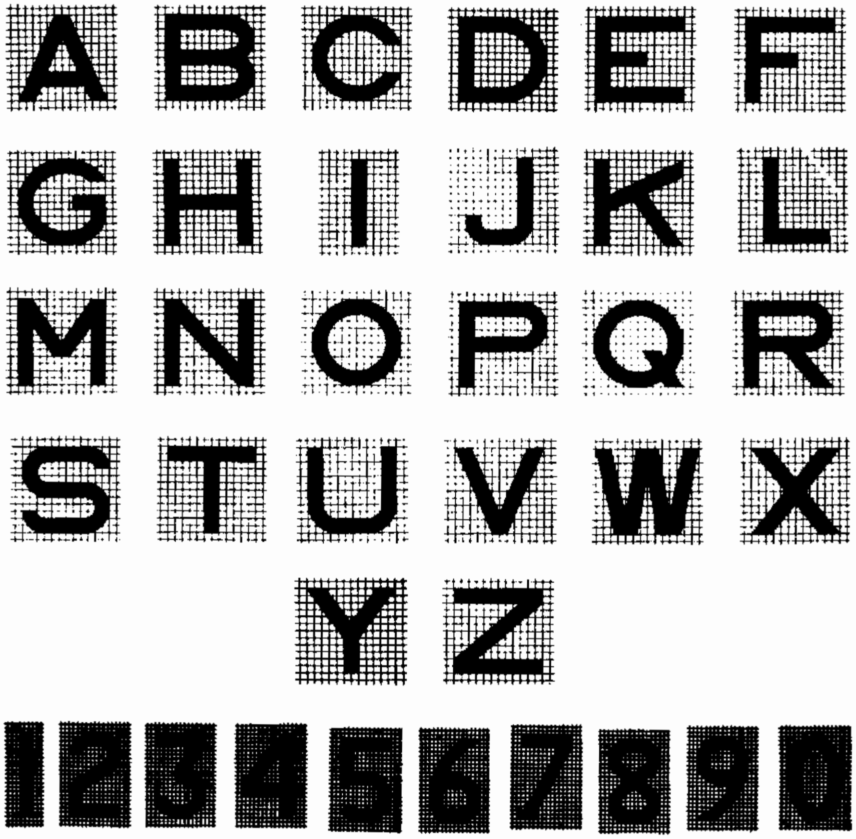
U V W X Y Z 1 2 3 4 5 6 7 8 9 0

*STANDARD LEROY ALPHANUMERICS*

A B C D E F G H I J K L M N O P Q R

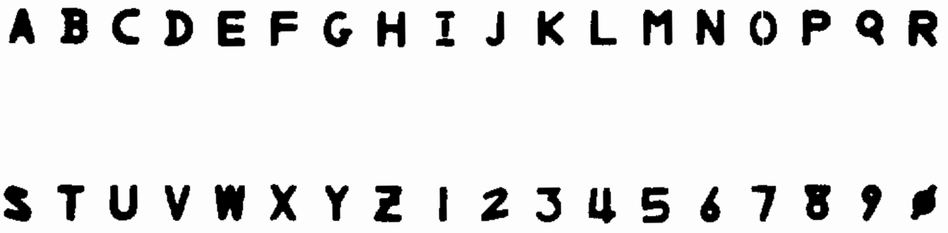
S T U V W X Y Z 1 2 3 4 5 6 7 8 9 0

*LINCOLN/MITRE ALPHANUMERICS.*

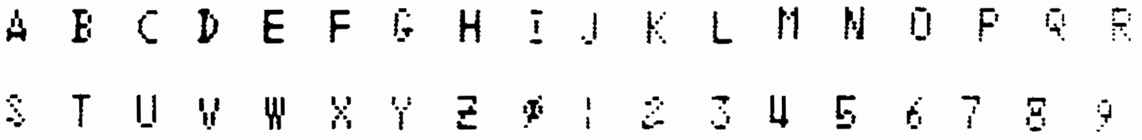


*MIL-N-18012 (NAMEL) ALPHANUMERICS*

Figure 40. Leroy, Lincoln/Mitre, and NAMEL fonts.



*STROKE WRITTEN LINCOLN/MITRE ALPHANUMERICS*



*5 x 7 DOT-MATRIX LINCOLN/MITRE ALPHANUMERICS*

Figure 41. Stroke and matrix Lincoln/Mitre Alphanumerics.

symbol definition, the more nearly the matrix symbols can be made to look like the parent stroke written font as is illustrated in Figure 42. The shape and arrangement of the emitters in a matrix display will also determine how well the activated emitters line up to form symbols of a given font. For example, hexagonal shaped emitters should be superior to square shaped emitters for fonts that employ non-orthogonal segments in the symbols. Unfortunately, no known research has been conducted to develop optimized fonts for matrix displays with different matrix sizes, emitter shapes and emitter arrangements.

Based on the information we have at this time, there appear to be several fonts that will provide good legibility of symbols for use with matrix displays. These include the Lincoln/Mitre, Leroy, NAMEL, IBM 029, modified Hazeltine, and Diamond Ordnance Fuse Laboratory fonts. Until research data become available on the design of fonts for matrix displays, the choice of any of the above fonts for matrix displays should be based on commonality of fonts within a crew station. In other words, different displays in a crew station should use the same basic font.

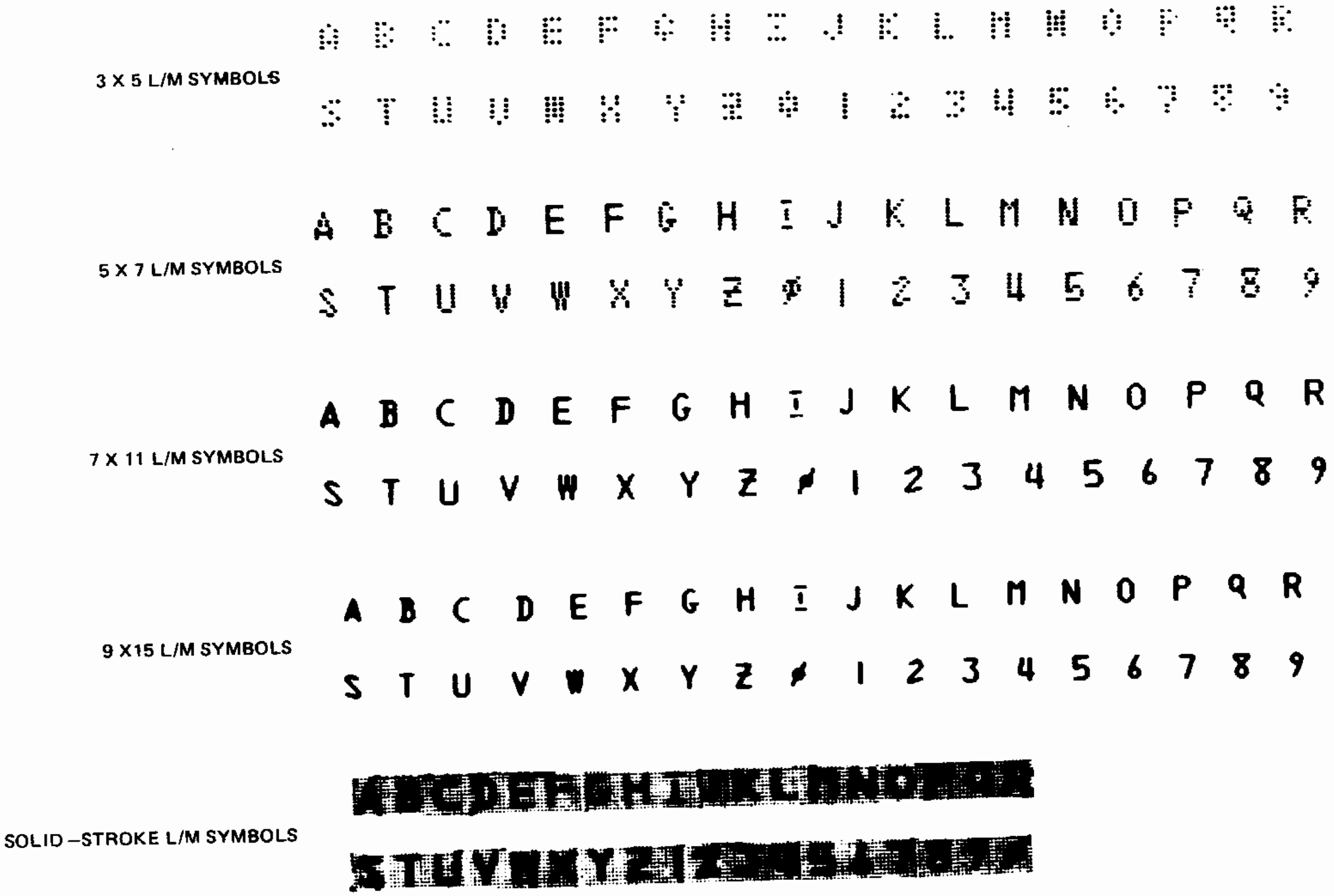


Figure 42. Lincoln/Mitre (L/M) symbols constructed from four matrices and solid-stroke symbols.

## 4.2 EMITTER SHAPE AND ARRANGEMENT

The emitters in matrix displays can be designed in different shapes (e.g., round, square, triangular, hexagonal) and in different arrangements (e.g., orthogonal and non-orthogonal). A single study (Vartebedian, 1970) investigated emitter shape in which circular dots were found to be superior to elliptical dots for speed and accuracy of symbol identification. There is no known data on the effects of emitter arrangement on the legibility of displays.

Different researchers have used different emitter shapes (Shurtleff, 1970a, b, c, d, e used round emitters; the present research used square emitters). Today's designers of matrix displays are using various shaped emitters. Light emitting diodes are physically square with the output luminance being circular, emitters in plasma displays are cross-shaped, the Hughes liquid crystal display has square emitters, and the display elements in the Digisplay are circular. What emitter shape and arrangement will provide the best symbol legibility and how much performance difference occurs with different emitter shapes and emitter arrangements cannot be specified at this time. Since the effects of emitter shape and arrangement on matrix display legibility are interdependent with emitter packing density, percent active area, emitter luminance, and symbol font, research is sorely needed in this area for the design of matrix displays.

## 4.3 EMITTER COLOR

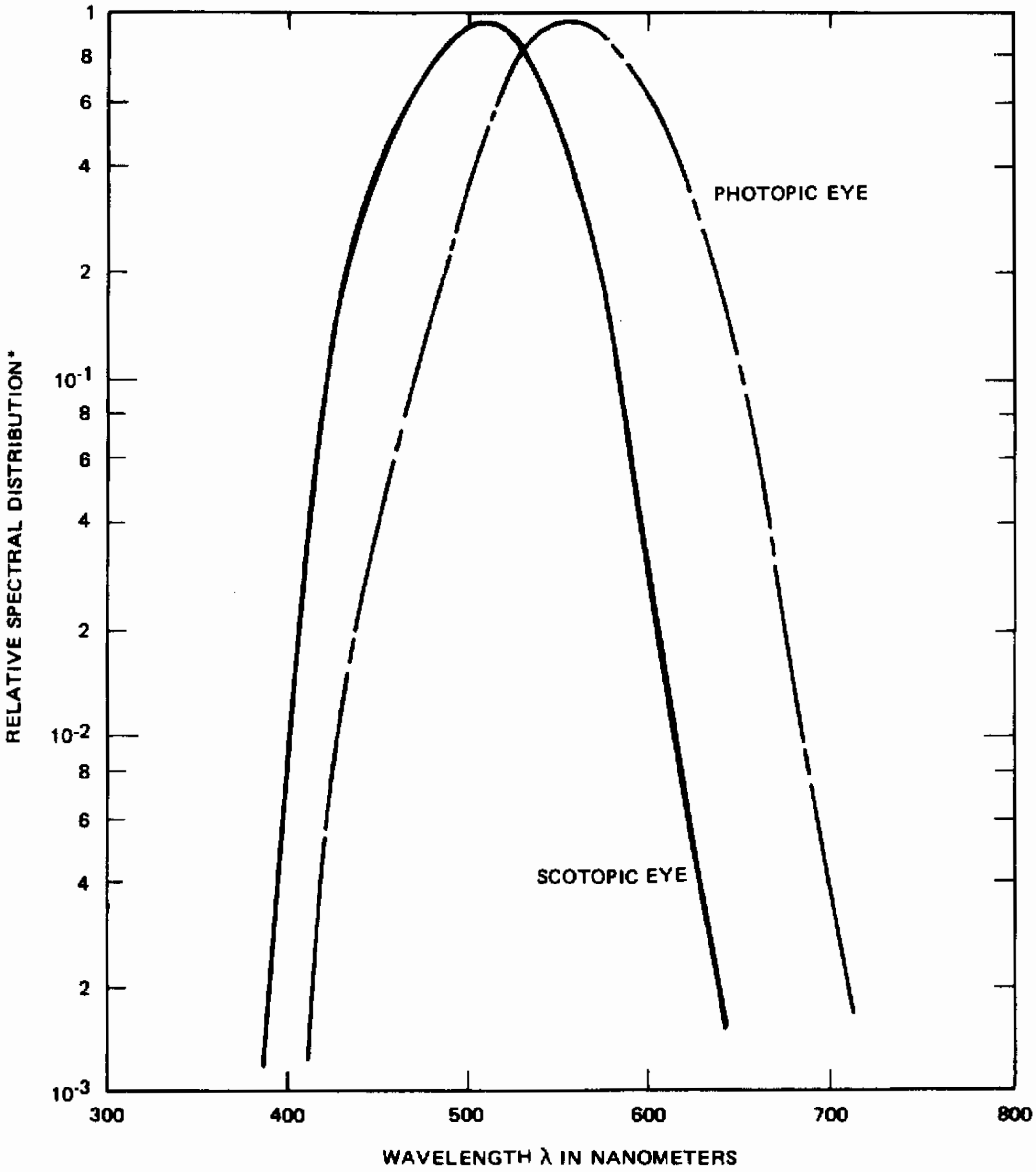
The matrix displays currently in production and under development offer the choice of several emitter colors. Thus, a monochrome matrix display can be obtained in several colors. Light emitting diodes are available in red, yellow, and green. Liquid crystal displays can be any color by using a color illuminant or a color filter. Neon plasma displays are orange; a zenon combination gas plasma display with a UV sensitive phosphor can be red, green, blue, or white. A digitally addressed CRT (e.g., the Digisplay) can be made in a variety of colors, depending on the phosphor used. The display designer, therefore, has a choice of colors to choose from.

From the standpoint of the observer and basic visual perception, green emitters would be recommended for monochrome matrix displays, because the photopic human eye is most sensitive to wavelengths at 555 mμ. The human eye is almost as sensitive to white light as it is to green light; thus green and white light emitters are the best choices for matrix emitters from the standpoint of the observer viewing a matrix display. Emitters of other monochrome wavelengths are less efficient for visual perception. For example, red at 660 mμ is only 6 percent as efficient as green at 555 mμ. Hence, red must provide 16 times the energy of green to be equally bright as seen by the observer. The orange plasma display at 585 mμ is 80 percent as efficient as green. Yellow at 575 mμ is 90 percent as efficient as the green. Figure 43 shows the relative sensitivity of the photopic and scotopic adapter eye for the visual spectrum. The display designer must trade off visual efficiency for emitter device efficiency when choosing a color for matrix displays.

Blue should, whenever possible, be avoided as an emitter color in monochrome displays. Normal human beings have what is called blue myopia. Blue light is focused myopicly by the eye and cannot be accommodated, resulting in an 80 percent reduction of visual acuity in white light.

A disadvantage of utilizing color emitters is that some people are color-defective. About 8 percent of all males and 0.4 percent of all females exhibit some form of color blindness, resulting in a decrease of visual sensitivity by at least 35 percent. For example, 1 percent of the population exhibits a form of color blindness known as protanopia (non-response to wavelengths greater than about 640 mμ). For these people a red 660 mμ LED would be essentially invisible.

The display designer must therefore take into consideration 1) the relative efficiencies of matrix display emitters and the human eye, 2) the reduced visual acuity that occurs for blue, and 3) the user population as regards color blindness when selecting an emitter of a given wavelength for matrix display applications.



*NOTE: RELATIVE SPECTRAL DISTRIBUTION DESIGNATES THE RELATIVE VISUAL STIMULATION FOR EQUI-ENERGY INPUTS FOR THE EYE RESPONSE.

Figure 43. Eye sensitivity to light wavelength.

## 4.4 SYMBOL SUBTENSE

The results of the laboratory studies conducted during the current investigation showed that there was no appreciable interaction between symbol subtense and symbol writing mode. It was therefore concluded that no differential effect of symbol subtense on matrix as opposed to stroke written symbology exists. In other words, the effect of symbol subtense is common to stroke and matrix displays, and the large body of existing data on symbol subtense can be applied in the design of matrix displays.

Summarizing from the literature survey (Appendix A), symbology should subtend between 22 and 26 minutes of arc to ensure good legibility under normal operating conditions. Under ideal viewing conditions, e.g., high contrast, no vibration, and no symbol motion, symbol subtenses as low as 16 arc-minutes can be tolerated but are not recommended. The decrement in legibility when symbol subtense is reduced from 22 to 16 minutes of arc is about 17 percent in symbol reading rate.

## 4.5 SYMBOL DEFINITION AND SYMBOL ROTATION

The most important implication of the data collected during the symbol orientation, definition, and rotation study is that for the vast majority of matrix display applications; namely, those using non-rotating upright symbology, symbology constructed in a 5 x 7 format provides sufficient symbol definition for good legibility. Other studies reviewed in the literature survey, namely, Shurtleff (1970) and Vartebedian (1970) have produced conflicting results as to whether any improvement accompanies an increase in matrix size from 5 x 7 to 7 x 11).

When displayed symbology is to be rotated within the framework of a fixed matrix array, 5 x 7 symbology is severely distorted, and a higher symbol definition is required. If a small decrement in time and accuracy of reading rotated symbology can be tolerated, a symbol definition of 8 x 11 elements is adequate. For critical tasks with rotated symbols, where speed and accuracy is important, it is recommended that a still higher symbol definition be used. No decrement in performance was observed when symbol definition reached the level of 15 x 21 elements.

The foregoing discussion is true for an X-Y matrix array of square elements. Further research is required to assess the effect of rotation on other types of matrix arrays such as a beehive arrangement of hexagonal elements.

## 4.6 EMITTER LUMINANCE, SURROUND LUMINANCE, CONTRAST, PERCENT ACTIVE AREA, EMITTER SIZE, AND EMITTER SPACING

Percent active area, emitter size, emitter spacing, symbol definition, and symbol subtense are non-independent parameters. Percent active area, emitter luminance, and surround luminance are behaviorally related as shown in this research program. The above seven parameters must therefore be considered together by the designer of a matrix display. The following formulae based on geometrical considerations, illustrate the interdependence of some of these parameters:

$$\text{Active Area (\%)} \triangleq \left(\frac{\text{Element Size}}{\text{Element Spacing}}\right)^2 \times 100$$

$$\text{Symbol Height} = (\text{Symbol Definition} - 1)(\text{Element Spacing}) + \text{Element Size}$$

$$\text{Symbol Subtense} \cong \text{Arctan}\left(\frac{\text{Symbol Height}}{\text{Viewing Distance}}\right).$$

The results of the active area and surround luminance study indicated that Blackwell's (1946) data can be used, with appropriate field factors and adjustment for illuminated area within the target symbol, to determine matrix display luminance and active area requirements for various surround luminances and to make tradeoffs between percent active area and emitter luminance. The good correlation with Blackwell's data allows the designer to have greater confidence when forced to extrapolate to adaptation levels not examined in this study. The design tradeoff between active area and emitter luminance is indicated by the relationship

$$\text{Area} \times \text{Emitter Luminance} = \text{Constant.}$$

where

$$\text{Contrast} \triangleq \frac{B_{max} - B_{min}}{B_{min}} = \frac{B_{emitter}}{B_{surround}}$$

the latter being for the special case of an unfiltered display and a display with only one intensity level. Other cases where filters are utilized and multiple gray shades exist, may be handled by proper determination of the adaptation level of the eye and the local area contrast.

To illustrate the practical use of the data from the active area, surround luminance study, the following example is presented. Assume that a matrix display must be designed to be comfortably visible in an environment having a surround luminance of 500 fL, a viewing distance of 28 inches, an active area of 35 percent, a symbol height of 0.20 inch, and a symbol definition of 8 x 11. What are the resulting requirements for emitter luminance, emitter size, and emitter spacing? Assume that the average symbol uses 40 elements of an 8 x 11 array or 0.455 of the total of 88 elements encompassed by the symbol. The area subtended by a symbol is:

$$S_A = \text{Symbol Height} \times \text{Symbol Width} = (0.20)\,\frac{(8)}{11}\,(0.20) = 0.03 \text{ inch}^2$$

The diameter of circular disk having the same area is:

$$D = \left[\frac{(0.03)(4)}{\pi}\right]^{1/2} = 0.19 \text{ inch},$$

which at 28 inches subtends 24 arcminutes. Blackwell's (1946) data yields a threshold contrast of $C_{0.5} = 0.0032$. (50 percent probability of detection.) A commonly accepted field factor of 2.5 should be applied to the above value of contrast to reach a probability of detection of near 1.0. In addition, a factor of 1/0.455 is applied to account for the reduced element utilization of the average symbol. Note that this represents the relation already established in these studies; namely that Area x Emitter Luminance = Constant.

$$\text{Contrast (C)} = \frac{0.0032 \times 2.5}{0.455} = 0.0176$$ (100 percent probability of detection and active area with 45.5 percent utilization)

At this point, percent active area and element luminance may be traded off directly by the relation $C_1A_1 = C_2A_2$. For an active area of 35 percent,

$$C_2 = \frac{C_1A_1}{A_2} = \frac{0.0176 \times 100}{35} = 0.05$$

since $B_{\text{emitter}} = \text{Contrast} \times B_{\text{surround}}$,

$$\Delta B_T = 0.05 \times 500 = 25 \text{ fL},$$

where $\Delta B_T$ is the required emitter luminance for threshold legibility. The field factor to obtain a viewing comfort level was determined in the active area, surround luminance study and is given by:

$$F = \frac{50 + 2A - 0.02A^2}{0.2} = \frac{50 + 2(35) - 0.02(35)^2}{(500)^{0.2}} = 27.6,$$

thus

$$B_c = 25 \times 27.6 = 690 \text{ fL}$$

where $\Delta B_c$ is the required emitter luminance for comfortable viewing. Note that emitter luminance is defined as being measured in a dark surround.

To illustrate the relation between symbol height, symbol definition, percent active area, emitter size and emitter spacing, the above example is continued.

Symbol Height = (Symbol Definition - 1)(Element Spacing) + Element Size

$$\text{Percent Active Area} = \left(\frac{\text{Element Size}}{\text{Element Spacing}}\right)^2 \times 100$$

Substituting known values yields:

$$0.20 = (10)\ \text{Element Spacing} + \text{Element Size, and}$$

$$35 = \left(\frac{\text{Element Size}}{\text{Element Spacing}}\right)^2 \times 100$$

Solving for the two unknowns yields

$$\text{Element Size} = 0.0112 \text{ inch and}$$

$$\text{Element Spacing} = 0.019 \text{ inch}$$

Other field factors may or may not be appropriate depending on the particular situation. Some of these field factors, taken from Blackwell (1959) and Taylor (1964), are presented in Table 10 as supplementary data.

The example given in this section represents only one set of initial design constraints. Any other set of constraints or initial assumptions may be handled in similar fashion. For example, one could start with a known emitter size and spacing and work the above design problem backwards and calculate the percent active area and required emitter luminance and symbol height.

## 4.7 VIEWING ANGLE

The conclusion reached in this research program is that the effect of off-axis viewing of symbology on matrix displays is the same as that for continuous stroke-written symbology. The effect of the visual foreshortening of symbology in the horizontal plane results in a reduction of detail that the eye can discriminate. This effect has been documented in detail by the studies reviewed in the Literature Survey and may be compensated for by increasing the visual subtense by an equivalent amount to the foreshortening by either

TABLE 10. FIELD FACTORS FOR VISUAL PERFORMANCE DATA.

| To obtain P of: | Multiply contrast for P = 0.5 by: |
|---|---|
| 0.90 | 1.50 |
| 0.95 | 1.64 |
| 0.99 | 1.91 |
| 1.00 | 2.50 |

Subject Task Variables

1 = Knowledge

0 = Lack of Knowledge

| Location $\pm 4^{o}$ or More | Time of Occurence | Size | Duration | Field Factor |
|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1.00 |
| 1 | 0 | 1 | 1 | 1.40 |
| 1 | 0 | 1 | 0 | 1.60 |
| 1 | 0 | 0 | 1 | 1.50 |
| 1 | 0 | 0 | 0 | 1.45 |
| 0 | 1 | 1 | 1 | 1.31 |

increasing the symbol size or reducing the viewing distance. For visual angles of less than 30 degrees, this amount is usually negligible.

Another effect of off-axis viewing is that of luminance falloff due to a non-diffuse surface or emitter. This effect is device dependent and therefore the data for each particular device should be consulted. Compensation for any sharp luminance falloff as a function of viewing angle may be made by increasing the emitter luminance by the appropriate factor or limiting the off-axis viewing angle of the observer.

## 4.8 VIBRATION

There is no reason to suspect that matrix symbology per se is differentially affected by vibration as compared to stroke written symbology. However, no data on this subject was collected to substantiate this hypothesis during these studies, and additional studies are recommended. Until more information is available, it is recommended that the documentation presented in the Literature Survey be used to design for vibration effects. Summarizing those results, it was concluded that the detrimental effects of vibration can be reduced by proper design of the symbology. This can be effected by increasing the symbol subtense and/or the contrast and surround luminance as demonstrated by Carel, McGrath, Hershberger, and Herman (1974). In other words, the effects of vibration are more detrimental to symbol legibility under poor viewing conditions than under good viewing conditions and vibration effects should be minimized by improving viewing conditions. This is further supported by the findings of Wulfeck, Weisz, and Raben (1958). A measure of the increase in symbol subtense that is necessary to compensate for vertical vibration representative of a UH-1 heliocopter is given in Table 11 which was taken from Carel, McGrath, Hershberger, and Herman (1974).

TABLE 11. PERCENT INCREASE IN VISUAL ANGLE DUE TO VIBRATION

| | Percent Increase Visual Angle | |
|---|---|---|
| Contrast/Luminance | Threshold Legibility | Comfort Legibility |
| 0.1/10 | 43.4 | 34.2 |
| 0.1/1000 | 39.3 | 29.7 |
| 0.8/0.1 | 50.3 | 36.6 |
| 0.8/10 | 21.7 | 15.9 |
| 6.0/0.1 | 53.7 | 41.2 |
| 6.0/1000 | 32.3 | 22.0 |

An effect that is peculiar to some matrix display devices is a strong interaction of refresh rate and vibration. A notable case in point is light emitting diodes which have very sharp turn-off characteristics and which are often operated with low duty cycles. When viewed under conditions of vibration, the emitter will tend to be seen in multiple locations much the same as the spokes of a wheel viewed under stroboscopic light. To overcome this effect, the refresh rate should be increased to the point where the motion due to vibration appears continuous. Preliminary data collected by the Air Force Flight Dynamics Laboratory indicate that a refresh rate in excess of 500 Hz is necessary to overcome this phenomenon; although, this probably depends on the duty cycle and particular frequency and amplitude of the vibratory motion. More data are needed to provide a solid design base.

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# APPENDIX A

# LITERATURE SURVEY ON MATRIX DISPLAY SYMBOL LEGIBILITY

As part of this research project, a review of existing literature in the field of matrix display symbol legibility was made. The objective of the literature review was to provide a data base from which the laboratory research parameters and the values of these parameters could be specified. After initiating the literature review, it soon became apparent that little behavioral research on matrix display legibility had been conducted. The bulk of the available literature on symbol legibility has been conducted with stroke or segmented characters. This literature was compiled along with the small amount of available research data on matrix displays under 10 topic headings. The 10 topic headings are:

- Alphanumeric font
- Non-alphanumeric symbol shape
- Symbol subtense and symbol definition
- Emitter shape and configuration
- Percent active area
- Viewing angle
- Contrast and adaptation level
- Color
- Symbol orientation and symbol motion, and vibration.

The behavioral data available for each of the topic areas was reviewed and compiled, and where appropriate, the implications to the laboratory research program conducted and to matrix display design are discussed.

A major source of information for this literature review was the alphanumeric design considerations chapter from the Semple, Heapy, Conway and Burnette (1971) technical report on Analysis of Human Factors Data for Electronic Flight Display Systems. The bibliography contains 90 references that were used in the preparation of this literature review.

## A. 1 FONT

There are many definitions of the word font. Speaking in terms of display systems design and usage, Semple (1971) defined font as referring to the "fundamental geometry or style of a particular set of alphanumerics." He declared it "the basic framework for the generation of a set of alphanumerics [influencing] other symbol characteristics such as width-to-height and stroke-width-to-height" (p. 151). Following is a review of the literature pertaining to changes in alphanumeric symbol "legibility" resulting from the use of varying alphanumeric fonts. Here, and throughout this literature review, legibility is operationally defined as a property of alphanumerics which can be measured in terms of three objective performance criteria: accuracy, speed, and rate (symbols per unit time) of symbol identification.

### A. 1. 1 Non-Electronic Display Studies

Literally hundreds of legibility studies have evaluated various discrete features of hardcopy characters (see Cornog and Rose, 1967). More importantly, a few investigators have attempted to develop maximally legible sets of alphanumerics (i.e., fonts) for specific applications. For example, in the 1950's research on the optimum design of alphanumeric characters for aircrew station displays led to the development of the NAMEL font which was standardized by the armed services in MIL-M-18012 and MS 33558 (see Figure 44).

In a study conducted by Brown (1953), the legibility of NAMEL letters was compared with that of another set designated Garamond Bold. The intent of the study was to compare the legibility of NAMEL letters, constructed with a uniform stroke-width-to-height and without serifs (a fine line or embellishment appearing chiefly at the ends of symbol strokes), to the legibility of Garamond Bold letters, constructed with a variable stroke-width-to-height ratio and with serifs. Only 19 of the 26 letters were used in the experiment (B, I, J, K, Q, V, and W were excluded due to their infrequent use on instrument and control panels). The 19 letters were presented for identification at a 0.20 second viewing time with brightnesses of 0.30, 0.80, 1.60, 2.60, and 3.30 foot-Lamberts (fL). Study results indicated that for accuracy of identification, NAMEL letters were superior to the Garamond Bold letters at all brightness levels tested, with the greatest differences falling at the 0.30 and

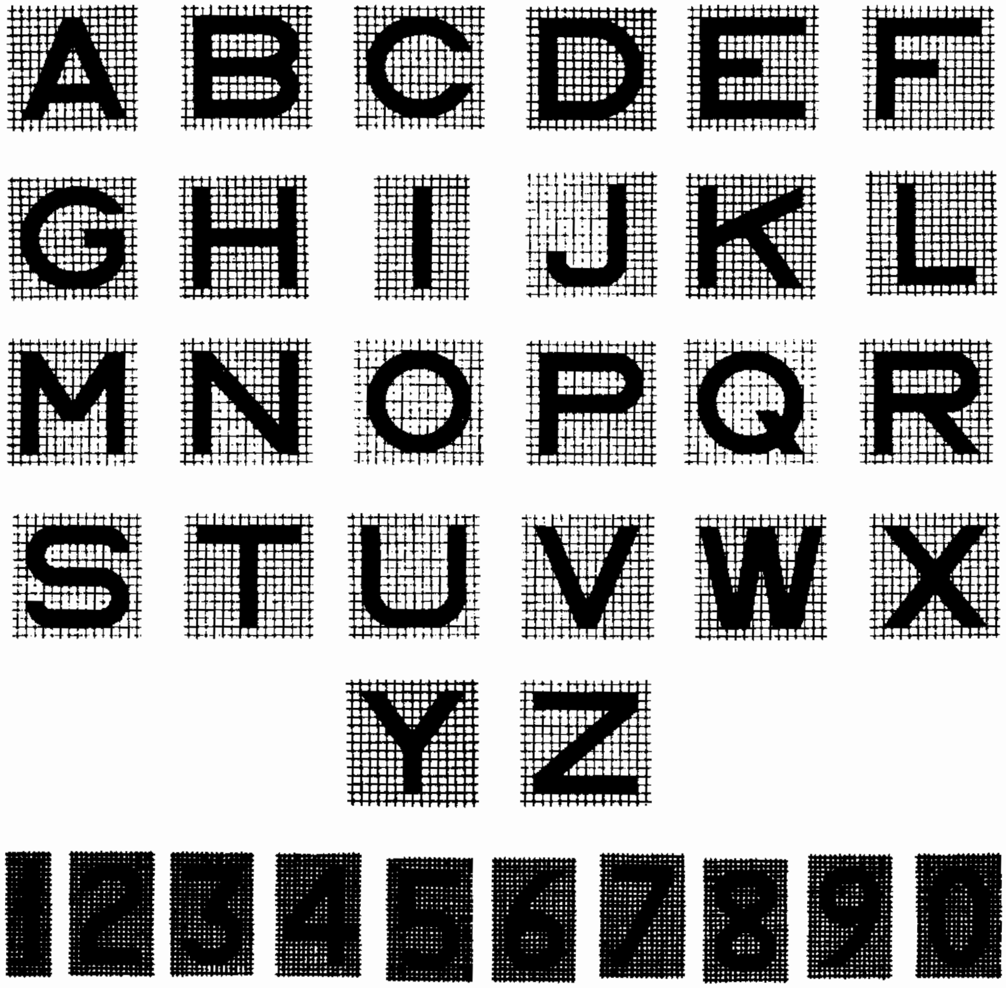


Figure 44. MIL-N-18012 (NAMEL) letters and numerals.

0.80 fL levels. Similarly, when symbol exposure time was shortened to 0.04 second, NAMEL letters retained their superiority. (The statistical significance of differences in accuracy of identification was not reported for any of the conditions studied). Thus the Brown study indicated that, for most of the conditions investigated, accuracy of identification was better for letters constructed with uniform stroke-width and without serifs.

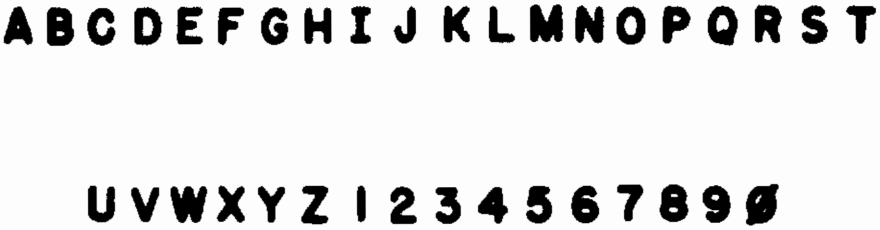
Noting the above results, D. A. Shurtleff (1966), in his report on the the classical factors in the legibility of numerals and capital letters, recommended that "letter styles featuring variable stroke-widths and serifs be avoided in display situations, particularly when factors such as symbol brightness and exposure times are at marginal values" (p. 77).

Another attempt to improve the legibility of an entire set of alphanumerics was launched by Mackworth (1944). The symbols Mackworth redesigned were those used on air raid sector maps. Mackworth evaluated his new symbol set against the existing one containing letters similar to the AND 10400 style and numbers similar to the Leroy style (see Figure 45). Mackworth conducted symbol identification tests on the two sets of alphanumerics with the angles subtended by the height of the symbols ranging from 6 to 9 minutes of arc. The symbols were presented one at a time for approximately 1-1/2 seconds at 10 fL illumination. The symbols in the old design were shown as dark on an orange background while the symbols in the new design were shown as dark on a yellow background. Mackworth found that for accuracy of identification, his font was superior to the old design. However, as Crook and Baxter (1954) pointed out, the use of different colored backgrounds probably gave the symbols of the new design higher brightness contrast than the old design, a factor which may have confounded Mackworth's findings of apparent superiority for his new font.

Noting the inconclusiveness of Mackworth's evidence, D. A. Shurtleff (1966) contended "It still might be argued, on the basis of the geometry of the symbols alone, that the new set of symbols is better than the old, since commonly confused symbols were redesigned to increase their geometric distinctiveness" (p. 74). Shurtleff cited some examples of the changes in symbol geometry made by Mackworth: the lengthening of the bars on the "Q" and "G", the addition of overhangs to the "B", and the enlargement of the gap in the "C".

MACKWORTH ALPHANUMERICS

AND 10400 NUMERALS



STANDARD LEROY ALPHANUMERICS

Figure 45. Three fonts: Mackworth alphanumerics, AND 10400 numerals, and standard Leroy alphanumerics.

Mackworth's work on the development of a universally legible font was taken up by Lincoln Laboratory in Lexington, Massachusetts, which modified Mackworth's original font. Further refinement of the symbol set originally designed by Mackworth, carried on by the MITRE Corporation of Bedford, Massachusetts, led to the development of a font called Lincoln/Mitre.

The Lincoln/Mitre (L/M) font (see Figure 46) was compared with the Leroy font (a standard lettering style used extensively in commercial art and advertising) by Showman (1966). Nine subjects were presented with letters shown one at a time with an exposure time of 10 msec. The symbols subtended 16 minutes of arc at the subject's eye, and the background luminance was 1 fL in all cases. The results of the study showed that subjects made fewer errors identifying the tachistoscopically presented L/M symbols than identifying Leroy symbols at each of several values of brightness contrast ratios (ranging from 4:1 to 10:1).

The results of the foregoing non-electronic display research are not necessarily applicable to the operational electronic displays where the method of symbol generation influences such crucial legibility factors as symbol shape, width-to-height ratio, stroke-width-to-height ratio, brightness contrast, and edge sharpness. According to Semple (1971), "Electronic display alphanumeric standards based on non-electronic display research represent an extrapolation which does not consider the large number of highly technical and interacting factors induced by the electronic system of symbol generation" (p. 160). In addition, many of the non-electronic display studies ignored variables of crucial importance thereby decreasing their utility. For example, as pointed out by Simpson (1971), "... only one out of 300 papers on digit legibility (reviewed by Shurtleff 1966) considered the effects of ambient light, which was likely to be a major variable, because of the self-illumination characteristics of electronic displays" (p. 499).

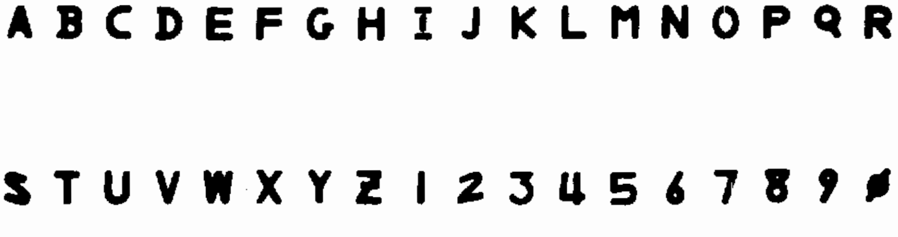


Figure 46. Lincoln/Mitre Alphanumerics.

### A. 1. 2 Electronic Display Research

A majority of the electronic display research on symbol legibility has been conducted on cathode ray type displays. An early attempt to construct an optimum font was conducted by Rowland and Cornog (1958) who examined the applicability of several commercially available printing fonts for use on closed-circuit television displays in an air traffic control system. Based on subjective evaluations, these investigators concluded that none of the existing fonts was acceptable. Attempting to produce an improved font design, Rowland and Cornog constructed a set of upper-case alphanumeric characters which they designated the Courtney font (see Figure 47). Again employing a subjective evaluation technique to compare the legibility of the new Courtney font with that of existing commercial fonts, subjects were asked to judge which designs were most readable. On the basis of these evaluations, Rowland and Cornog concluded that their new Courtney font was superior.

In a study conducted by Moore and Nida (1958), the apparent superiority of the Courtney font was reconfirmed. Employing a subjective method of evaluation, these investigators arrived at a conclusion parallel to that of Rowland and Cornog: that for CRT application, the Courtney font was superior to 67 commercially available fonts.

Shurtleff and Owen (1966), however, conducted an objective assessment of the Courtney font. They compared it with the standard Leroy font using a Miratel 14-inch video monitor and a 525-line Fairchild television camera. Legibility was measured in terms of both accuracy and speed of symbol identification. Study results showed that for symbol resolutions of 6, 8, 10, and 12 lines per symbol height, subjects with a small amount of practice identified the televised Courtney font less rapidly and less accurately than the Leroy font

Figure 47. Courtney Alphanumerics.

(see Figures 48 and 49). With additional practice, however, subjects found the Leroy and Courtney fonts to be similar in speed and accuracy of identification (see Figures 50 and 51). Differences between fonts were not statistically significant, nor was there a significant interaction between font and resolution. Shurtleff and Owen concluded, "There seems little to be gained by using the Courtney symbols for television, since the performance was not better than that obtained with the Leroy alphanumerics. Furthermore, the data suggest

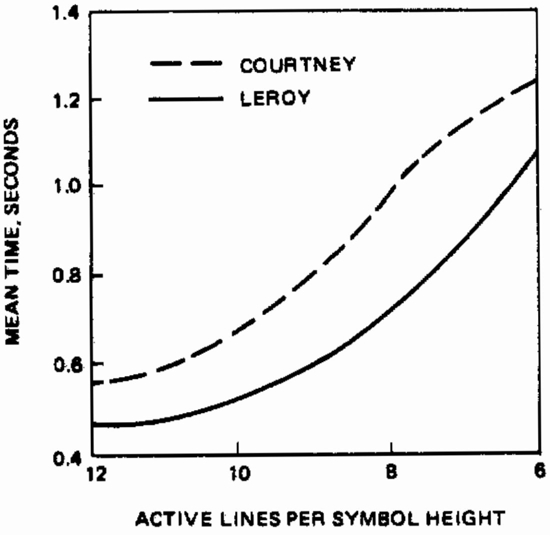


Figure 48. Average identification time as a function of vertical resolution for the Small Amount of Practice Group, Part I.

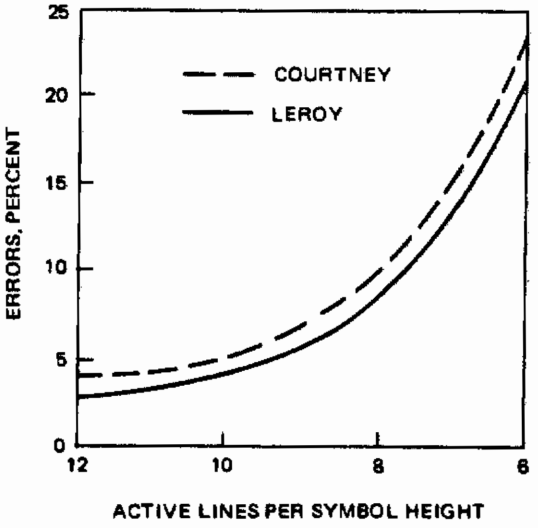


Figure 49. Identification errors as a function of vertical resolution for the Small Amount of Practice Group, Part I.

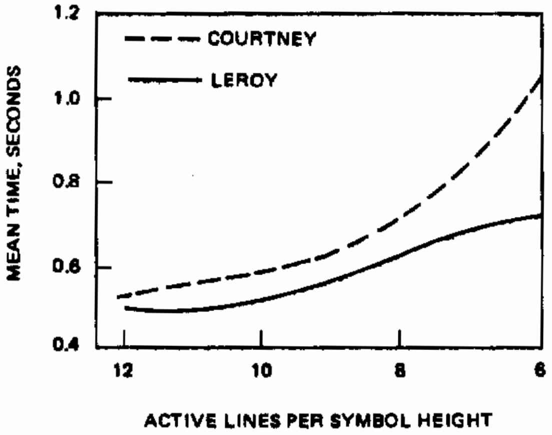


Figure 50. Average identification time as a function of resolution for the Additional Practice Group, Part II.

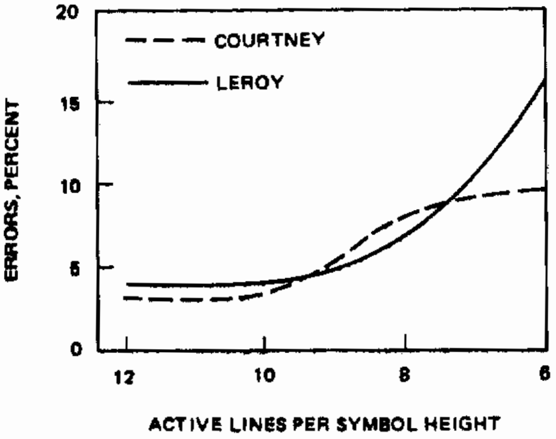


Figure 51. Identification errors as a function of resolution for the Additional Practice Group, Part II.

that the viewer must be given practice with the Courtney symbols before performance becomes as good as that obtained without practice with a standard lettering font" (p. 24). On the basis of the above, Leroy symbols were recommended for television displays due to their "familiarity, ease of construction, and greater availability."

Shurtleff, Marsetta, and Showman (1966) attempted to improve standard Leroy symbols for television use by redesigning a subset of 11 symbols which previous investigations had shown to be easily confused. (The symbols B, G, H, K, Q, S, Z, 1, 5, 6, 7 were modified for CRT usage). Using a General Precision 945-line television camera and a Conrac 21-inch video monitor, minimum symbol sizes (converted to visual angle of subtense) were established for both the standard and revised Leroy fonts for 85 and 99 percent correct levels of symbol identification. Across all resolutions studied (6, 8, and 10 active raster scan lines per symbol height) visual angles of subtense were similar for both fonts (see Table 12). Thus, for the conditions tested, neither of the fonts appeared superior for CRT usage. Of the 11 symbols modified in the revised style, only the H and B were recommended for inclusion in the standard Leroy font for use on television. Semple (1971) also, in a review of the literature, concluded that "the standard Leroy font is acceptable for electronic display usage" (p. 162).

Based on the findings of Shurtleff and Owen (1966) and on the results of their own literature review, Ketchel and Jenny (1968) reaffirmed the legibility of the Leroy font. However, noting the similarity between the Leroy font and MIL-M-18012 alphanumerics, and due to the relative availability of the latter set, Ketchel and Jenny made the following statement: "As to character font, stroke width, and width-to-height ratio, we also conclude that MIL-M-18012 is suitable as a goal for EO displays so long as allowances are made for departures from this norm due to the techniques of generation and the vertical and horizontal resolution of the display system" (p. 153).

TABLE 12. VISUAL ANGLES OF SUBTENSE REQUIRED FOR 85 AND 99 PERCENT ACCURACY OF IDENTIFICATION OF STANDARD AND REVISED LEROY SYMBOLS.

| Resolution, Lines per Symbol Height | Identification Accuracy, Percent* | | | |
|---|---|---|---|---|
| | Standard Symbols | | Revised Symbols | |
| | 85% | 99% | 85% | 99% |
| 10 | 7.58 | 13.15 | 7.59 | 13.37 |
| 8 | 7.57 | 12.82 | 7.70 | 15.09 |
| 6 | 10.35 | 35.97 | 11.01 | 30.08 |

*Tabled entries are required minutes of arc

Semple, in a review of the literature, pointed out that the proported suitability of MIL-M-18012 for electronically generated alphanumerics was an extrapolation based upon the apparent similarity of this font to the standard Leroy (which had been empirically tested). Differences between the two fonts do exist, however, (differences were noted for the C, I, J, M, 4, 5, 6, 9, and zero) and until the effects of such differences on symbol legibility are objectively determined the suitability of this font is suspect.

It will be recalled that Showman (1966) demonstrated the superiority of the solid-stroke Lincoln/Mitre (L/M) font over the standard Leroy font. However, it has been pointed out above that information relating to non-electronic display alphanumerics may not be directly applicable to electronically generated displays. Support is provided for this theory by the finding that televised L/M symbols were not superior in legibility to televised Leroy symbols (Shurtleff, 1967). More specifically, Shurtleff (1967) compared the legibility of standard Leroy alphanumeric symbols to the L/M font on a television monitor at resolutions of 8, 10, 12, and 14 lines per symbol height. The L/M font was not found to be superior in legibility to the Leroy font at any of the values of resolution tested. It seems likely that the symbol generation technique and display media employed in TV displays played a major role in the result of no superiority of legibility for the L/M font. Indeed Shurtleff himself commented upon some of the unique factors involved in TV symbol design. He noted two major characteristics of television which influence symbol geometry: "The cutting up of symbols by the active lines of the television raster, and the 'on-off' characteristics of the scanning element" (p. 4). He noted that, "the first characteristic affects symbol geometry by deleting selected parts of the symbol, while the second characteristic may affect symbol geometry by smearing, which is caused by the lack of a sharp 'on-off' response of the scanning element in horizontal transitions from light to dark areas" (p. 4).

Looking back on the data presented thus far concerning both hardcopy and CRT displayed fonts, it becomes evident that no one font has been proven to be consistently superior in legibility. Indeed inspection of figures 1 through 4 show there to be little physical difference between the Leroy, Courtney, Lincoln/Mitre, MIL-M-18012, and Mackworth alphanumerics. Thus, one is led to anticipate little difference between fonts displayed on matrix displays.

A small amount of research effort has been directed to the investigation of the relative legibility of symbols constructed on a matrix display. Of particular importance is a study reported by Shurtleff (1970) in which legibility comparisons were made among four 5 x 7 dot fonts (See Figure 52). The four fonts selected for investigation, as well as the stated reasons for their selection, were as follows:

(1) IBM 029 - Selected because of its use on the IBM 029 key-punch machine,

(2) HAZELTINE (HAZ) – Selected because the modified HAZ font is recommended for use in digital television displays,

(3) A font proposed by the Diamond Ordnance Fuse Laboratory (DOFL) – Selected because it was designed to be easily read by both man and machine,

(4) The Lincoln/Mitre font (L/M) – The 5 x 7 dot font employed here attempted to duplicate as closely as possible the solid stroke L/M font which had been shown to be superior in legibility to a standard Leroy font (Showman, 1966). (See Figure 9 for examples of the four 5 x 7 fonts investigated).

The apparatus employed in the study consisted principally of a PDP-8 computer (used to construct the symbols and generate symbol sequences) and a Tektronix type RM oscilloscope (DEC type 34) fitted with a P-7 phosphor. Symbol sequences were arranged such that nine symbols were displayed in a 3 x 3 array on the oscilloscope. The height of the 5 x 7 matrix out of which symbols in each of the four fonts were constructed was 0.150 inch and its width was 0.092 inch. The height-to-width ratio of the matrix was 1.63 and the stroke width of the symbols was 0.024 inch. The luminance of dots composing the symbols ranged from 14 to 16 fL. (Note: no precautions were taken to insure a consistent luminance distribution across the spot). Four operators viewed symbols whose height subtended 6 minutes of arc. A second group of four operators viewed symbols whose height subtended 22 minutes of arc. In a given array, the symbols were spaced horizontally 50 percent of symbol height and vertically 100 percent of symbol height. Operators were asked to read each array as fast and as accurately as possible (in normal

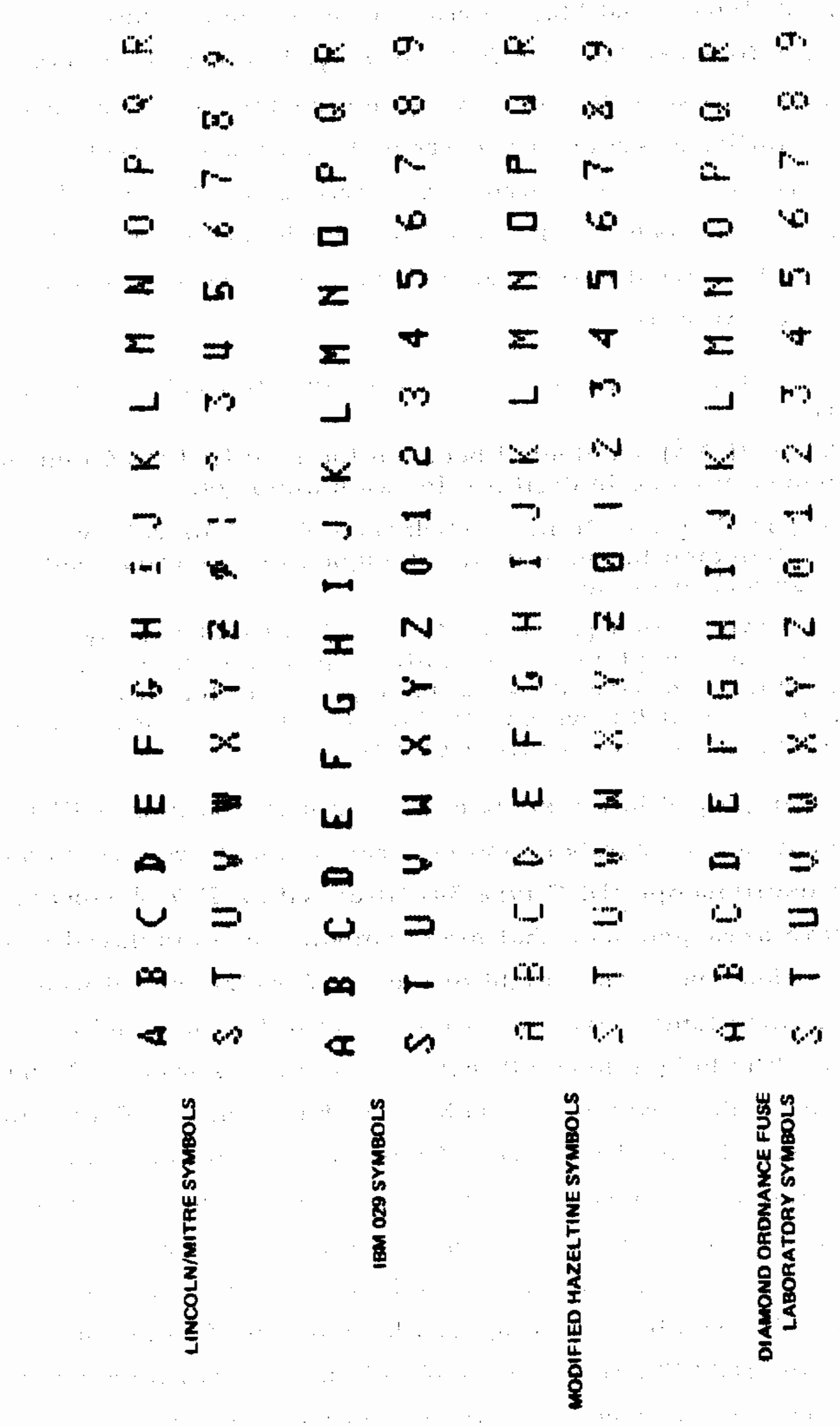


Figure 52. The four 5 x 7 fonts that were compared by Shurtleff (1970).

reading fashion: left to right, top to bottom). Study results showed that no one symbol set was significantly superior in legibility to any of the other sets.

As pointed out above, physical differences between several of the existing fonts are small, with reports of superiority of one over another proving inconsistent. Thus the Lincoln/Mitre font was chosen for use in the laboratory research due to this lack of differences between fonts and the fact that the Lincoln/Mitre font has already been defined for matrix contruction (see Shurtleff, XXI, 1970; and Anderson, 1970). Some evidence already exists as to the legibility of matrix presented Lincoln/Mitre alphanumerics displayed under a variety of conditions. While not employing font as a variable, several studies conducted by Shurtleff (Studies of Display Symbol Legibility: XXI, XXIII, and XXV, 1970) utilized the Lincoln/Mitre font in investigations of the effects of matrix construction techniques, matrix size, and symbol overprinting. In addition, Semple (1971) reviewed preliminary results of a study conducted by Anderson (1970) in which it was reported that subjects viewing CRT displayed L/M alphanumeric matrices were capable of 98.14 percent accuracy and 120.64 character-per-minute identification rates. All symbols were formed in a 7 x 9 matrix and were 0.095 inches in height and subtended 7 minutes of arc at a viewing distance of 46.6 inches. Commenting upon the limitations of the study (no reported luminance values and an extremely rapid exposure time), Semple concluded that "CRT viewed Lincoln/Mitre alphanumeric dot-matrices are highly legible even for the relatively small symbols presented" (p. 183).

It is important to note here that a consideration of "font" in the more comprehensive sense is important when dealing with matrix legibility. While the present research is investigating the legibility of L/M alphanumerics constructed with from 7 to 21 dots in the vertical dimension, it is impossible, of course, to equate symbol style exactly as matrix size increases. Thus, as stated in the beginning of this review, the word font refers to the geometry of a symbol and geometry necessarily changes as spacing of dot elements or the number of constituent elements changes. Shurtleff (1970) has stated that the major advantage of increasing the number of dot elements is that the symbols can be designed to approximate more closely the conventional styles constructed with a solid stroke. He goes on to state that "while symbol style is inherently associated with increasing the number of dot elements, some degree of control can be placed on this factor by trying, with each matrix size, to form a set of symbols which approximates as closely as possible some standard design" (p. 3). Thus in the present research, while alphanumerics at all matrix sizes were designed to approximate the Lincoln/Mitre font, font in the broad sense of the word changed with changes in matrix size to the extent that these approximations were imperfect.

## A. 2 SYMBOL SHAPE

Although alphanumeric codes are employed extensively in display systems, shape codes are also used for the encoding of information. Extensive research has been conducted on the relative discriminability of shapes. Most of this research has been directed toward determining the most discriminable shapes and the least confusable combinations of shapes.

Casperson (1950) conducted a study to determine the discrimination thresholds of six different geometric forms. (The influences of symbol maximum dimension, area, and perimeter, were also explored.) The six forms were the ellipse, rectangle, triangle, diamond, cross, and star (see Figure 53). The stimulus figures were solid black photographic prints; the illumination on the cards was 11.2 foot-candles. Twenty male subjects viewed the stimulus cards from a distance of 20 feet. Subjects were asked to report the form name of the symbols presented (i. e., ellipse, rectangle, triangle, etc.). Percentages of correct responses were calculated. The results showed circular and elliptical shapes to be most difficult to identify. In ranking the discriminability of the six forms, it was found that the triangles, rectangles, and crosses consistently were the most legible, while the stars, diamonds, and ellipses were less visible.

Ketchell and Jenny reported a study by Slight (1952) who investigated the relative discriminability of 21 geometric forms (see Figure 54). Six

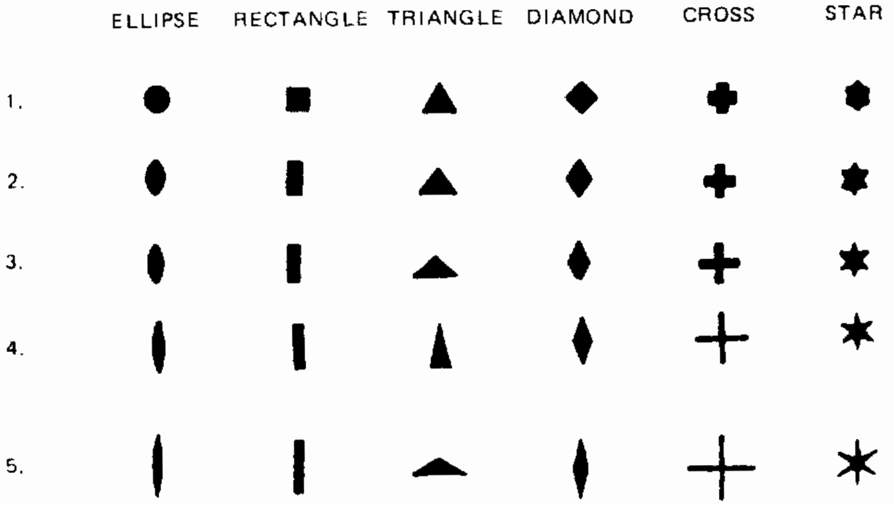


Figure 53. Forms used by Casperson (1950).

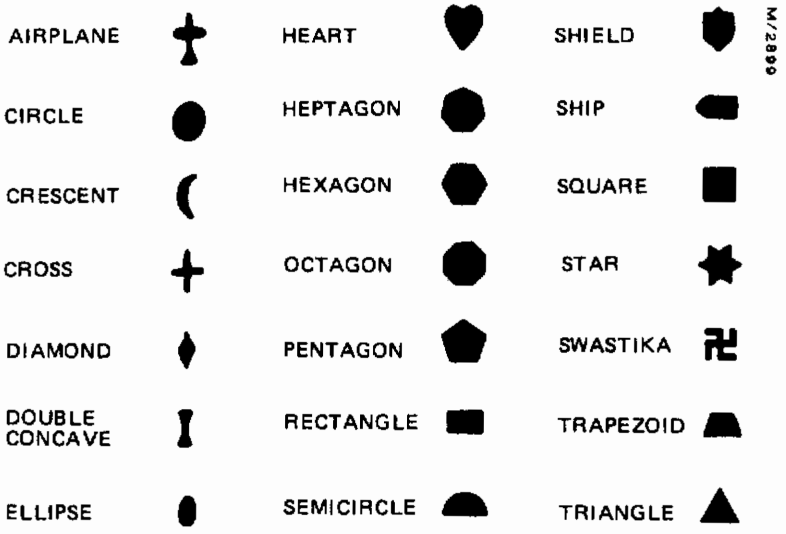


Figure 54. Forms used by Sleight (1952).

examples of the 21 forms were presented to subjects, mounted on 1-1/4-inch clear lucite squares. The figures were the maximum size that could be inscribed in a 1-inch circle. A 25-inch circle, painted flat white, was used as a display background. Twenty-one subjects were instructed to sort the forms into the correct form compartment as quickly and as accurately as possible. The forms that were most quickly and accurately identifiable were, in order, swastika, circle, crescent, airplane, cross, and star. Rectangles and triangles ranked eighth and tenth, respectively.

Honigfeld reported a study by Gerathewohl and Rubinstein (1953) who investigated the relative discriminability of a circle, square, triangle, rectangle, ellipse, and trapezoid. (Target size and position were also investigated). The results showed that the triangle, circle, and trapezoid ranked high, while the square, rectangle, and ellipse ranked low. Gerathewohl (1953) repeated the study with four symbols, under conditions of heavy video noise and found the triangle to be the easiest to recognize, followed by the square, circle, and cross.

Bowen, Andreassi, Traux, and Orlansky (1959), in a study to determine the optimum symbols for radar displays, established the absolute discriminability of a set of 20 geometric shapes (see Figure 55), under various

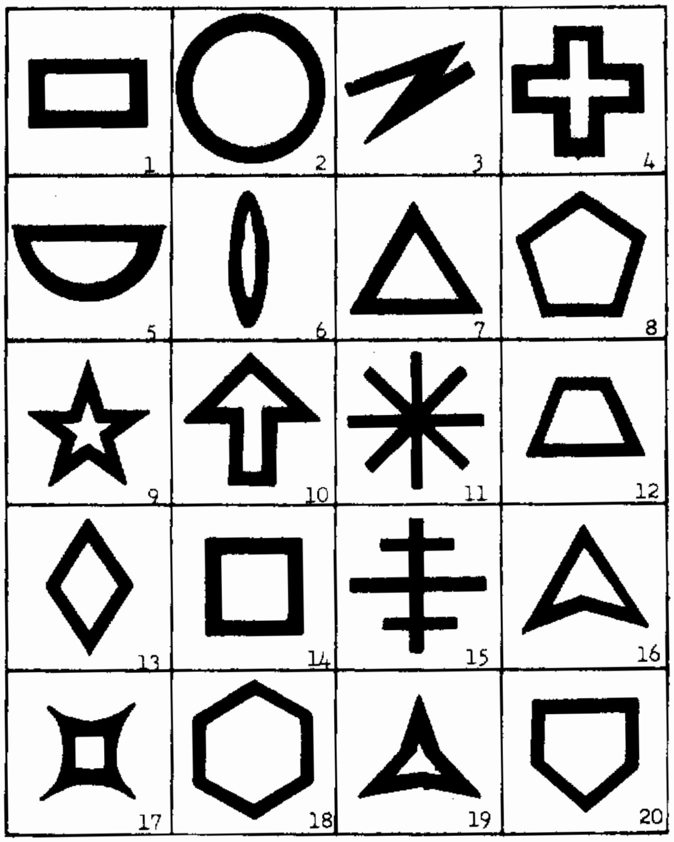


Figure 55. Symbols used by Bowen et al. (1959).

conditions of noise, distortion, and blur. Slides were made for each symbol under each of the 12 viewing conditions and were rear-projected onto the center of a 5-inch screen. Symbols subtended approximately 34 minutes of arc; display brightness was 4 to 5 fL. Seven subjects observed the 480 slides individually for 0.5 seconds. Significant differences in response accuracy were found between symbols (see Table 13), with the first seven positions being occupied by the rectangle, circle, zag, cross, half-circle, ellipse, and triangle, respectively.

Honigfeld (1964) after a review of the literature, concluded that the circle, rectangle, cross, and triangle were the most distinctive geometric forms. Semple (1971) went a step further, ranking symbols in degree of legibility; he concluded that in general, research results reviewed by him indicated the triangle was superior in legibility, followed by the square, circle, and rectangle, respectively (see Table 14).

TABLE 13. PERCENTAGE OF CORRECT RECOGNITION FOR THE 20 GEOMETRIC SHAPES USED BY BOWEN, et al.

| Symbol No. | Percentage Correct | Symbol No. | Percentage Correct |
|---|---|---|---|
| 1 | 0.916 | 11 | 0.785 |
| 2 | 0.898 | 12 | 0.756 |
| 3 | 0.869 | 13 | 0.779 |
| 4 | 0.869 | 14 | 0.506 |
| 5 | 0.839 | 15 | 0.762 |
| 6 | 0.881 | 16 | 0.553 |
| 7 | 0.875 | 17 | 0.458 |
| 8 | 0.833 | 18 | 0.720 |
| 9 | 0.839 | 19 | 0.559 |
| 10 | 0.863 | 20 | 0.690 |

It is evident that there is a lack of agreement as to the absolute ranking of discriminability for symbol shapes. One possible explanation of the diversity of findings concerns the possible confounding of study results. Many studies attempted to equate symbol "size" by equating form internal area, thus giving the triangle an advantage in terms of angular subtense when compared with other figures, and in several studies the triangle was the only form that was not similar to (thus likely to be confused with) any other form being examined. Thus, perhaps only a broad generalization is possible at this time – in general the triangle, square, circle, cross, and rectangle are typically ranked highest in legibility. There appears little reason to anticipate vast differences in legibility results due to matrix construction techniques. However, the inconsistent results obtained with solid-stroke forms makes an investigation of shape for matrix applications advisable.

TABLE 14. RANKING OF FORMS IN STUDIES REVIEWED BY SEMPLE (1971).

| | Triangle | Square | Circle | Rectangle | Hexagon | Star | Other Cross | Parallelogram |
|---|---|---|---|---|---|---|---|---|
| Kleitman | 1* | 3 | 2 | | | 4 | | |
| Collier | 1 | 2 | 4 | | 5 | | | 3 |
| Munn and Geil | 1 | 2 | 3 | 4 | 5 | | | |
| Helson, et al. | 1 | 3 | 4 | 2 | | | | |
| Whitmer | 1 | 3 | 5 | 4 | 6 | | 2 | |
| King, et al. | 1 | 2 | 3 | | | | | |
| Hockberg, et al. | | 2 | 1 | | | | 3 | |
| Hanes | 1 | 2 | 3 | | | | | |
| Fehrer | | 3 | 1 | | 2 | | | |
| Kafka | | | 1 | | | | | |

*1 = most discriminable

*2 = second most discriminable, etc.

## A. 3 SYMBOL SUBTENSE AND SYMBOL DEFINITION

A question of primary importance in display system design concerns the height of displayed symbols required for good legibility under an anticipated range of operational conditions. More specifically, it is the symbol height at the eye of the observer that affects legibility. Consequently, research results relate operator performance to the visual angle subtended by the height of the symbol at the observer's eye. This visual angle (defined as the angle formed by lines drawn from the cornea of the eye to the top and bottom of the character viewed) is a function of both the symbol size and the distance between the displayed symbol and the viewer.

The particular symbol subtense required for legibility in a given situation is dependent upon the environmental conditions under which the symbology is displayed. That is, conditions of vibration or blur, and extremes of ambient illumination or low contrast, to name a few, necessitate larger visual angles for acceptable legibility. Conversely, the larger the size of the letters and numerals, the less important become the effects of symbol background and illumination (Semple, 1971). However, practically speaking, the systems designer must restrict the available range of displayed symbol size to one that is relevant to his particular display application. As pointed out by Semple (1971), "Limitations on available display space, considerations of information density, and general economic constraints often compel the systems designer to employ symbols no larger than those required to meet the legibility requirements of the system task." (p. 165). Thus it is important to establish the minimal acceptable symbol subtense required for legibility.

Several investigators have studied the effects of symbol subtense on operator performance. For example, Howell and Kraft (1959) investigated the functions relating size, blur, and contrast to legibility of Mackworth alphanumerics on a radar-type display. The angles subtended by the height of the stimulus symbols were 36.8, 26.8, 16.4 and 6.0 minutes of arc. The solid-line white-on-black printed symbols were projected one at a time on a ground-glass screen at a rate controlled by the subjects' responses. Legibility was measured in terms of rate and accuracy of symbol identification.

The Howell and Kraft data indicated that for the non-blurred conditions, a visual angle of 16.4 minutes of arc was adequate for approximately 97 percent accuracy of identification. As size increased above 16 minutes of arc, there was little improvement in legibility except under conditions of reduced contrast and/or increased blur (see Figures 56 and 57). From their time and error data, Howell and Kraft concluded that a minimal size of approximately 16 minutes of visual angle of letter height must be exceeded "before any practical degree of legibility can be attained" (p. 14).

A study by Crook, Hanson, and Weisz (reported in Shurtleff, June 1966) investigated accuracy of identification for symbols whose height subtended 22.0, 16.0 and 11.0 minutes of arc. Study results showed a decrease in accuracy of identification for all values of stroke-width and brightness contrast when the angle of subtense was reduced from 16.0 to 11.0 minutes of arc. The average decrease in rate of identification when the visual angle was reduced from 22 to 16 minutes of arc was approximately 17 percent. The average decrease in rate of identification when the visual angle was reduced from 22 to 11 minutes of arc was approximately 54 percent.

Based on the above studies, Shurtleff (1966) concluded that symbol height should subtend between 22 and 26 minutes of arc to obtain the fastest possible rates of symbol identification for conditions similar to those of the above studies. He further concluded that symbol heights subtending less than 16 minutes at the eye should be avoided.

Meister (1969) in his Guide to Human Engineering Design for Visual Displays listed 12 to 15 minutes of arc as being the typically accepted minimal visual angle for alphanumerics presented on TV and projected displays. Semple (1971), after a review of the literature, recommended that a symbol height of 10 to 30 minutes of visual angle be investigated for various combinations of display brightness, contrast, vibration, etc. to further specify quantitative relationships between performance and visual angle.

Luxenberg and Bonness (1965) stated that for alphanumerics to be legible, the vertical angle subtended at the eye should be at least 10 minutes of arc. Noting that 10 minutes of arc is approximately 1/360 radian, they calculated that for each foot of viewing distance the character must be at least 1/30 inch in height. They further noted that while the eye can resolve

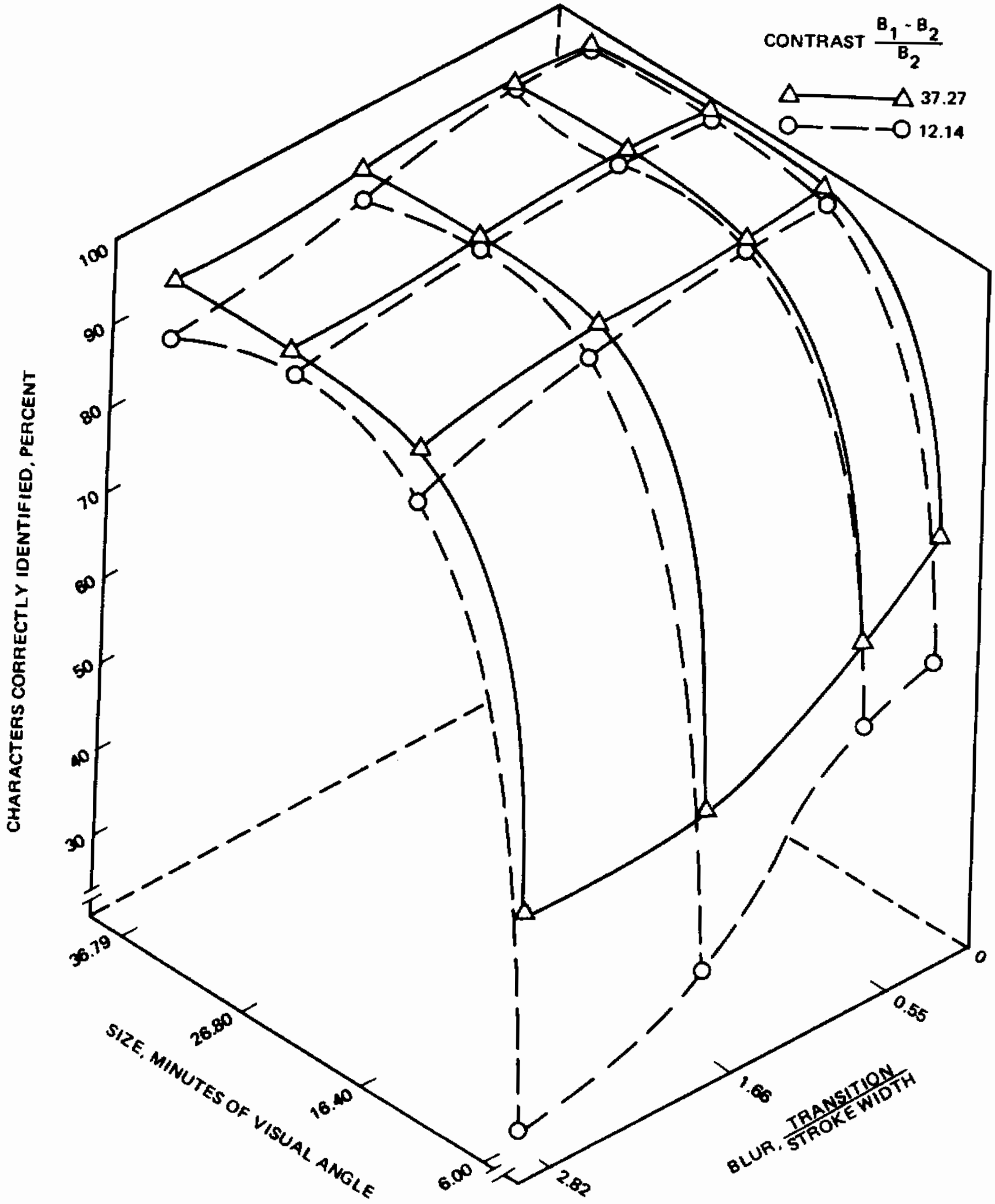


Figure 56. Percent of characters correctly identified as a function of size, blur, and contrast of letters and numbers.

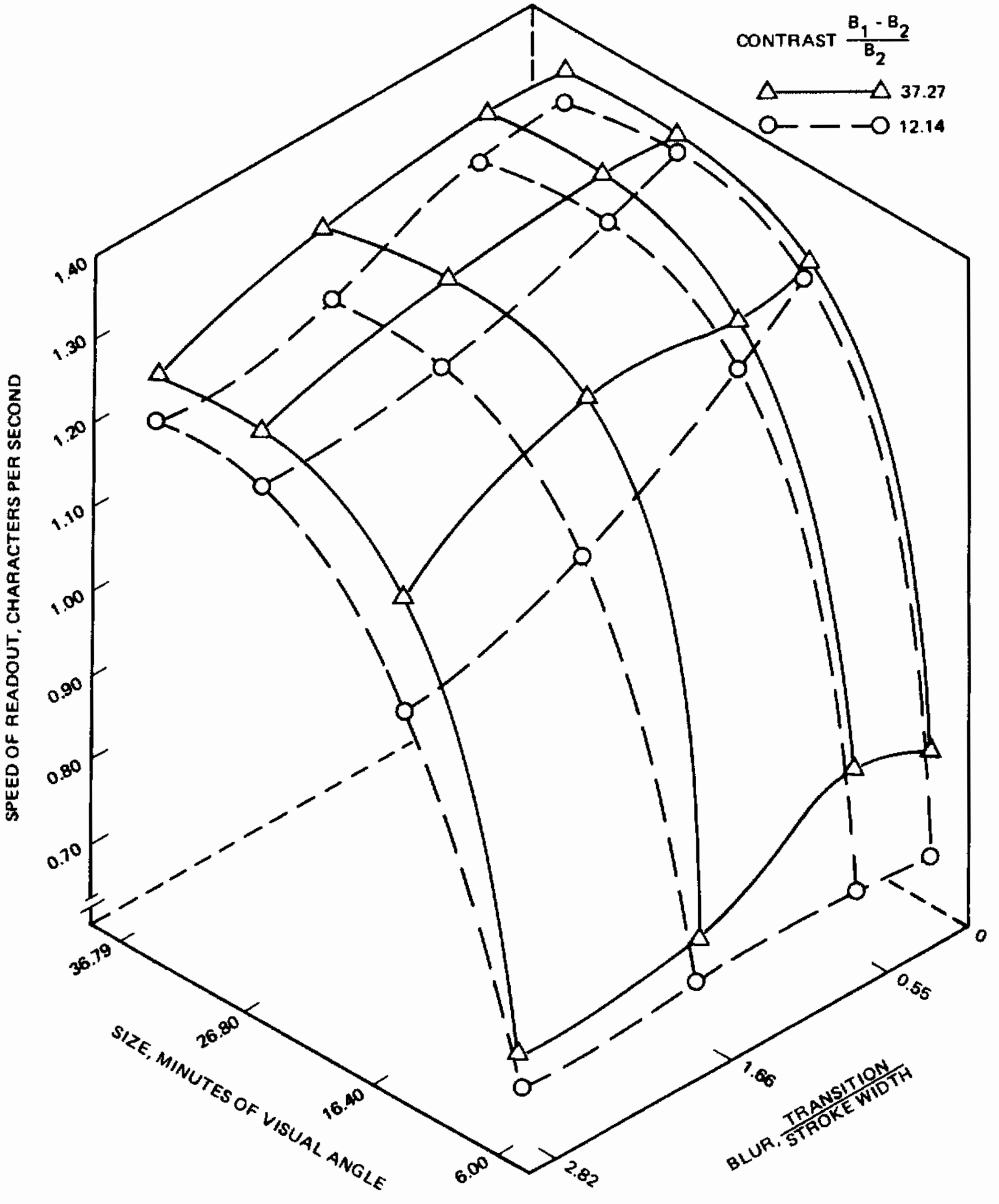


Figure 57. Speed of readout of letters and numbers as a function of their size, blur, and contrast.

10 optical line pairs in 10 minutes of arc (optimum visual separable acuity is usually accepted as 1 minute of arc) this does not mean that the detail present in an alphanumeric character requires 10 line pairs for legible presentation. This points up another critical variable affecting displayed alphanumeric legibility - the number of active scan lines per symbol height.

The number of scan lines crossing each character is a function of both character size and the vertical resolution of the display. Semple (1971) noted that the number of scan lines required for 100 percent legibility is a function of "(1) the type of symbology displayed, (2) the environmental conditions under which it is viewed, (3) observer viewing distance, and (4) the nature of the observer's task requirements" (p. 22). After a review of the literature Semple (1971) concluded that alphanumerics require a minimum of 10 to 12 active scan lines per symbol height for a reasonably high probability of correct identification, while 16 to 20 lines per symbol height are required for the same degree (90 percent plus probability) of correct identification of geometric-pictorial symbols.

Using a standard 525-line Fairchild Model TC-100 camera and a Miratel 14-inch video monitor, Shurtleff and Owen (1966) performed a study on the legibility of capital letters and numerals with vertical resolutions of 6, 8, 10, and 12 active scan lines per symbol height. The symbols were presented singly on the monitor, and subject's speed and accuracy of identification were recorded. They reported that for subjects with little practice, accuracy of identification decreased as resolution decreased from 12 to 6 lines per symbol height (see Figures 58 and 59). After subjects were given practice, accuracy was similar for resolutions of 10 and 12 lines per symbol height (see Figures 60 and 61). Speed of identification, on the other hand, decreased progressively as symbol resolution was reduced from 12 to 6 lines regardless of the level of practice. On the basis of these findings, a minimum resolution of 10 lines per symbol height was recommended for systems applications.

Elias, Sandowsky, and Rizy (1964) determined accuracy of identification for nine values of symbol definition from 3 to 11 lines per symbol height. Elias (1965) determined speed of identification for seven values of definition from 5 to 11 lines per symbol height. The results of both studies showed a marked decrease in accuracy when symbol definition was reduced below

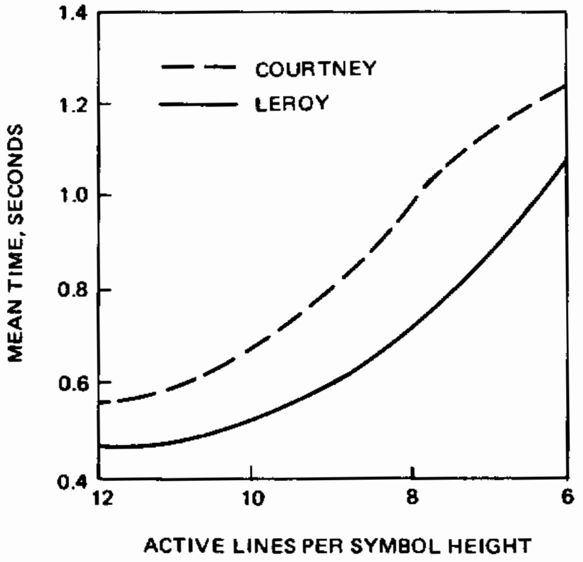


Figure 58. Average identification time as a function of a vertical resolution for the Small Amount of Practice Group, Part I.

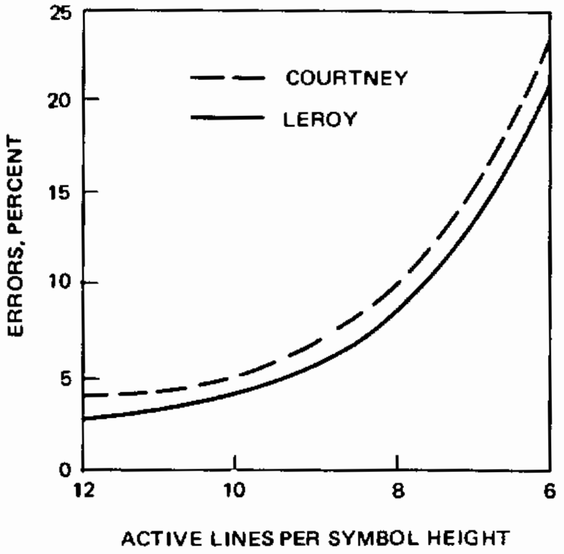


Figure 59. Identification errors as a function of vertical resolution for the Small Amount of Practice Group, Part I.

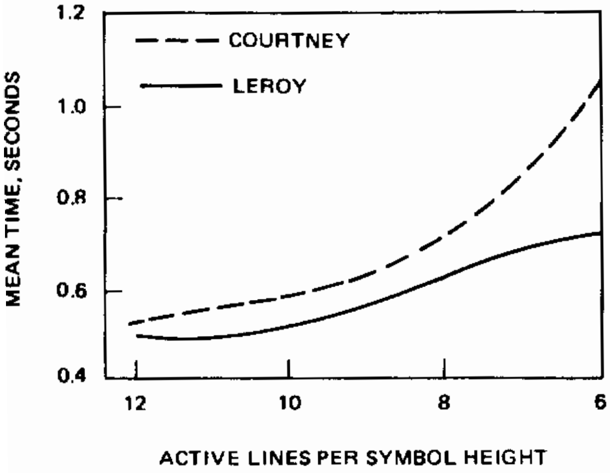


Figure 60. Average identification time as a function of resolution for the Additional Practice Group, Part II.

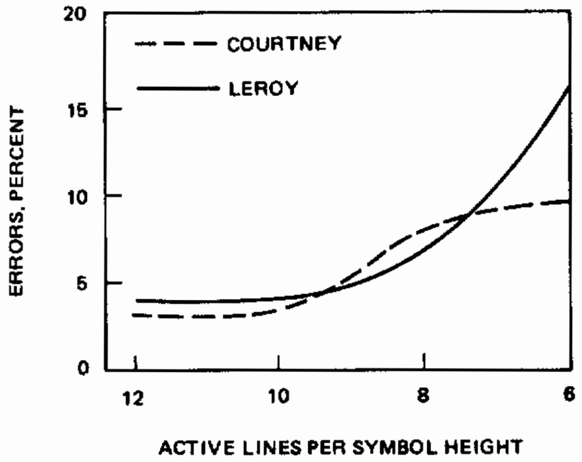


Figure 61. Identification errors as a function of resolution for the Additional Practice Group, Part II.

5 lines, and a large decrease in speed of identification when definition was reduced below 6 lines (see Shurtleff, 1967). While the results of Elias seem to conflict with those of Shurtleff and Owen (1966) and others, in that accuracy did not deteriorate appreciably until symbol resolution was decreased below 5 or 6 lines per symbol height, Shurtleff (1967) suggested that this apparent conflict probably resulted from differences in the quality of the interlace which led to associated differences in the definition of a scan line. Shurtleff proposed that the 5 lines in the Elias study were roughly comparable to the 10 lines in the Shurtleff and Owen study.

Shurtleff (1967) compared the legibility of standard Leroy and Lincoln/Mitre alphanumerics on a television monitor at resolutions of 8, 10, 12, and 14 lines per symbol height. Symbol subtense remained constant at 16 minutes of arc. Rate and accuracy of symbol identification were recorded. Based on the study results (see Figures 62 and 63), Shurtleff concluded that a minimum resolution of 10 lines per symbol height is required for a 90 percent or better accuracy of identification.

Simulated CRT studies of symbol resolution have obtained results similar to live television studies. In several studies by Botha and Shurtleff (Botha and Shurtleff, July, 1963; Botha and Shurtleff, Sept., 1963; Shurtleff, Botha, and Young, May 1966), television symbols were simulated by superimposing photographic grids made up of alternate transparent and opaque lines on solid-stroke symbols. The data from these studies with idealized

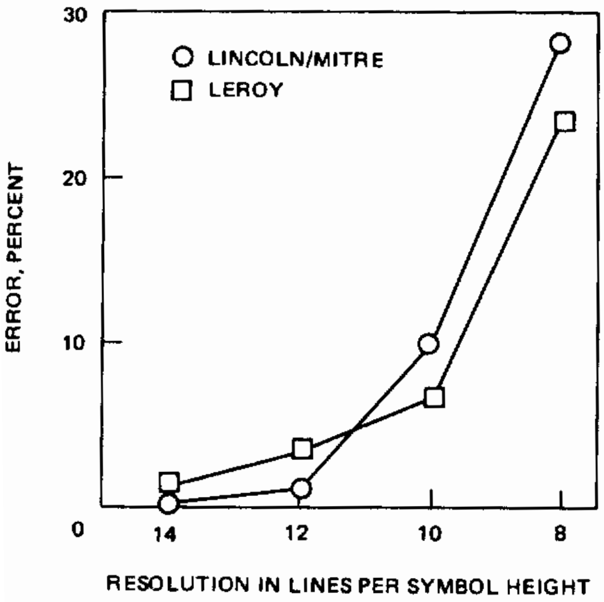


Figure 62. Percentage error for Lincoln/Mitre and Leroy symbols.

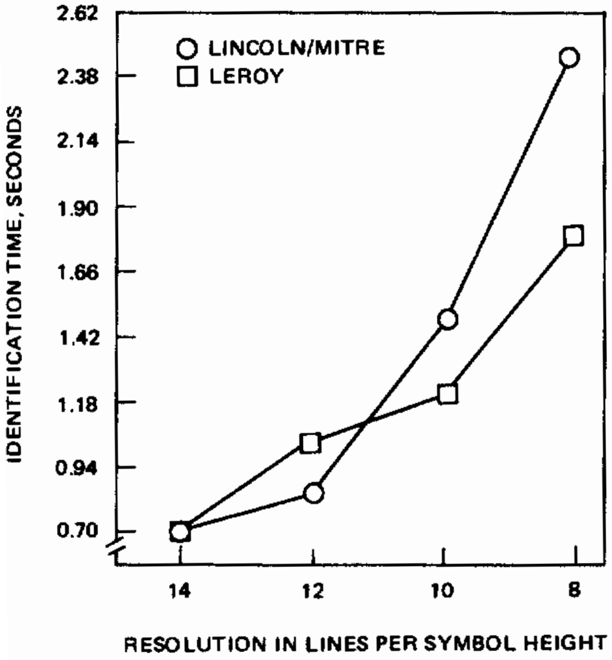


Figure 63. Identification time for Lincoln/Mitre and Leroy symbols.

television suggest that the minimally acceptable symbol resolution is between 5 and 11 lines. Shurtleff (1967) has pointed out, however, that while it is possible to achieve good legibility at 5 lines with optimal ratios of active to inactive elements and optimum registration of scan lines, these conditions of registration and ratios would be difficult to achieve on a television monitor. A required resolution of 11 lines, on the other hand, is well in line with the previous data from live television.

Meister (1969) in his Guide to Human Engineering Design for Visual Displays, listed a value of 10 TV scan lines per symbol height as being a minimum for adequate recognition.

Riche and Kinney (no date), examining the results of a number of Mitre Corporation investigations on symbol resolution provide a suscinct summary: "The finding is...oversimplified, but the curve seems always to make a break for the worse at about 10 active TV lines per symbol height. This has been for simulated TV using striped film, which gives a theoretically perfect TV rendition and therefore the best possible legibility, and for actual TV, whether on an inexpensive 525-line system or on a very expensive 945-line system. It has been found for different letter fonts, including one especially chosen for television, and for words. Regardless of the symbols, or the method of breaking them up into horizontal lines, it always comes out that 10 lines is very nearly the least permissible number if losses in legibility are to be avoided" (p. 98).

Thus far, minimum symbol subtense and minimum vertical symbol definition have been considered relatively independently of each other. However there is evidence that a strong interaction exists between these two parameters, and it appears that it is no longer reasonable to consider them separately. Thus, both the minimum number of lines per symbol and the minimum angular symbol height requirements must be satisfied simultaneously.

Ketchel and Jenny (1968) contend that for raster-type displays, symbol "size" should be specified in terms of number of lines per symbol as well as visual subtense. They recommended the following: "under good contrast conditions, vertical symbol height should be 15 minutes of arc or 10 raster lines, whichever is greater. Under poorer conditions of contrast, vertical symbol height should be 21 to 25 minutes of arc or 16 raster lines, whichever is greater" (p. 153).

Seibert, Kasten and Potter (1959), and Seibert (1964) found that for high accuracy of identification (98 to 99 percent correct) viewers required a visual angle between 12 and 15 minutes of arc, and a vertical resolution between 8 and 12 lines per symbol height.

Shurtleff and Owen (1966) confirmed that a vertical resolution on the order of 8 to 10 lines was minimal if symbol size was to be kept at about 15 minutes of arc.

The interdependency of symbol resolution and symbol subtense was further illustrated by Shurtleff, Marsetta, and Showman (1966). These investigators noted that in previous studies of symbol resolution (Botha and Shurtleff, 1963a; Botha and Shurtleff, 1963b; Kosmider, 1966; Kosmider, Young, and Kinney, 1966; Shurtleff, Botha, and Young, 1966; and Shurtleff and Owen, 1966), where a common visual angle of subtense was used across the various values of resolution, results indicated a significant increase in identification time occurred when symbol resolution was decreased from 10 to 8 lines, and from 8 to 6 lines. Errors of identification (Shurtleff and Owen, 1966) on the other hand, showed no significant differences between 10 and 8 lines, but did show a significant difference between 8 and 6 lines. Based on the above, they hypothesized that a larger angle of subtense would be required for good identification with a symbol resolution of 6 lines (and possibly 8 lines) than would be required for a symbol resolution of 10 lines. Consequently, they conducted an investigation to determine the visual sizes required for the identification of standard and revised Leroy alphanumerics televised at resolutions of 10, 8, and 6 lines per symbol height. They found that the visual angle needed for 99 percent identification accuracy was similar for resolutions of 8 and 10 lines, but that a significantly larger visual angle was required for symbols resolved by 6 lines. Specifically, visual angles required for 99 percent accuracy varied from approximately 13 minutes of arc for a resolution of 10 lines, to 36 minutes of arc for a resolution of 6 lines (see Table 15).

As can be seen from the above, symbol subtense and symbol resolution are two variables which need to be considered simultaneously in system design. Indeed, Semple has suggested that in maintaining system legibility, some trade-off is possible between the number of scan lines per symbol and the angular subtense of the symbol. A similar conclusion was reached by Erickson and Hemingway (1970) who stated, "As the lines per symbol decrease, the same performance level can be maintained by increasing the angular subtense of the symbol; however, this statement holds only for symbol subtenses from 7.8 to 16 minutes of arc," (p. 28). They proposed a constant-product rule

TABLE 15. SUBTENDED ANGLES REQUIRED FOR 85 AND 99 PERCENT ACCURACY OF IDENTIFICATION OF STANDARD AND REVISED LEROY SYMBOLS

| Resolution, Lines per Symbol Height | Identification Accuracy, Percent* | | | |
|---|---|---|---|---|
| | Standard Symbols | | Revised Symbols | |
| | 85% | 99% | 85% | 99% |
| 10 | 7.58 | 13.15 | 7.59 | 13.37 |
| 8 | 7.57 | 12.82 | 7.70 | 15.09 |
| 6 | 10.35 | 35.97 | 11.01 | 30.08 |

*Tabled entries are required minutes of arc.

whereby the 95 percent correct response curve is closely approximated by the equation $SA = 90$ for $6 \le A \le 16$, where S is the number of lines per symbol, and A is the angular subtense of the symbol in minutes of arc.

### A. 3. 1 Symbol Subtense and Symbol Definition – Matrix Display Applications

The CRT variables of symbol subtense and lines per symbol height have their counterparts in matrix displays – symbol subtense and number of dots per symbol height. In noting the requirement for 10 active scan lines per symbol for CRT legibility, Gould (1968) proposed that, by analogy, the minimum legible matrix would also be 10 dots high. Based upon this supposition, he concluded that characters generated in 5 x 7 dot matrices would be marginal in terms of legibility.

Fortunately there is some objective data available on the subject. Shurtleff (1970) conducted a study to determine the legibility of symbols formed from matrices containing different numbers of dot elements. Matrix sizes investigated were the 3 x 5, 5 x 7, 7 x 11, and 9 x 15. While two symbol subtenses were investigated in the study (22 and 6 minutes of arc), symbol subtense was held constant across matrix size. That is, increases in the number of dot elements did not result in corresponding increases in the subtense of the matrix. This was due to the fact that matrix size was increased by placing the dots closer and closer together (by decreasing the distance between adjacent dots in both the X and Y dimensions). Any remaining small variations in symbol height were compensated for by seating operators at different distances to equate visual angle subtended by symbol height. All symbols were constructed to approximate the geometry of the Lincoln/Mitre font (see Figure 64). A PDP-8 computer was employed to construct the symbols and generate symbol sequences. Nine symbols, arranged in a 3x3 array, were presented at one time. Symbols were displayed on a Tektronic type RM 503 oscilloscope fitted with a P-7 phosphor. Symbol luminances were equated and approximated 16 fL; 15 ft-candles of ambient light fell at the scope face. Performance was measured in terms of both speed and accuracy of identification.

When symbols subtended 22 minutes of arc and when operators were given practice, performance reached a higher level (expressed in terms of correct identifications per minute) with each enlargement of the matrix from 3 x 5 to 5 x 7 to 7 x 11. At the same time, when symbols subtended only 6 minutes of arc, performance improved for matrix enlargement from 3 x 5 to 5 x 7, but not from 5 x 7 to 7 x 11, even if the operator was given some practice with the symbol fonts (see Figure 65). By way of explanation Shurtleff proposed that due to the small subtense in the 6 minute condition, subjects were not able to resolve very well the greater symbol detail provided by matrices larger than the 5 x 7 and consequently their symbol identification failed to improve when matrix size was enlarged from 5 x 7 to 7 x 11 or 9 x 15.

Comparing correct identifications per minute obtained with dot-matrices with results obtained in an unpublished study which determined symbol identification rates for good quality capital typewritten symbols, Shurtleff further concluded that performance with a 7 x 11 or 9 x 15 dot-matrix was equivalent to performance with solid stroke symbols.

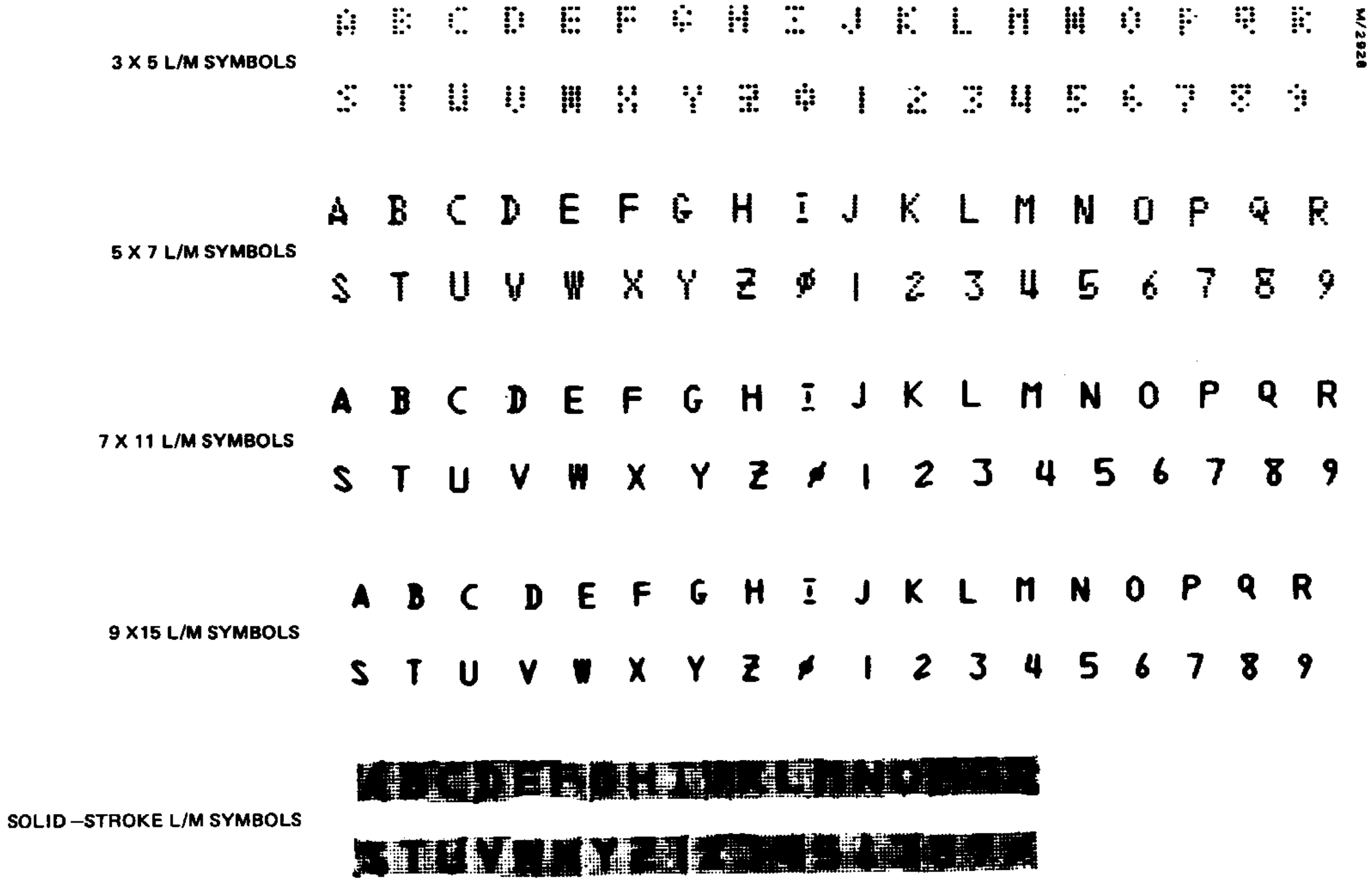


Figure 64. Approximation of Lincoln/Mitre (L/M) symbols constructed from four dot matrices and solid-stroke symbols.

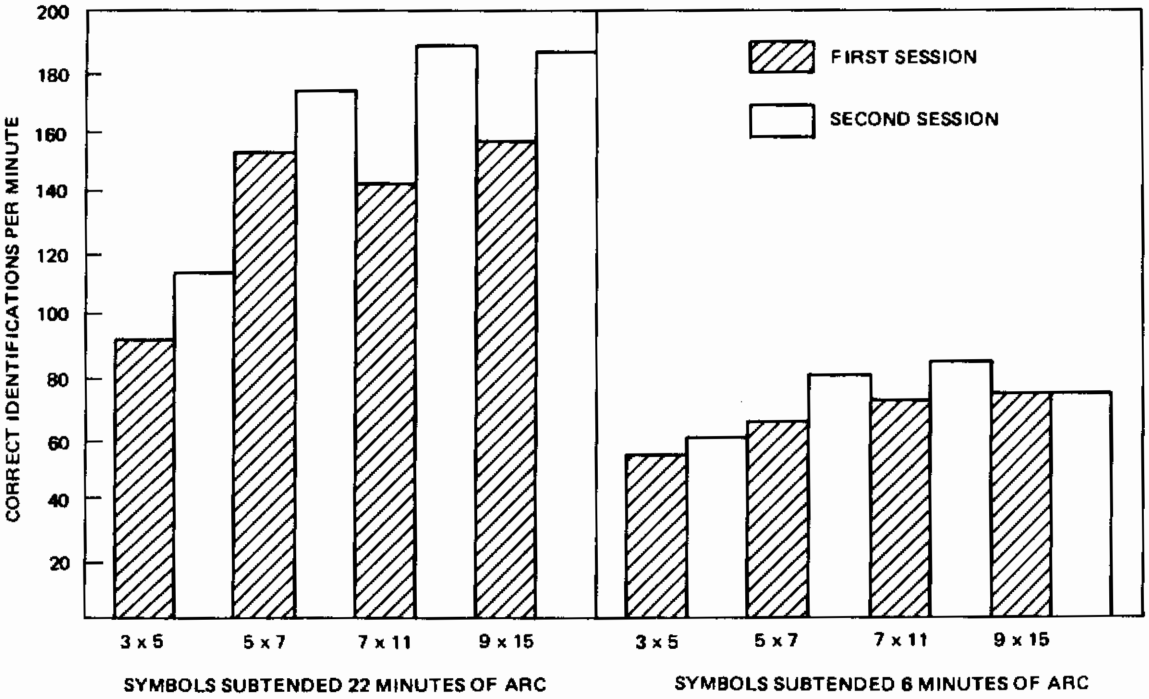


Figure 65. Effect of matrix size, symbol subtense, and practice on symbol identification.

Shurtleff (Feb. 1970) conducted another study to determine if matrix sizes falling between the 5 x 7 and 7 x 11 would also yield performance equivalent to that obtained with solid-stroke symbols. Four matrix sizes were investigated: 5 x 7, 5 x 9, 7 x 9, and 7 x 11. All symbols subtended 22 minutes of arc. The apparatus and procedures were basically the same as in the previous study. Results of the study failed to show significant differences between the 5 x 7, 5 x 9, 7 x 9 and 7 x 11 matrices for either identification rate or accuracy. However, it was discovered that scores for one of the four subjects were considerably different from the others. Shurtleff speculated that a significant difference might have been found between the 5 x 7 and 7 x 11 matrices if the performance of this one operator had not been so aberrant. He further noted that performances for the other three operators on the 5 x 9 and 7 x 9 matrices were more similar to that for the 5 x 7 than to that for the 7 x 11 matrix and speculated the break in the performance curve might have occurred between the 7 x 9 and 7 x 11 matrix sizes.

Shurtleff (1970) also compared the relative legibility of special symbols constructed from 5x 7, 5 x 9, 7 x 9 and 7 x 11 dot-matrices. Thirty symbols, selected from those used in the 407L (TAC) and BUIC systems, composed the special symbol set investigated in the study. Results indicated that symbol identification was better for the 7 x 9 matrix than for the 5 x 7 matrix (see Figure 66).

Vartebedian (1970) compared 5 x 7 and 7 x 9 matrix sizes. Twenty-six letters and 10 numbers were tested. Symbol brightness was 11 fL; background brightness measured 2.0 fL. All symbols subtended 17.2 minutes at the observer's eye. Symbols were presented briefly on a CRT, and subjects attempted to identify the symbol shown. Legibility was measured in terms of speed and accuracy of identification. From the results of his study, Vartebedian concluded that the 7 x 9 matrix was superior to the 5 x 7 (see Table 16).

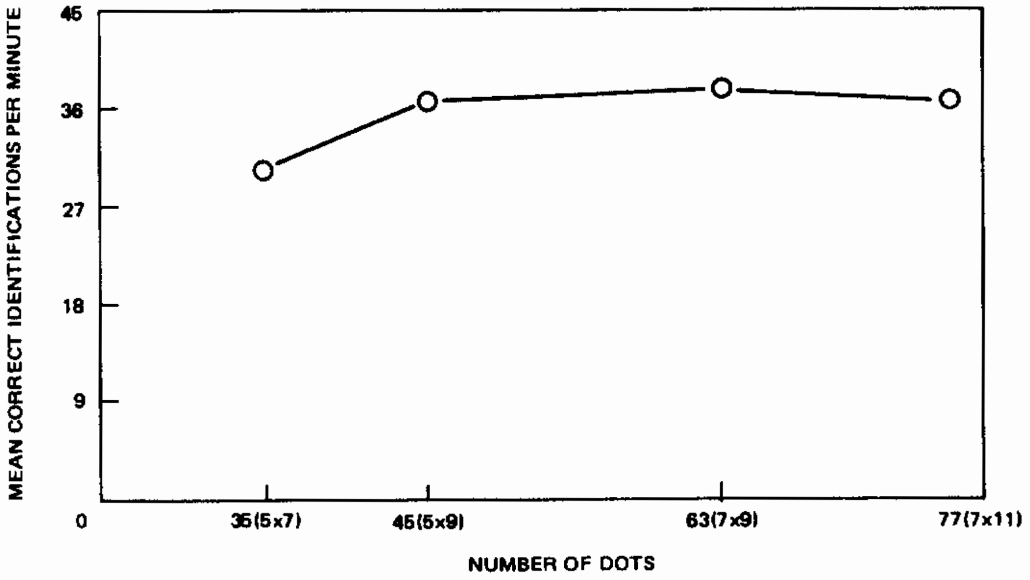


Figure 66. Correct identifications per minute for symbols used by Shurtleff (1970)

TABLE 16. AVERAGE REACTION TIME AND ERROR RATES FOR THE 5 X 7 AND 7 X 9 MATRICES INVESTIGATED BY VARTEBEDIAN (1970).

| Condition | Reaction Time, milliseconds | Percent Errors |
|---|---|---|
| 5 x 7 circle dot | 697 | 2.9 |
| 7 x 9 circle dot | 602 | 2.6 |

In the dot-matrix studies cited, symbol subtense was held constant across matrix sizes, the results being that in general 7 dots per symbol height have proved adequate for legibility. In another study by Varebedian (1971), however, matrix size was held constant at 7 x 9 while symbol subtense varied from 14.7 to 17.2 to 19.6 minutes of arc. Display brightness was held constant at 25 fL; background brightness was 2.9 fL. Subjects searched a CRT for a word voiced by the experimenter. Study results showed that the medium size symbols (17.2 min) were searched faster than either the smallest (14.7 min) symbols or the largest (19.6 min) symbols. Vartebedian explained the result by noting that as letter size increased, the dots spread apart. Since dot diameter remained constant, beyond a certain point the dots began to disassociate and the letter "came apart".

Again it is important to realize that the parameters of symbol subtense and symbol definition cannot be considered independently. As Shurtleff (1970) pointed out, if symbol size is small (6 minutes of arc) legibility fails to improve with increases in matrix size (symbol definition) presumably due to operator inability to resolve the greater symbol detail provided by matrices larger than the 5 x 7. Shurtleff concluded that when symbols subtended only 6 minutes of arc "some improvement is obtained by using the 5 x 7 matrix [as opposed to the 3 x 5], but further improvement in performance as matrix size is enlarged is prevented by the small visual size" (p. 30). Vartebedian (1971), on the other hand, holding matrix size constant (at 7 x 9) while increasing symbol subtense (14.7, 17.2, 19.6 arc minutes) was forced to conclude that "for dot symbols, the beneficial effects on search time of increased letter size are offset at some point by the deleterious effect of dot dissociation" (p. 367).

This brings us to one final point. In attempting to consider both symbol subtense and symbol definition in display design, another determinant of legibility presents itself. It has been suggested (Gould, 1968; Biberman, 1973; Groves, 1973) that whatever the values of symbol resolution and subtense selected, the display should present the observer the illusion of a continuous image. That is, scan lines or matrix dots should not be resolved by the viewer. Support for this proposition was provided by Thompson (1957) who cited experimental results showing that television viewers tend to select as optimum a viewing angle at which the TV line structure just begins to disappear.

Similarly, Biberman presented evidence that while an image containing a visible line structure may appear sharper, more detail becomes visible when the line structure is removed by integration. He noted that when a CRT with a visible line structure was modulated with wideband noise (the noise constituted a signal in this situation), the noise became much more visible when the interfering line structure was removed by defocusing the CRT spot or by increasing the viewing distance. Biberman concluded that the line structure "is an interfering signal which, like noise, prevents detection of small detail" (p. 239-240).

Finally Groves (1973), discussing a human factors study of character size conducted on simulated light emitting diode modules, noted that a 0.125 inch high character was found to be more legible at close viewing distances "because it gave the appearance of an almost continuous line, where larger characters, particularly over 0.25 inch high, appeared as a series of separated dots at close viewing distances and were, therefore, somewhat less legible" (p. 14).

In summary, it appears that increases in matrix size are associated with increased legibility under those conditions where symbol subtense is sufficient to allow subjects to resolve the greater symbol detail provided by the larger matrices, but not so large as to cause the symbols to appear dissociated.

## A.4 EMITTER SHAPE AND CONFIGURATION (DOT PLACEMENT)

There is one variable under the control of the display designer in the construction of solid state matrix displays which has no counterpart in cathode ray tube design: the variable is emitter shape. Thus in matrix displays not only symbol font and number of dots but also dot shape and configuration influence symbol geometry.

Shurtleff (1974) commented that variations in emitter shape "naturally" affect symbol appearance and might "possibly" effect symbol identification performance. Shurtleff conducted his experiments using circular dots (Shurtleff, 1970).

Vartebedian (1970), compared the legibility of symbols composed of circular versus eliptical dots. Thirty-six alphanumerics were presented briefly on a display screen in 5 x 7 and 7 x 9 dot-matrix sizes, slanted and upright symbol orientation, and circular and eliptical dot shapes. Speed and accuracy of symbol identification were the measures of legibility. Symbols constructed with circle dots were displayed with a P31 phosphor. Symbols constructed with eliptical dots were displayed with a P4 phosphor. (Vartebedian commented that both of these phosphors emitted energy in a range near the center of the visible spectrum and were found to have nearly identical decay properties). Symbols were displayed in the center of the CRT at a brightness of 11 fL against a background brightness of 2.0 fL. Symbols were 0.14 inches in height and subtended 17.2 minutes of arc at the subjects' eyes. Study results showed circular dots were superior to elongated dots for accuracy and speed of identification across all comparisons (see Tables 17 and 18). Vartebedian concluded that in the implementation of a dot-matrix, "legibility would be enhanced by using clearly circular dots rather than elongated ones" (p. 26).

While Vartebedian's results provide an indication that circular matrix emitters might prove superior in legibility to eliptical emitters (vertically elongated circles) care must be taken in extrapolating results obtained with CRT simulated dot-matrices to actual solid state dot-matrices. Generally, differences are found to exist between simulated dots and solid state dots;

TABLE 17. AVERAGE REACTION TIME AND ERROR RATES FOR THE SIX CONDITIONS STUDIED BY VARTEBEDIAN (1970)

| Condition | Reaction Time, Milliseconds | Percent Errors |
|---|---|---|
| 5 x 7 circle dot | 697 | 2.9 |
| 7 x 9 circle dot | 602 | 2.6 |
| stroke upright | 659 | 4.5 |
| stroke slant | 677 | 6.7 |
| 7 x 9 elongated dot | 678 | 3.2 |
| 7 x 9 slant elongated dot | 814 | 7.7 |

TABLE 18. SELECTED COMPARISONS AMONG THE SIX CONDITIONS (DIFFERENCES ARE IN FAVOR OF THE TOP METHOD FOR EACH COMPARISON)

| Comparison | Difference | |
|---|---|---|
| | Reaction Time | Error Rate, Percent |
| (1) Stroke upright vs 5 x 7 circle dot | 38 ms | -1.6 |
| (2) 7 x 9 circle dot vs stroke upright | 57 | 1.9 |
| (3) 7 x 9 circle dot vs 5 x 7 circle dot | 95 | 0.3 |
| (4) Stroke upright vs stroke slant | 18 | 2.2 |
| (5) 7 x 9 elongated dot upright vs 7 x 9 elongated dot slant | 136 | 4.5 |
| (6) 7 x 9 circle dot vs 7 x 9 elongated dot | 76 | 0.6 |

for example, solid state emitters are characterized by sharp edge gradients where as CRT spots typically are not (due to the gaussian spatial luminance distribution of the CRT spot). The effects of such differences have not yet been empirically investigated.

Semple (1971) presented six emitter shapes and configurations which he felt warranted investigation (see Figure 67). These included triangular,

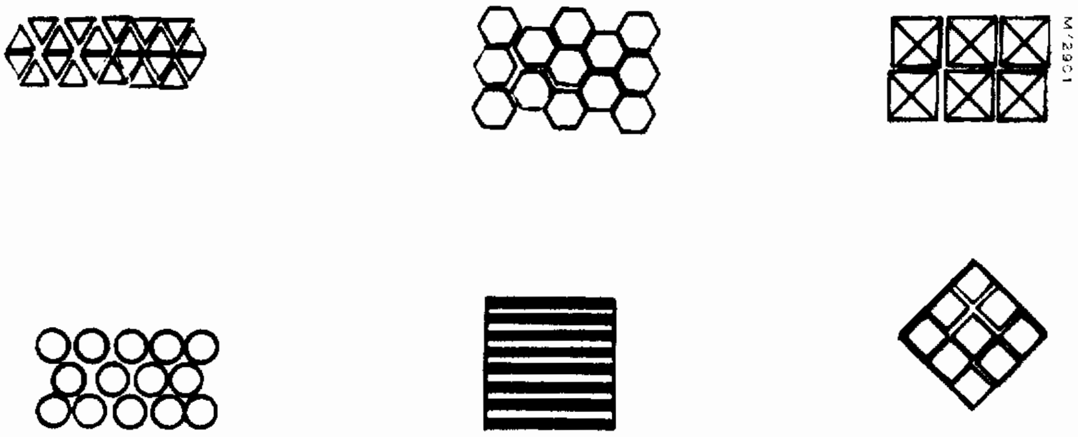


Figure 67. Representative Emitter Shapes and Configurations.

square, circular, hexagonal and line emitters arranged in both regular and staggered element configurations. Unfortunately, no solid state matrix research could be located which investigated the effects of emitter shape or configuration.

Emitter shape has the potential to influence symbol geometry. Thus an important consideration when selecting emitter shape should be the type of symbology which is to be displayed. For example, as pointed out by Semple (1971), round or square emitters "provide considerable latitude for presenting alphanumeric or other symbols, lines or shades of gray areas" (p. 342). The use of triangle or diamond emitter shapes, on the other hand, may place restrictions on the angles with which various symbols or lines can be displayed, a fact that could prove of operational significance with relatively large emitters (e.g., 25 to 50 mils minimum dimension).

A second implication of emitter shape relates to emitter density considerations. As was pointed out in the previous section on symbol subtense and definition, several investigators (Gould, 1968; Thompson, 1957; Beiberman. 1973; Groves, 1973) have suggested that for maximum legibility a display should present the observer with the illusion of a continuous (unsegmented) image. Indeed, Vartebedian noticed detremental effects on displayed letter legibility when dot spacing increased with increases in symbol size such that symbols tended to dissociate or "fall apart". It therefore appears desirable to maximize emitter area while minimizing gaps and spaces between emitters.

High emitter density also appears desirable on the basis of another consideration. As pointed out by Semple (1971), the brightness sensitivity of the human eye is affected by the area of the source of illuminance, such that for a given illuminance level, larger luminous objects can be detected more easily than smaller luminous objects (i.e., the eye can integrate luminous flux over a finite area, such that the larger the area, the less luminous intensity is needed for threshold discrimination). Thus, it is desirable that emitter gaps be minimized, such that matrix symbol luminance thresholds will be related to symbol size not emitter size. (The term "threshold" as used here refers to an observer decision criterion.)

Consideration of both resolution and luminance requirements argue for high emitter density. Emitter density in turn is clearly dependent upon emitter shape and configuration. Thus, for example, due to strictly physical considerations, square elements result in a larger active area than circular elements for a given center-to-center spacing. In the final analysis, selection of emitter shape should be made only after consideration of the type of symbology to be displayed and the implications in terms of emitter packing density.

## A.5 PERCENT ACTIVE AREA

A primary factor influencing the legibility of displayed alphanumerics is symbol definition, traditionally defined as the number of active scan lines per symbol height. This concept can be easily applied to a consideration of dot-matrix displays where the parameter becomes the number of emitters per symbol height. The number of lines or emitters per symbol height is related to the "amount of information being transmitted." That is, each additional line or dot can be seen as contributing an additional increment of information (i.e., more precisely defining the shape of the symbol being transmitted). There is, however, another related concept which needs to be considered in assessing optimum display conditions – it is percent active area. This concept refers to the "size" of a given symbol definition line or element in relation to the background area between lines or elements.

For a matrix display containing square dots, percent active area can be defined as follows:

$$\text{Percent Active Area} = \left(\frac{\text{Dot Size}}{\text{Dot Spacing}}\right)^2 \times 100.$$

As percent active area increases, no new information is presented (contrasted to when the number of lines per symbol height is increased) but rather the old information is presented in a different format. As is evident from the formula above, there are two ways of increasing the percent active area of a matrix display: (1) by increasing emitter size or (2) by decreasing emitter spacing. If symbol subtense is held constant, each naturally implies the other. The same principle can be applied to television and cathode-ray-tube displays by considering the relative widths and the spacing of the active scan lines used in symbol construction.

One study was found which examined the effect of percent active area on the legibility of matrix displays. Ellis, Burrell, Wharf, and Hawkins (1974) conducted a study using two different dot-space ratios to determine whether in maximizing the legibility of an emissive display it was preferable to concentrate the emission into a series of small bright areas (thereby maximizing local contrast) or to present a more continuous character of lower luminance (but having the same total optical emission). These investigators employed a simulated emissive display, rear projecting 4mm high alphanumerics. (This back illumination was filtered to red - 630 nm.) Thirty-six alphanumerics composed the symbol set. Symbols were presented one at a time for 0.7 seconds each. Subjects read each symbol as it was presented; reading errors and omissions were recorded. The surround illuminance was 10,000 ft-c, with subjects eyes adapted to a background of $3.4 \times 10^4$ nits. One set of 36 characters was composed of small bright dots (144 nits; dot-space ratio 1:1) while the other set contained larger dimmer dots (72 nits; dot-space ratio 2:1). Thus while the total illuminated area differed by a factor of two, the total optical output per symbol was the same for both dot-space ratios.

Results showed that for the 68 subjects without known visual defects the format with the larger (but dimmer) dots was more legible (error rate of 7.8 percent) than the smaller dot format (error rate of 11.4 percent). Over all 125 subjects (including those with visual defects), a similar result was found. Error rate for large-dot format was 11.9 percent, and for small-dot format error rate was 15.7 percent. The authors concluded that a quasi-continuous character was preferable to one with smaller, brighter dots. Some theoretical support for the validity of this finding is presented below.

As stated above, increasing percent active area implies decreasing emitter (or line) spacing, thus reducing perceived gaps in the displayed symbology. There are some indications that such a reduction in gaps would serve to increase display legibility. As noted in the section on symbol subtense and definition, several investigators (Gould, 1968; Biberman, 1973; Groves, 1973) have suggested that regardless of the values of displayed symbol resolution selected, a display should present an observer the illusion of a continuous image. That is, scan lines or matrix spots should not be resolved by the viewer. Support for this proposition was provided by Thompson (1957) who cited experimental results showing that television viewers tended to select as optimum a viewing angle at which the TV line structure just began to disappear. Biberman argued that line structure "is an interfering signal which, like noise, prevents detection of small detail" (p. 239-240). In addition, Groves (1973) commented that when matrix (LED) displayed alphanumerics were viewed at a near viewing distance, such that the dot structure was visible (i.e., symbols "appeared as a series of separated dots") legibility was degraded. The implication of the above seems to argue that legibility should increase as percent active area is increased.

Further support for the above conclusion is provided by the following. As noted in the section on emitter shape and configuration, the brightness sensitivity of the human eye is affected by the area of the source of illuminance, such that for a given illuminance level, larger luminous objects can be detected more easily than smaller luminous objects. That is to say, one determinate of the threshold of vision is the retinal area stimulated. Even with overall symbol subtense fixed, increasing percent active area (decreasing emitter gaps) appears desirable in that the stimulated retinal area will be larger, thus possibly reducing required symbol luminance thresholds.

It seems evident that variations in percent active area may influence perceived symbol contrast. The effects of this factor on matrix legibility have been quantitatively assessed only in the previously cited study by Ellis, Burrell, Wharf, and Hawkins (1974).

A study conducted by Botha and Shurtleff (1963) perhaps provides some objective indication as to the potential effects of percent active display area on operator performance. These investigators simulated television symbol construction, varying the ratio of the widths of inactive to active elements within a TV scan line. A television linear scan construction of five lines per symbol height was simulated by placing a photographic negative successively in front of 26 stimulus letters. Each negative consisted of alternate transparent and opaque lines. A pair of lines, one transparent and one opaque, was 0.045 inch in width, and five of the line pairs were needed to cover the letters which were 0.225 inch in height (viewing distance was 60 inches). Three different negatives with opaque to transparent line width ratios of 1:2, 1:1, and 2:1 were used to simulate different ratios of the widths of inactive to active elements within a TV scan line (see Figure 68). Subjects were instructed to identify each letter, shown at a 0.03 second exposure, as accurately and as quickly as possible. The speed and accuracy of subjects responses were recorded. Study results showed that both accuracy and speed of response decreased as the ratio of the widths of inactive to active elements within a TV scan line increased (see Figures 69 and 70). The results of this study appear as applicable to consideration of dot-matrix legibility as to television legibility. Again one is led to the tentative conclusion that increases in percent active area on matrix displays lead to increased displayed symbol legibility.

It is important to note that in the laboratory research conducted in the present program, unlike that conducted by Ellis, Burrell, Wharf, and Hawkins (1974), individual dot brightness, not total symbol emission, was

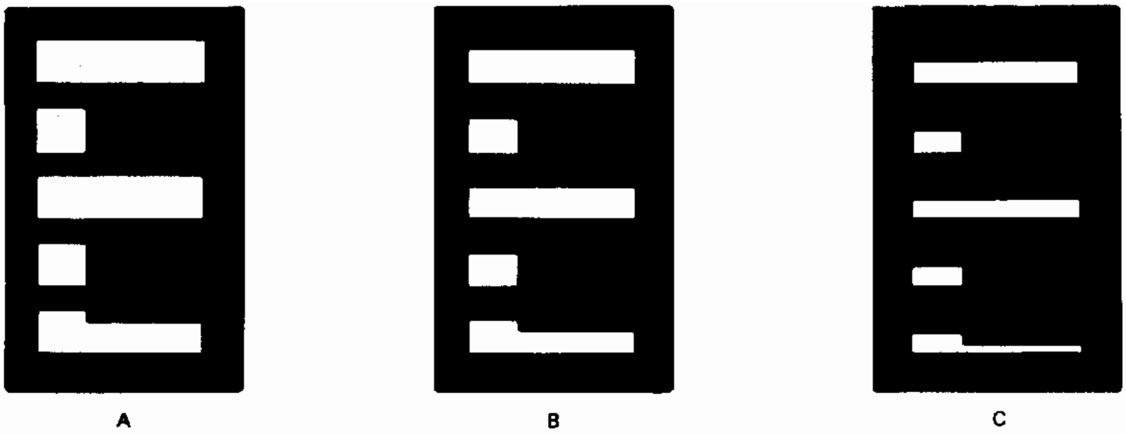


Figure 68. The letter "E" is shown as an example of letter constructions obtained by the use of three different ratios of inactive to active elements within a simulated linear TV scan line. A, B, and C indicate the letter constructions obtained by the use of a 1:2 (.50) ratio, 1:1 (1.0) ratio and 2:1 (2.0) ratio, respectively. In each case the first term of the ratio refers to the relative width of the inactive element (opaque strip) and the second term to the relative width of the active element (transparent strip).

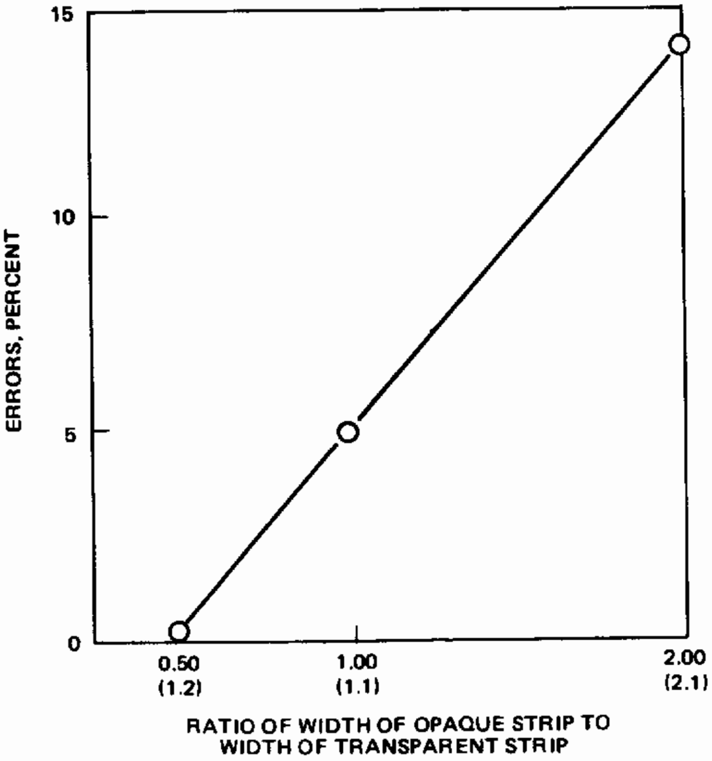


Figure 69. Effect or ratio of inactive to active elements on letter identification error.

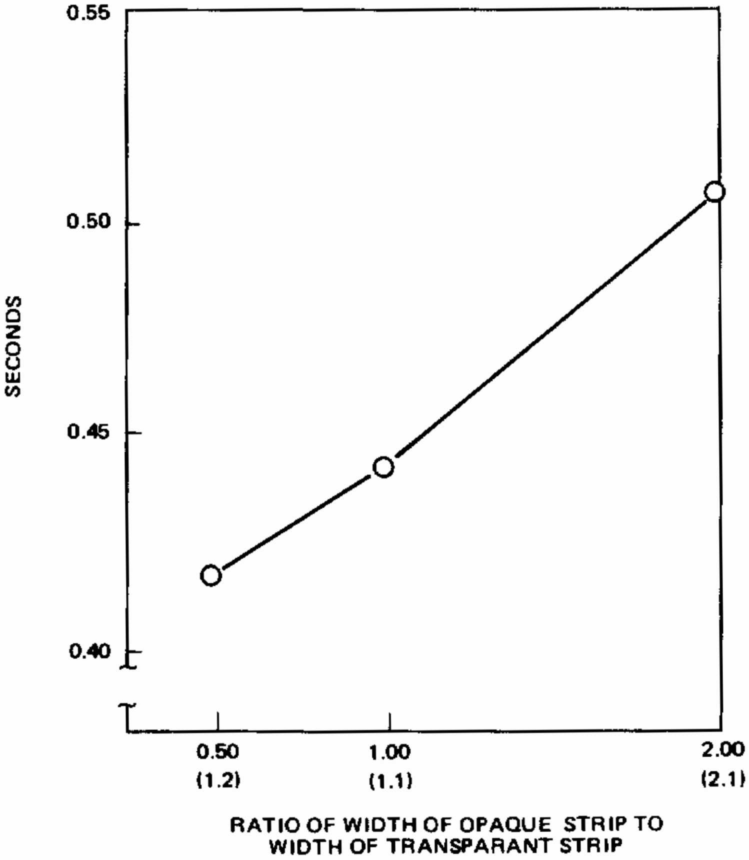


Figure 70. Effect of ratio of inactive to active elements on letter identification speed.

held constant. Thus in the present study, increases in overall perceived symbol brightness accompanied increases in percent active area. Differences in percent active area, where observed, reflected the effects of perceived symbol brightness as well as the effects of dot-space ratio.

## A.6 VIEWING ANGLE

Viewing angle refers to the angular relationship expressed in degrees between the longitudinal axis of the display and the viewer's line of sight. Normal (straight-on) viewing occurs when this angle is zero. (NOTE: some authors refer to the viewer's line of sight relative to the display face, and hence normal viewing is referred to as 90 degrees.)

Off-axis viewing causes foreshortening of the viewed image. This foreshortening reduces the apparent image size which can degrade legibility. Several researchers have investigated the relationship between viewing angle and legibility. Seibert, Kasten and Potter (1959) investigated the effects of symbol size, viewing distance, direction of contrast (dark on light versus light on dark) and viewing angle on accuracy of symbol identification. Seibert found that angles up to 19 degrees from the normal line of viewing did not decrease accuracy of identification. The critical angle at which some loss in accuracy of identification occurred was between 19 and 38 degrees from the normal line of sight. Unfortunately, Seibert failed to present a complete description of the experimental situation in which his data were gathered. Symbol brightness, background brightness and brightness contrast were not reported.

Carel, McGrath, Hershberger, and Herman (1974), after a review of the literature, reported that behavioral research data indicated legibility remained essentially unchanged for lateral and vertical viewing angles between zero degrees (straight on) and 30 degrees off the perpendicular visual line of sight. Meister (1969) in his Guide to Human Engineering Design for Visual Displays also recommended that the maximum off-axis angle be 30 degrees. In addition, he presented a table showing visual angles in minutes of arc required for viewing television displays at varying angles (see Table 19).

Foley and Scott (1957) investigated the legibility of Leroy digits while varying intensity of illumination, viewing distance, and viewing angle. Three viewing angles were investigated: 90 degrees straight-on, 45 degrees left, and 45 degrees right of the normal line of sight. Table 20 presents symbol subtense in minutes of arc required for errorless identification under the various experimental conditions. Study results showed the median angle subtended by the symbols was smallest for straight-on viewing, only slightly larger for 45 degrees left of the normal line of sight, but 2 to 3 minutes larger for 45 degrees right of the normal line of sight. Simpson (1971), who similarly observed that digits were harder to read from the

TABLE 19. VISUAL SIZES IN MINUTES OF ARC REQUIRED FOR VIEWING TV DISPLAYS AT VARYING ANGLES

| Symbol Resolution In Lines | Viewing Angle in Degrees | | | | |
|---|---|---|---|---|---|
| | 90 | 75 | 60 | 45 | 30 |
| 10 | 20 | 24 | 28 | 36 | 63 |
| 8 | 24 | 28 | 32 | 44 | -- |

right than from the left (although his results were confounded by the placement of his ambient lighting), suggested this result might be due to the existance of fewer cues to digit shape on the right side of digits.

Three studies by Reinwald (1954; undated) reported symbol legibility for horizontal and vertical viewing angles of zero degrees (straight on), 15, 30, 45, 60, and 75 degrees (off-axis). Horizontal viewing angles were measured to the right of the normal line of sight, and vertical angles were measured upward from the normal line of sight. Legibility was measured in terms of 100 percent threshold. Study results showed that for AND10400, Mackworth, and Berger symbols, a slight increase in subtended visual angle was required for 100 percent threshold legibility at 15, 30 and 45 degrees off-axis over that found for zero degrees. Substantially larger angles of subtense were required for viewing angles of 60 and 75 degrees. The author reported that his data were described well by a function in which legibility (subtended visual angle) decreased according to "an exponential cosine of the angle of displacement" (Shurtleff, 1966, p. 92). To calculate the maximum distances from the display at which observers could be positioned for various angles of viewing, the author proposed the following formula:

$$D_{ft} = b\ (\text{cosine}\ \theta)^{2/3}$$ for horizontal angles and

$$D_{ft} = b\ (\text{cosine}\ \theta)^{1/2}$$ for vertical angles, where

b = distance in feet required to correctly identify symbols displayed normal to the line of sight, and $\theta$ = the angle in degrees between the position of interest and the normal line of sight. The constant "b" varied with conditions of viewing (i.e., brightness, contrast, font, etc.).

## TABLE 20. SYMBOL SUBTENSE IN MINUTES OF ARC REQUIRED FOR ERRORLESS SYMBOL IDENTIFICATION UNDER EXPERIMENTAL CONDITIONS OF FOLEY AND SCOTT (1957).

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

After a review of the literature, Shurtleff (1966) concluded that little change in symbol legibility was occasioned by viewing angles up to 45 degrees off axis. In support of his conclusions, he noted that the Reinwald data indicated substantial increases in angle of subtense were required for viewing angles greater than 45 degrees.

Kinney, Manning, and Smith (1965) investigated the effects of viewing angle on the time required to read common five-letter words for two different symbol sizes. The viewing angles investigated were 90 degrees (straight on), 60, 45, and 30 degrees. Two symbol heights were investigated (10 and 16 minutes of arc) as it was anticipated that the effects of viewing angle might be different depending upon symbol subtense. Over 100 common five-letter words were printed on white paper. The words were subsequently photographed on 35-mm film and the transparencies were mounted in glass. A projector was mounted behind a black screen. Symbols were projected through a piece of opalized glass in the center of the screen which diffused the light sufficiently to provide constant brightness at all angles out to less than 30 degrees; 0.4 foot candles of cool white fluorescent light was present at the display face. Forty-eight subjects were employed, each being assigned a particular viewing angle (90, 60, 45, or 30 degrees) and a viewing distance/symbol subtense (10 or 16 minutes of arc). Subjects viewed the projected words displayed one at a time in an unpredictable order. Subjects were instructed to read each word aloud as rapidly as possible. Each subject's median reaction time for 50 words was taken as representative of his performance. If a subject failed to read a word or read it incorrectly, the data were recorded but not included in the analysis.

Study results are shown in Figure 71. For symbols subtending 16 minutes of arc, analysis of variance showed no significant differences among means for the four angles. For symbols subtending 10 minutes of arc, differences among means for the four angles were statistically significant at the 0.01 level. For the 10-minute symbols, Duncan's Range Test showed the mean for 30 degrees to be significantly different than the means for 90, 60, and 45 degrees. Thus at the 10 minute symbol size, while the mean for 90, 60, and 45 degrees were not distinguishable from each other, each was significantly smaller than the mean time for 30 degrees. The

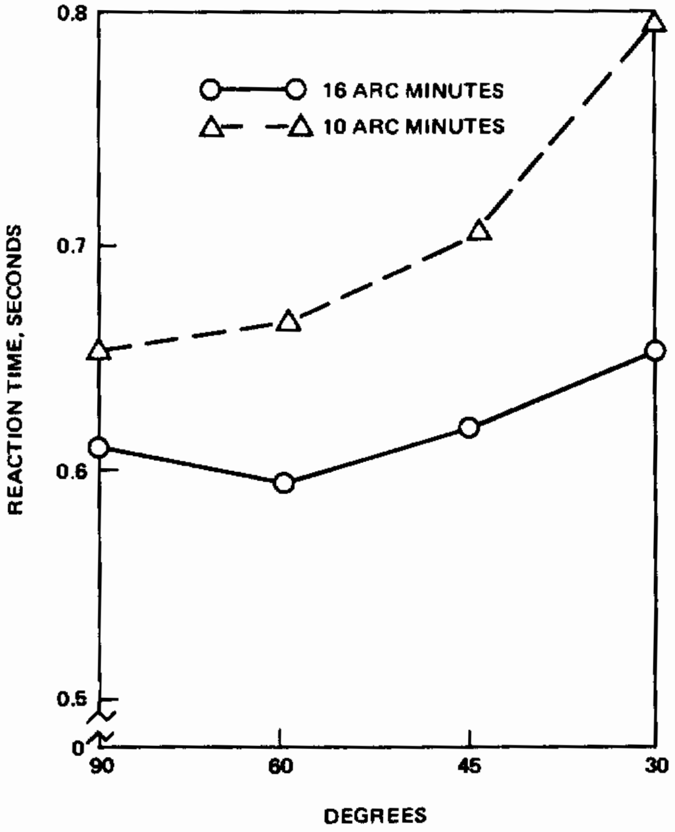


Figure 71. Study results of Kinney, Manning, and Smith (1965): mean reaction time for symbol identification as a function of viewing angle, for two symbol sizes.

investigators concluded that reaction time did depend upon viewing angle and that the effect of viewing angle on reaction time depended upon the symbol size. They recommended that no viewer be seated at a viewing angle smaller than 45 degrees.

Riche and Kinney (no date), after a review of the literature, reported that a general result obtained with singly presented letters, numerals, and words was that relatively good reading performance is obtained when the angle between the line of sight and the display surface is more than 60 degrees (less than 30 degrees off the perpendicular).

Neal (1968) investigated the legibility of televised alphanumeric symbols while varying scan lines per character height, bandwidth, angular symbol subtense, and off-axis viewing angle. The legibility of the televised symbols was measured in terms of the accuracy with which viewers could copy the random character sequences on an input/output typewriter connected to a computer. Study results showed that decrements in legibility occurred with off-axis viewing. Under conditions where vertical resolution and visual angle gave high legibility (better than 90 percent) at zero degrees off-axis, there was no decrement in legibility until the off-axis angle became 40 degrees. Under less favorable conditions, the effect of the off-axis angle was more severe, reducing the legibility even at 20 degrees (see Figure 72). Neal concluded simply that "if the viewer's line of vision is more than 30 degrees off axis, he may not be able to read the displayed material accurately" (p. 43).

The results surveyed seem to indicate that viewing angles up to ±30 degrees off axis cause little decrement in symbol legibility. The above studies, however, considered mainly the effects of symbol distortion and symbol foreshortening associated with oblique viewing angles. The effects of a nondiffuse surface or emitter seem to have been ignored or uncontrolled in many studies. In reference to the matrix-type displays, the applicability of the above findings would seem to be highly device dependent. That is, while it is not possible to anticipate all of the additional factors which influence the legibility of matrix symbols presented at off-axis viewing angles, an obvious one would be the large variability in fall-off of symbol brightness between reflective-type (liquid crystal) displays and active emitters such as an LED array. The research conducted during the present program utilized a simulation of matrix parameters via a cathode ray tube display. Therefore, it was not possible to assess the effects of brightness variations produced by off-axis viewing angles on the legibility of dot-matrix displayed symbology.

In summary, the results of the studies surveyed are probably directly applicable to matrix displays from the standpoint of symbol foreshortening. Luminance fall-off, due to high gain screen properties, has the effect of reducing display brightness and should be predictable, assuming the amount of luminance fall-off with off axis angle is known for specific matrix displays.

## A.7 CONTRAST AND ADAPTATION LEVEL

To be legible, electronically generated symbology must be brighter than the immediately surrounding display. However, as pointed out by

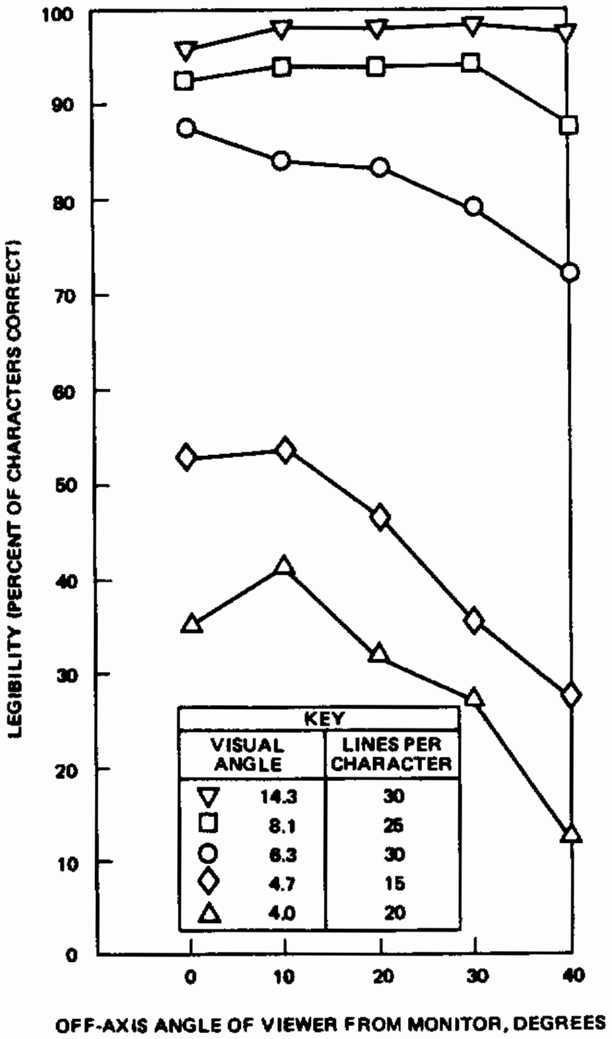


Figure 72. Average legibility as a function of off-axis angle for five representative test conditions (from Neal, 1968).

Semple (1971), simply specifying symbol brightness is an inadequate approach to identifying requirements for symbol legibility; rather, it is necessary to identify the degree to which symbol brightness is different from the immediately surrounding display background brightness in order to provide for criterion performance. A standard method for specifying the difference between display background brightness and symbol brightness is through the use of the contrast ratio equation. Luxenberg and Bonness (1965) similarly proposed that "Contrast, not brightness, is the significant factor in display legibility" (p. 8).

Brightness is generally specified, because it is dependent only on the equipment, whereas contrast is generally a function of ambient lighting. Brightness is also specified, because it would seem that the higher the brightness the greater the visibility under high ambient light. This is not necessarily true, since some displays of lower intrinsic brightness have better visibility than far brighter ones (see Ketchel and Jenny, 1968).

While several formulas for calculating the contrast ratio exist, the following equation is perhaps the most common:

$$C = \frac{B_t - B_o}{B_o} = \frac{\Delta B}{B_o}$$

where "C" is luminance contrast, $B_t$ = luminance of the target, and $B_o$ = luminance of the background. Note that with this formula, the contrast of targets brighter than their backgrounds can vary between zero and infinity, while those darker than their backgrounds can vary from zero to minus one.

There is no one required contrast ratio applicable to all conditions of symbol luminance and background luminance. As display background luminance increases, symbol luminance also must increase to maintain legibility, but not in direct proportion to display background luminance. Indeed, there are a variety of factors influencing the selection of proper symbol luminance and contrast values for a particular display application.

One of the most important factors influencing required symbol luminance is the display background luminance levels with which symbology must compete in order to be legible. Factors of incident illumination display reflectivity, and display-induced background luminance are important. In conjunction with background luminance, symbol luminance values determine contrast. Symbol luminance can be affected by attenuation features of the display face and filters employed.

In operational situations, another factor referred to as "adaptation level" (i.e., the luminance level to which the observer's eyes are adapted) may also influence contrast requirements. An observer may be adapted to a light level either higher or lower than that of the display background. Carel (1965) has suggested that as long as the general background surround area does not exceed 10 times the display background luminance required symbol/background contrast ratios will not differ markedly from conditions in which surround luminance level is equal to or lower than the display background luminance. As can be seen from Figure 73, minimum legibility contrast ratio requirements rise sharply when general surround luminance exceeds approximately 10 times the display background luminance.

In the present matrix research program, surround luminance level was kept matched to the display background luminance; thus the display background was the eye adaptation level. Display background luminances investigated ranged from 2000 to 0.05 foot lamberts. It is expected that lower background luminances will require less symbol luminance, but higher symbol contrast ratios in order to provide the same legibility.

In general, "optimal visual discrimination under conditions of very low luminance can be made only if the visual system is adapted to the level of the prevailing photic environment, or even lower" (Taylor, 1973 p. 654). When a light adapted eye is suddenly exposed to darkness, initial sensitivity is low. Taylor notes that as time in the dark increases, sensitivity increases as a result of photochemical regeneration, certain neural changes, and (to a much smaller degree) enlargement of the pupil of the eye. Figure 74 depicts a general adaptation curve obtained with white light. The left portion of the curve, extending to about 10 minutes, reflects the adaptation of the retinal cones. Subsequent increases in sensitivity are due to rod adaptation.

Taylor (1973) has listed some general consequences of the dark adaptation process and its properties:

> "(1) Best performance on a task at low luminance requires that the eye be preadapted to an appropriately low level for sufficient time so that maximum sensitivity obtains.
>
> "(2) Since the rods are more sensitive than the cones at low luminances, best detection capability will occur on those parts of the retina where rods abound (10 to 30 degrees from the fovea), and averted vision is required for optimal performance.
>
> "(3) Since the rods are relatively insensitive to extreme red wavelengths, dark adaptation will proceed if the observer dons suitable red goggles or if the illumination provided .. is very deep red," (p. 654).

Other factors besides symbol luminance, display background luminance and eye adaptation level have been noted to affect contrast ratio requirements.

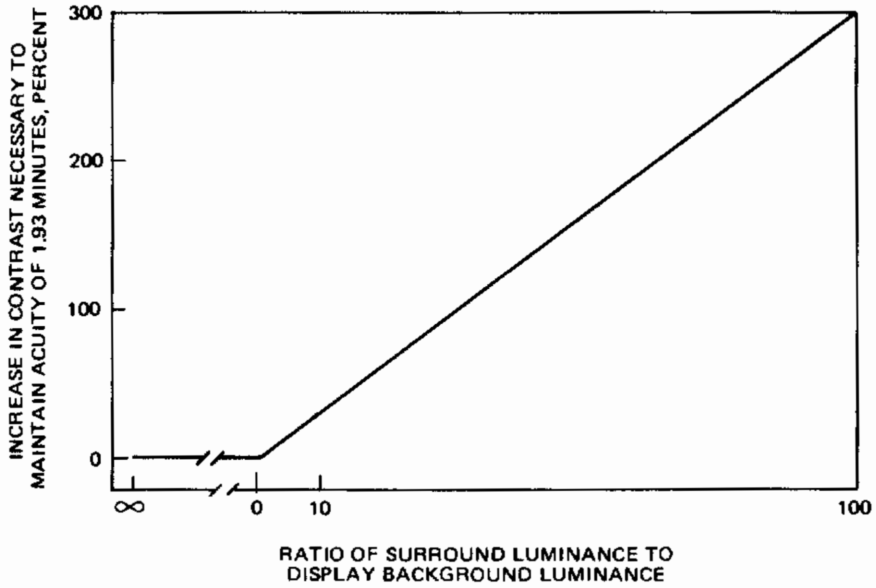


Figure 73. Percent increase required in contrast ratios as a function of the ratio of surround luminance to display background luminance.

Semple (1971), after a review of the literature, commented that a significant factor influencing contrast requirements was symbol size and shape, such that smaller and less solid symbols (symbols containing gaps as in a matrix display) required greater contrast for legibility. This is most likely related to the fact that the brightness sensitivity of the human eye is affected by the area of the source of illuminance such that, for a given illuminance level, larger luminous objects can be detected more easily than smaller luminous objects. That is to say, one determinate of the visual threshold is the area of retinal stimulation. Thus in reference to the development of contrast ratio design criteria for solid state matrix displays, emitter size (area) and placement (spacing of emitters relative to other emitters) should receive consideration as legibility is influenced by the area of the fovea stimulated by symbology.

Direction of contrast, light symbols on a dark background versus dark symbols on a light background, is also a factor to be considered. While Semple (1971), after a review of the literature, concluded that contrast polarity has little practical impact upon symbol identification, Taylor (1973) noted that Patel and Jones (1968) found significantly higher thresholds for positive (light) than for negative (dark) targets at low luminance levels.

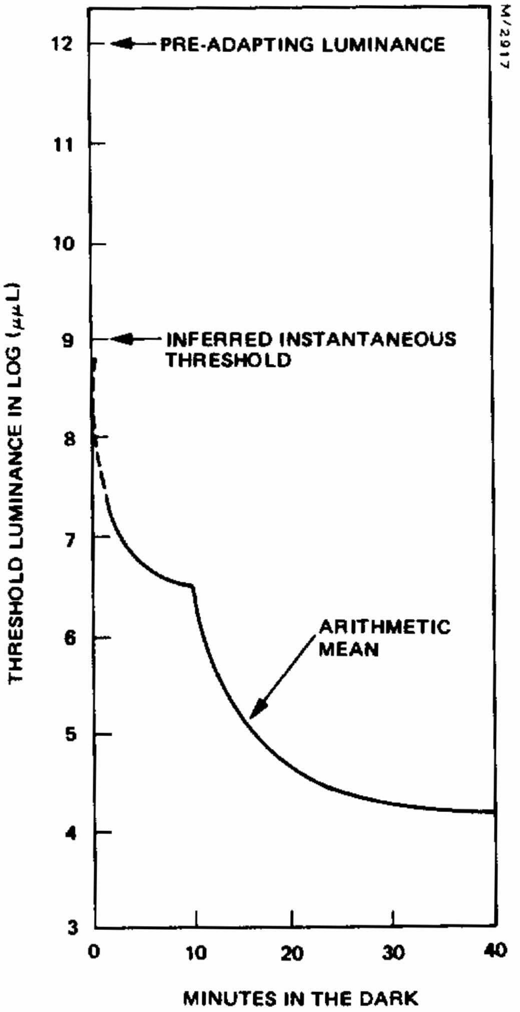


Figure 74. Course of dark adaptation following exposure to a luminance of about 1000 ft-L. Measurements made using a test spot 1° in diameter imaged on a retinal region 15° in nasal periphery where both rods and cones are present.

Luminosity discrimination has been the subject of classic experiments in which the observer was shown a target image and then asked to report whether it was brighter or darker than its background. One of the most comprehensive of these studies was conducted by Blackwell (1946). He employed a sharply defined circular spot as the target and obtained contrast thresholds as a function of target size and observer adaptation level. Blackwell defined contrast as:

$$C = \frac{B_s - B_o}{B_o} \quad \text{(bright targets, dark ground)}$$

$$C^1 = \frac{B_o - B_s}{B_o} \quad \text{(dark targets, bright ground),}$$

where $B_s$ = target brightness and $B_o$ = background brightness. (Note that this definition of contrast yields different values of contrast for the same pair of luminance values depending upon whether it is the symbol or background that has the higher luminance). Carel, McGrath, Hersberger, and Herman (1974) utilized a psychometric function and a field factor applied to Blackwell's (1949) 50 percent contrast threshold data in an attempt to predict 98 percent discrimination probability for projected map display alphanumerics (see Figure 75). The derived curves represent an estimate of the minimal image contrast required in an operational environment and are based on a situation where the adaptation level of the eye was approximately matched to the average luminance of the display.

While relatively few studies have attempted to define contrast requirements for alphanumerics, some information is available. A good

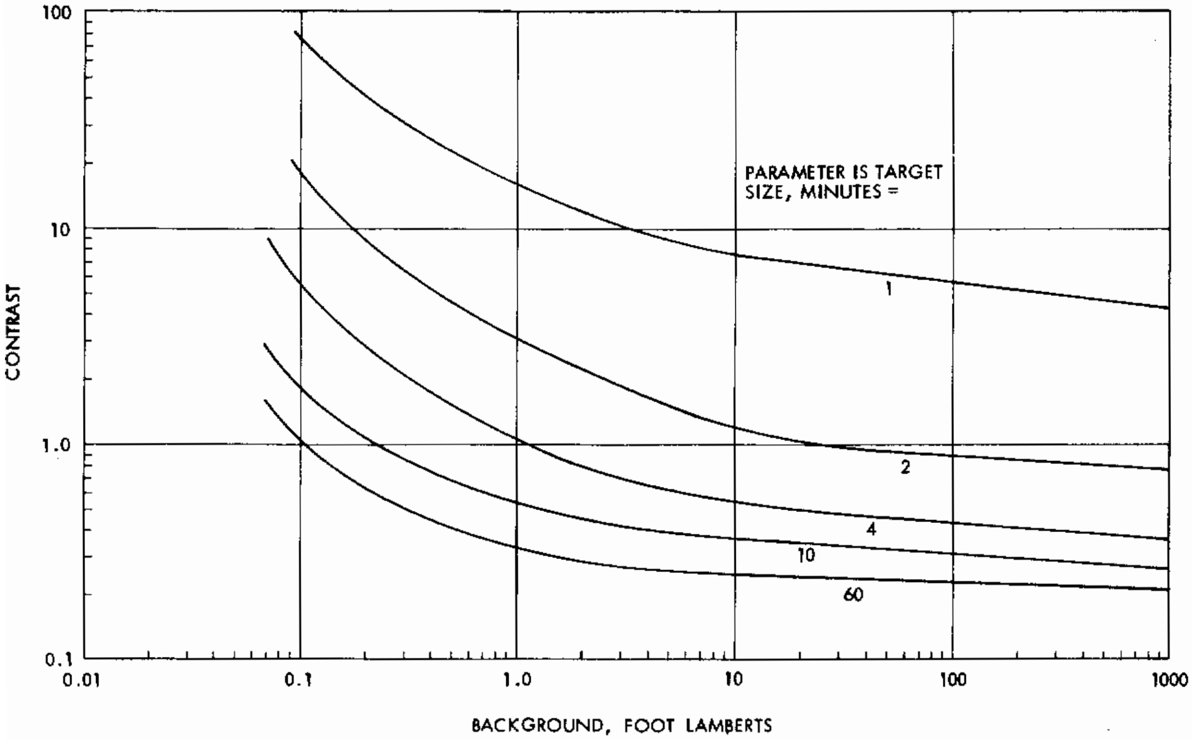


Figure 75. Operationally useful contrasts (adapted from Blackwell, 1946).

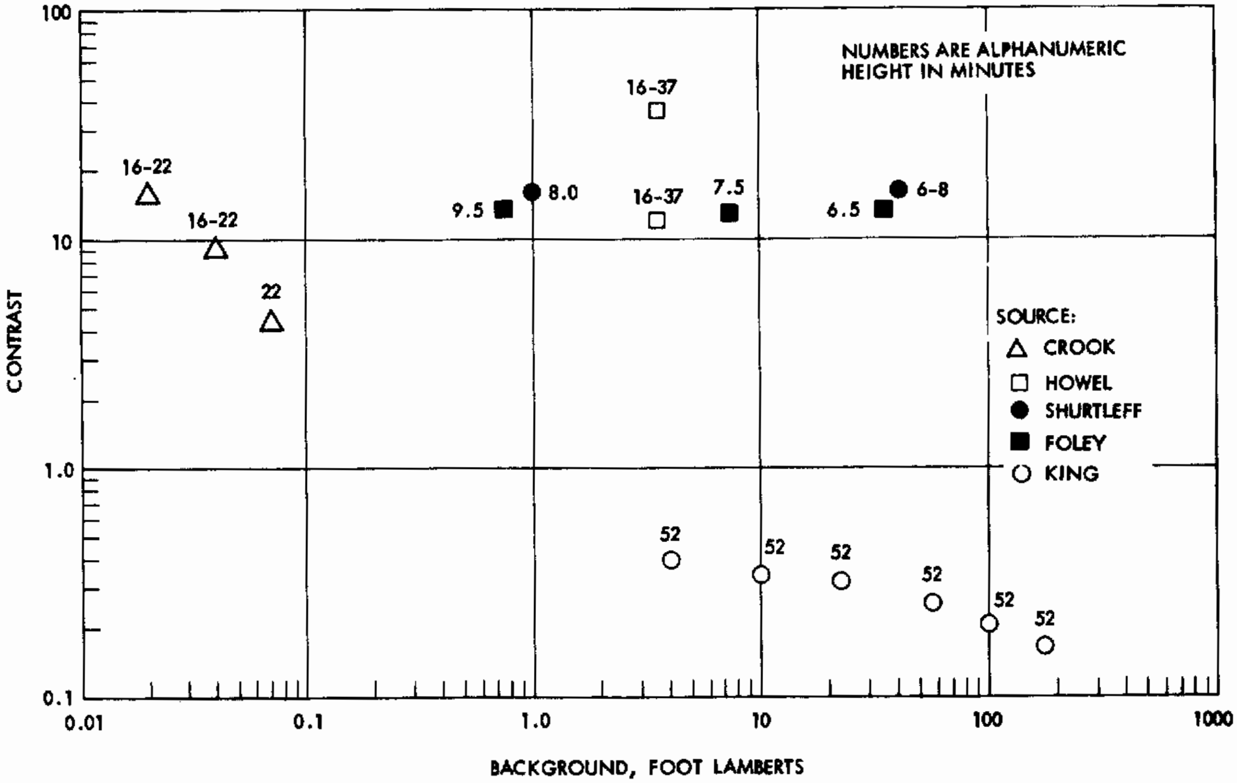


Figure 76. Error-free alphanumeric recognition data.

general review of alphanumeric legibility studies has been provided by Shurtleff (1966). Carel, McGrath, Hersberger and Herman (1974) culled data points from those experiments reported by Shurtleff which dealt with contrast as a variable and provided enough information to determine background brightness. These selected data points were plotted (see Figure 76), showing the values of contrast, background brightness, and symbol size that resulted in greater than 95 percent correct identification. Also plotted were data points from a study by King, Wollentin, Semple, and Goettelmann (1970), denoting mean threshold results for numerals. Thus Figure 76 represents a compilation of legibility data from a number of experiments conducted under varying conditions. The scatter of data points in Figure 76 provides a direct index of the combinations of contrast, symbol size, and average display brightness that were found to yield near perfect legibility.

In further reference to the study by King, Wollentin, Semple, and Goettelmann (1970) cited above, it is interesting to note that the numerals employed were seven-segment electroluminescent numerics. Further, Semple (1971) noted that results obtained by King, Wollentine, Semple, and Goettelmann (1970) suggested that the effects of display background luminanance level were of considerably greater significance than eye adaptation level in determing emitted symbol luminance required to produce consistent display legibility. Thus it appears that in the absence of a severe adaptation mismatch, contrast would prove the more important variable influencing legibility.

A recent study by Carel, McGrath, Hersberger and Herman (1974), concerned with developing design criteria for airborne map displays, investigated the effects of contrast and total display luminance (adaptation level) on the threshold level and comfort level legibility of map alphanumerics. (Symbols were dark on lighter backgrounds). Results are plotted in Figure 77. Analysis of variance performed on the data indicated that the main effects of both contrast and total display luminance were statistically significant at the 0.001 level and accounted for large percentages of the total variance in the experiment (24.76 percent and 38.30 percent respectively for threshold legibility). The luminance by contrast interation was also statistically significant, and accounted for 17.82 percent of the variance.

The above reported studies provided some basic information concerning contrast requirements for displayed alphanumerics. While the majority of legibility contrast ratio requirements have been obtained using white (or green-yellow) symbols against gray backgrounds, they should prove equally valid when applied to monochromatic matrix displays. Thus while the eye is differentially sensitive to various wave-lengths (hues), when perceived brightness is equated, color itself has an insignificant effect on legibility (i.e., brightness contrast is the critical variable — see Figure 78, Stevens, 1960). Because human visual perception is influenced by color combinations as well as by brightness differences, however, it seems likely that contrast ratios derived using achromatic symbology will not be directly applicable to polychromatic displays. Semple (1971) noted that no design-oriented data exist which relate to contrast ratio requirements as a function of symbol-background color combinations.

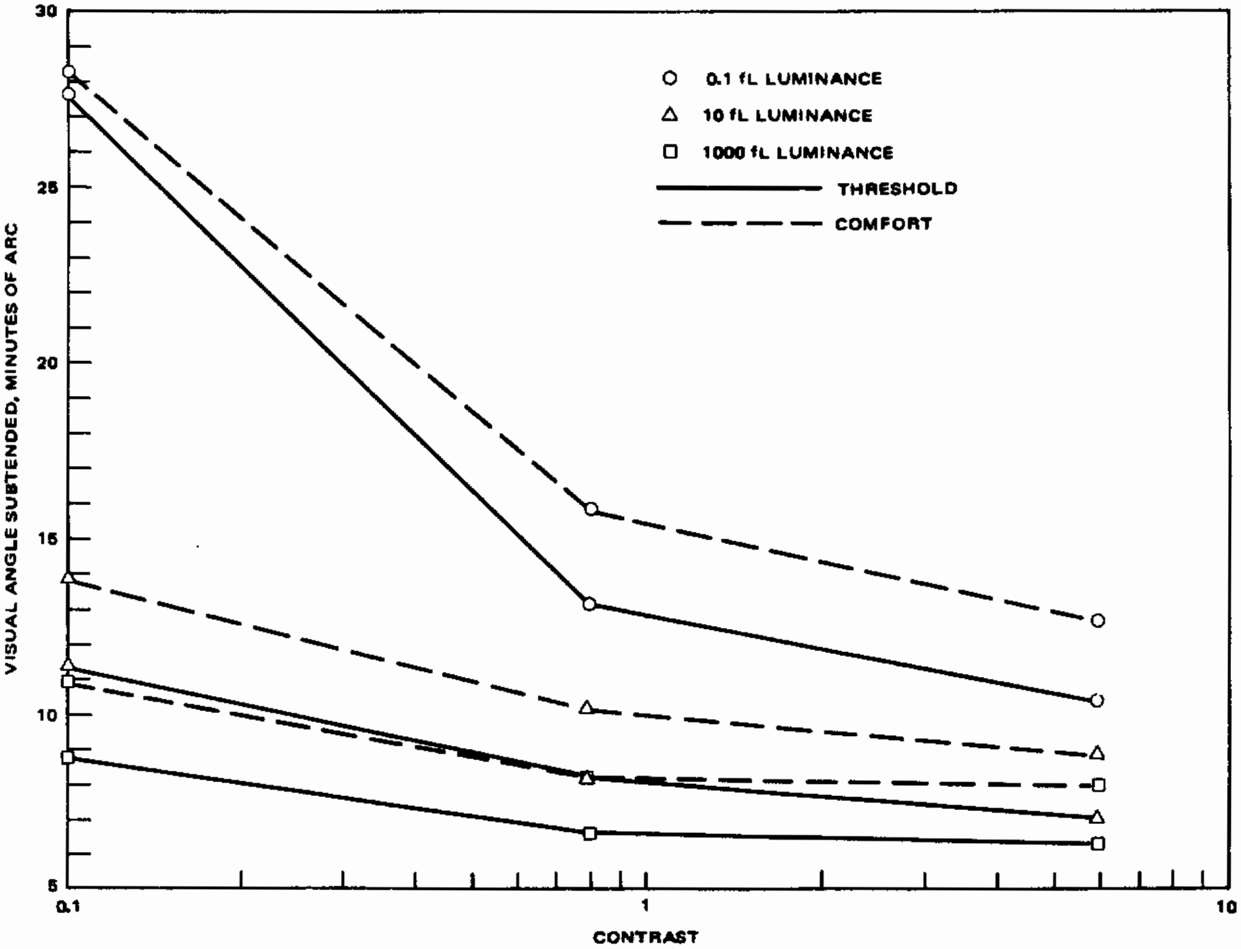


Figure 77. Effect of display luminance and contrast on alphanumeric legibility.

It appears that the above reported contrast ratio requirements should be applicable to monochromatic matrix displays. There is no reason to anticipate that contrast requirements for matrix displays will be different than for CRT or projected displays except as possible interactions occur (e.g., an interaction between contrast and percent active area).

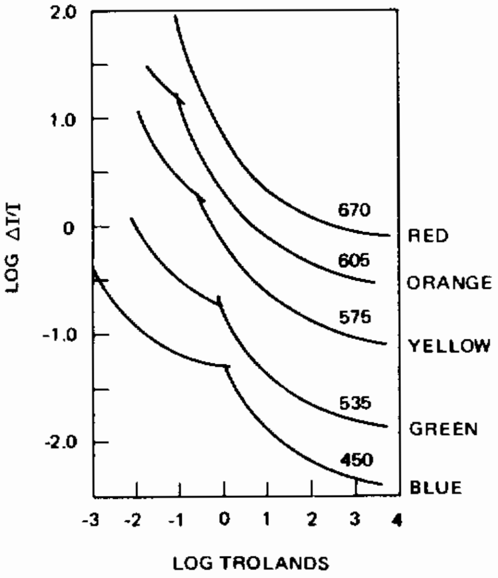


Figure 78. Human brightness discrimination for the red, orange, yellow, green, and blue parts of the spectrum. The labeling on the ordinate applies to the data for yellow (575 mμ). The orange and red curves have been raised 0.5 and 1.0 log unit, respectively, and those for green and blue have been lowered 0.5 and 1.0 log unit, respectively. (Hecht, Peskin, and Patt, 1938).

## A.8 COLOR

The visual thresholds of the human eye vary as a function of incident wavelength (color) as well as with luminous intensity. The shortest wavelength luminance which ordinarily is perceived as a color stimulus is 380 millimicrons (mu), although, Semple has reported that under certain laboratory conditions luminance of wavelengths as short as 300 mu may be visible. The longest wavelength luminance which ordinarily is perceived as a color stimulus is 770 mu; although, again under carefully controlled conditions this has been extended up to 1,000 mu. For practical purposes, the human visible spectrum lies between 380 and 770 mu. Hue is the psychophysical counterpart of the physical dominant wavelength of a stimulus. Table 21 presents some color names typically associated with the various wavelengths in the visible spectrum.

TABLE 21. SOME TYPICAL COLOR NAMES ASSOCIATED WITH LUMINANCE WAVELENGTHS COMPRISING THE VISIBLE SPECTRUM

| Wavelength Band | Typically Associated Color Name |
|---|---|
| 380-470 | Reddish Blue |
| 470-475 | Blue |
| 475-480 | Greenish Blue |
| 480-485 | Blue-Green |
| 485-495 | Bluish Green |
| 495-535 | Green |
| 535-555 | Yellowish Green |
| 555-565 | Green-Yellow |
| 565-575 | Greenish Yellow |
| 575-580 | Yellow |
| 580-585 | Reddish Yellow |
| 585-595 | Yellow-Red |
| 595-770 | Yellowish Red |

Color vision is mediated by retinal receptors called cones. Color vision occurs at photopic luminance levels (where cones are active) and is optimum at and near the center of the field of view where the cones are most densely packed. Figures 79 and 80 show the differential sensitivity of the cones to wavelengths comprising the visible spectrum. As can be seen from Figure 80, maximum cone sensitivity occurs at 555 mu, corresponding to green-yellow light. (The human eye is almost as sensitive to white light as it is to green-yellow light.) More radiant energy is required to produce visibly detectable stimuli for wavelengths lying near the ends of the visible spectrum than for those lying near the center. To put it another way, the sensation of brightness differs for different wavelengths when the amount of radiant energy is the same. Thus factors affecting perceived symbol color will affect perceived symbol luminance.

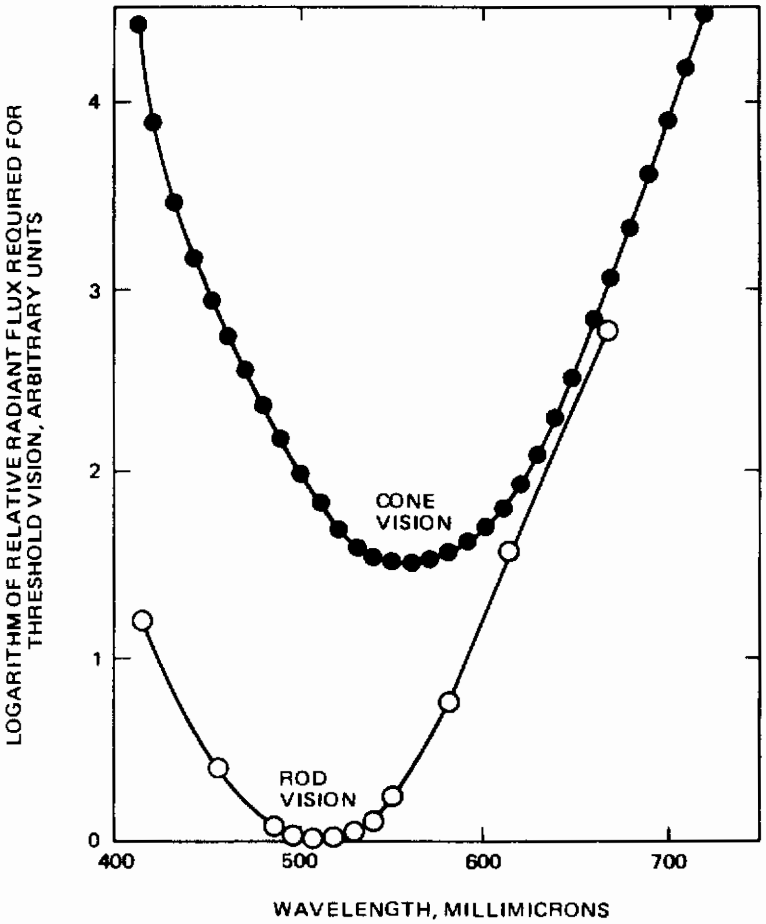


Figure 79. Relative amounts of radiant flux required to stimulate rods and cones.

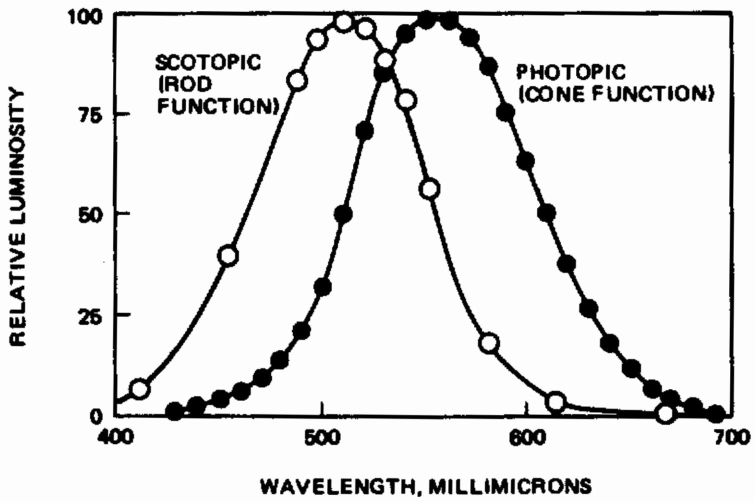


Figure 80. Photopic and scotopic relative luminosity curves.

Background color has been shown to affect perceived symbol color. In addition, discriminability of both color difference and saturation (amount of color) have been shown to be degraded at very low and very high levels of illumination. These additional factors must be considered as they affect color perception.

Semple (1971) noted that research addressing legibility contrast ratio requirements for electronically-generated symbology has not systematically taken emitter (and thus symbology) and display background colors into account. Reasoning that human visual perception is influenced by color combinations as well as brightness differences, Semple (1971) concluded that contrast ratios derived using achromatic symbology might not be directly applicable to colored symbology. He pointed out the need for design-oriented color contrast data.

Graham (1965) noted that visual acuity was poorer at the ends of the visible spectrum than at mid-spectrum. Similarly, Semple pointed out that visual discrimination was superior at mid-spectrum under yellow-green (or white) light, the eye being able to detect a smaller point source of light at such wavelengths. He further stated that "For red . . . [light] the resolving power of the eye is only about 1/3 as good as for white light and for blue it is only about 1/5 as good as white" (p. 282). Taylor (1973) also commented that for tasks illuminated by monochromatic or narrow-band sources there was a small but measurable difference in acuity as a function of the dominant wavelength used (when colors were equated for luminance under photopic vision conditions). He noted that in comparison with acuity measured in white light, blue and violet light visual acuity was poor.

Differences in visual acuity noted for different colors of equal radiant energy can be partially explained by reference to the above mentioned fact that the eye is differentially responsive to wavelengths in the visual spectrum, responding to certain colors as being "less bright". However differences in visual acuity occurring when colors are equated for perceived luminance can perhaps best be explained by reference to the concept of chromatic aberration. Duke-Elder (1949) discussed the fact that the lens of the eye functions in some respects like a prism in that both refract light. In both the prism and the lens of the eye, shorter wavelength light is refracted (bent) to a greater extent than longer wavelength light. The degree of refraction (bending) is inversely proportional to the wavelength. Myers (1967) suggested that because of this characteristic, only one wavelength could be focused on the retina at a time. Thus, for example, when yellow-green objects are focused on the retina (as is also the case when viewing a white object) radiant energy in both the blue and red wavelengths are out of focus, their focal points falling to the front and the rear of the focal plane, respectively. Further, the larger the diameter of the pupil of the eye at the time of entry of the light — i.e., the lower the display luminance level — the more "out-of-focus" the blue and red light sources will appear. This effect is commonly referred to as chromatic aberration. Measurements of chromatic aberration in the human eye have been made by several investigators with similar results (see Figure 81).

In displays utilizing multiple colors, chromatic aberration may cause loss of acuity due to blurring, resulting from colors imaging in different planes. In addition, small colored stimuli may be perceived to be at different distances according to their spectral composition.

For monochromatic displays, visual accommodation (bringing displayed symbology into focus on the retina) is possible except in the case of blue light. Due to the fact that red light is initially focused behind the

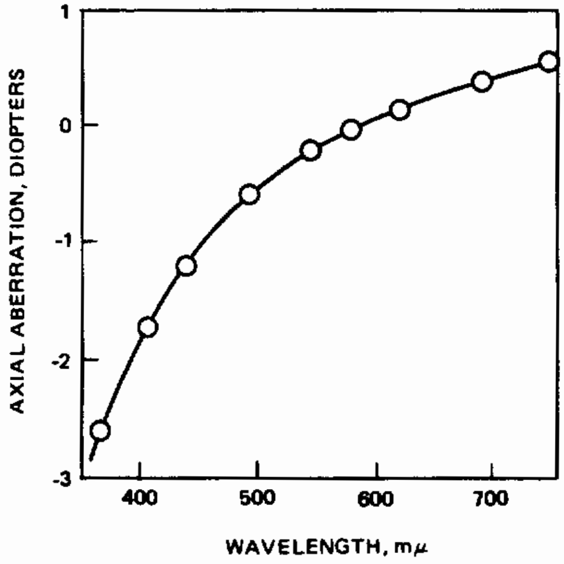


Figure 81. Axial chromatic aberration of human eye. Averages of measurements on 14 observers. Ordinates show lens correction in diopters needed to give each eye same refractive power it possesses when accommodated for distance vision at 578 mμ (from Wald and Griffin, 1947).

retina, the eye can successfully accommodate to bring it into focus. However, as noted by Mitchell and Mitchell (1962), under blue light distant objects (6 feet or more away) are imaged in front of the retina, with the normal emmetropic eye being unable to adjust to clearly focus them. In other words, the accommodation power of the eye was found to be already at its minimum when viewing distant objects.

Jones (1962) stated that the myopic reaction of the eye to blue light (focusing it in front of the retinal plane) was of critical concern due to its effect on visual acuity. Thus she suggested that the use of blue colored stimuli of small visual subtense was inadvisable for presentation of critical information.

Myers (1967) concluded that, with the exception of blue, the small differences in acuity resulting from accommodation differences with various colors would not be a serious impediment to the use of color displays. Blue was to be excluded, however, as the eye does focus this color myoptically. Even though larger symbol sizes might result in correct identification with blue light, the image would still remain out of focus, causing visual fatigue.

Some indirect support for this conclusion was provided by Radl-Koethe and Schubert (1971) who conducted a comparison of the legibility of nine existing light emitting numeral displays (presenting segmented, dot, and solid numerals). Of the displays they compared, five had white readouts, two had red, and two had red-orange. These investigators concluded that color of illumination did not show direct influence on legibility for the colors tested.

In further support, after a review of the literature, Rogers (1974) concluded that red (long wavelength, narrow bandwidth) light emitting diodes would not interfere with visibility under photopic viewing conditions. Similarly, Semple (1971), after a review of the literature, suggested that hues in the yellow-green and red range of the color spectrum appeared to offer the most promise for color displays.

One disadvantage of utilizing color displays is that some people are color-defective. About 8 percent of all males and 0.4 percent of all females exhibit some form of color blindness, resulting in a decrease of visual sensitivity by at least 35 percent. For example, Rogers (1974), considering the legibility of red LED displays, pointed out that for 1 percent of the population exhibiting a form of color anomaly known as protanopia (non-responsive to wavelengths greater than about 640 nm), a red display would be essentially invisible. However, color blindness effects are not likely to be an important consideration in an Air Force pilot population.

With reference to the above articles, it would appear that little differences in operator performance should be observed with either monochromatic or multicolor displays utilizing colors - except for blue. Such a conclusion is of special significance in the case of solid state displays many of which inherently produce colored symbology. However, one empirical result, obtained with a simulated LED display, provided some contradictory evidence. Specifically, Ellis, Burrell, Wharf, and Hawkins (1974), conducted an experiment to assess the relative performance of red and green displays (of equal luminance) in an illuminance of 10,000 ft-c. These investigators employed a simulated emissive display, rear projecting 4 mm high alphanumerics (three dot-space ratios were also investigated). This back illumination was filtered giving peak transmission corresponding to GaAs/P red (peak 660 nm) and GaP green. The character luminance for each color was 100 units. Thirty-six alphanumerics composed the symbol set. Symbols were presented one at a time for 0.7 seconds each. Subjects read each symbol as it was presented; reading errors and omissions were recorded.

Results showed the total error rate for red symbols, for 68 subjects with normal vision, was below that for green by almost a factor of three (5.8 percent compared with 15.9 percent). A similar ratio was found in the overall results for all 125 subjects (including those with visual defects). The authors concluded that for displays of equal luminance, used with high background brightness, green characters were far less legible than red. The authors offered no explanation of their finding and none seems readily apparent. Examination of this result was not within the scope of the present research where dot color was white.

## A.9 SYMBOL ORIENTATION AND SYMBOL MOTION

The readability of words and numerals varies with their mode of presentation. Two factors to be discussed in this section — static symbol orientation and symbol motion — have been shown to influence symbol legibility under certain conditions.

### A.9.1 Static Symbol Orientation

Vartebedian (1970) investigated the effects of letter generation method (matrix versus stroke), matrix size, dot geometry, and letter orientation (slanted versus upright) on the legibility of CRT displayed alphanumerics. Twenty-six letters and ten numbers were presented briefly on the display screen. Subjects' speed and accuracy in identifying displayed symbols served as measures of legibility.

The stroke font employed in the study was based on the Leroy font. The matrix symbols were designed by Vartebedian for legibility. All symbols were displayed in the center of a CRT with a symbol spot brightness of 11 fL and a background brightness of 2.0 fL. Symbols were 0.14 inches in height and subtended a visual angle of 17.2 minutes at the observer's eye. Upright symbols were compared with those slanted 20 degrees to the right of vertical. Study results showed that slanting had a detrimental effect on both dot and stroke written symbols. For identification errors, comparisons between the upright and slanted symbols favored the upright orientation for both stroke and dot symbols; however, the difference between the error percentages for upright versus slanted stroke-written symbols was only half as great as the difference between the percentage error for upright versus slanted matrix symbols (i.e., image degradation due to symbol rotation was worse for the matrix symbols). Similarly, reaction time differences showed the dot symbols to be more adversely affected by slanting than the stroke symbols (see Table 22). Vartegedian concluded that "the use of slanted symbols in a display would result in a loss of legibility" (p. 26).

Plath (1970) compared the readability of slanted segmented digits with upright segmented digits and solid stroke Amel numerals. The stimulus materials consisted of 108 35mm slides, each containing a 5-digit number. Thirty-six of the numbers were designed in the AMEL font. Another 36 numerals were made up of digits formed by seven-segment matrices and were vertically oriented. The remaining 36 numbers were similarly constructed of seven-segment digits with each digit slanted 15 degrees to the right of vertical. The width of all numerals was approximately three-fifths of the height. All numerals were projected as white characters on a dark background. The size of the numerals projected on the screen was held constant at 3/8 inches. Subject's viewing distance was 30 inches. Brightness contrast

$$\left(\frac{\text{Bmax} - \text{Bmin} \times 100}{\text{Bmin}}\right)$$

between the numerals and the immediate background was 96 percent. Ambient room illumination was 75 ft-C. The dependent variable was the accuracy with which numbers could be read at three exposure times. Symbols were presented on a tachistoscope, and subjects were instructed to

TABLE 22. RESULTS FROM VARTEBEDIAN'S (1970) STUDY ON LETTER ORIENTATION

| Condition | Reaction Time | Percent of Errors |
|---|---|---|
| stroke upright | 659 | 4.5 |
| stroke slant | 677 | 6.7 |
| 7 x 9 upright circle dot | 602 | 2.6 |
| 7 x 9 slant elongated dot | 814 | 7.7 |

record in writing their perception of each five-digit number immediately after its appearance on the screen. Ten subjects viewed numbers exposed for 1/2 second. Symbol exposure time for a second group of 10 subjects was 1/10 second and for the third group was 1/50 second. Plath found only small differences between total errors per group for slanted versus upright segmented numbers (See Table 23). Plath concluded that slanted and upright segmented numerals could be read with comparable accuracy.

Sgro, Elam, and Dougherty (1964), in a study conducted for the JANAIR Committee, investigated the ability of subjects to read alphanumeric information at various degrees of rotation, including inverted. Subjects were seated 18 inches from a translucent screen upon which 35mm slide stimulus images were projected. Each subject saw 100 slides, each depicting a photographed section from a 1:500,000 scale aeronautical chart of the Southern United States. Each slide contained a small black arrow, which pointed to a particular word or number on the map. The words, which varied in size, indicated various cities, towns, and rivers, while the numbers designated elevations. The words (N=67) and numbers (N=33) were displayed at various angles. Symbol display angle was defined as the angle between the word axis and the vertical axis ($0^{\circ}$). The 360 degrees of possible rotation were divided into four sectors of 90 degrees each. Slide presentation was preceded by a 5-second flashing yellow warning light; upon presentation subjects were required to read aloud the number or word indicated by the arrow. As soon as the subject responded, the slide was turned off. Two response measures were recorded: (1) response latency and (2) response

TABLE 23. TOTAL ERRORS FOR VERTICAL AND SLANTED DIGITS

| Numeral Style | Exposure Time<br>1/50 sec. | 1/10 sec. | 1/2 sec. | Total |
|---|---|---|---|---|
| AMEL | 68 | 90 | 29 | 187 |
| Slanted Segment | 174 | 181 | 36 | 391 |
| Vertical Segment | 158 | 177 | 53 | 388 |
| Total | 400 | 448 | 118 | 966 |

error. Response latency was defined as the total amount of time which elapsed before a correct response was elicited. (See Tables 24 and 25 for a summary of study results.) As can be seen from Table 24, mean response latencies for numbers varied only slightly across sectors. Mean response latencies for words, on the other hand, showed the inverted position to be most difficult; the sideways positions were also more difficult than the upright orientation. Data were subjected to an analysis of variance and Scheffe's test for multiple comparisons or Wilcoxon signed-ranks test. On the basis of these analyses, the authors concluded that (1) the legibility of word information is most difficult when displayed in an inverted or near inverted position and (2) the legibility of numeric information does not pose a problem when displayed at any rotation angle.

TABLE 24. MEAN RESPONSE LATENCIES (SEC.) FOR WORD, NUMBER, AND COMBINED WORDS AND NUMBERS IN SECTORS OF ROTATION

| | Sectors I through IV, degrees | | | |
|---|---|---|---|---|
| | 45-134 | 135-224 | 225-314 | 315-44 |
| Words | 1.61 | 3.08 | 5.80 | 2.74 |
| Numbers | 1.73 | 1.82 | 1.92 | 2.03 |
| Combined | 1.65 | 2.66 | 4.52 | 2.51 |

TABLE 25. PERCENTAGE OF WORD, NUMBER, AND COMBINED WORDS AND NUMBERS INCORRECTLY RESPONDED TO WITHIN EACH SECTOR

| | Sectors I through IV, degrees | | | |
|---|---|---|---|---|
| Slides | 45-134 | 135-224 | 225-314 | 315-44 |
| Numbers | 0.02 | 0.04 | 0.02 | 0.04 |
| Words | 0.01 | 0.05 | 0.12 | 0.06 |
| Total (Combined) | 0.02 | 0.05 | 0.09 | 0.05 |

It is interesting to note that Vartebedian, who observed a decrement in legibility due to symbol slanting, employed more letters than numbers, while Plath, who found no such decrement, employed only numbers. Care must be taken, however, in generalizing the results of the Sgro, Elam, and Dougherty study to the legibility of rotated alphanumerics presented on dot-matrix displays. Unlike the case of solid stroke symbols, the orientation of matrix symbology affects symbol geometry. Because matrix letters are formed by fixed position emitters, symbol shape varies with symbol presentation angle, depending upon such factors as emitter size, shape, and density. While quantitative information on the legibility of rotated matrix symbols is sparse (only the Vartebedian study was found), it is anticipated that the effects of rotation on symbol legibility will be more severe for dot-matrix symbols than for stroke written symbols due to the above mentioned symbol distortion caused by the construction of rotated matrix symbols with fixed-position emitters.

### A.9.2 Symbol Motion

As stated earlier, both static symbol orientation and symbol motion have been found to affect legibility. In the more general sense, the recognition of any type of detail (alphanumeric or otherwise) when the observer, test object, or both are moving is treated under the topic of dynamic visual acuity.

A study of Ludvigh and Miller (1958) measured subjects' ability to locate the gap in a Landolt C as it moved across a display. Angular velocity ranged from 10 to 170 degrees per second. Study results showed that as angular velocity increased, the importance of static acuity decreased. At high angular velocities, there was little correlation between static and dynamic visual acuity.

Miller (1958) conducted an experiment similar to the one by Ludvigh and Miller (1958) in which he investigated the effects of horizontal as well as vertical movement. He employed angular velocities of 20, 80, 110, and 140 degrees per second in both the vertical and horizontal axes. The study results showed a consistent and statistically significant difference between vertical and horizontal movement; horizontal movement produced a consistently greater degradation of acuity (See Figure 82).

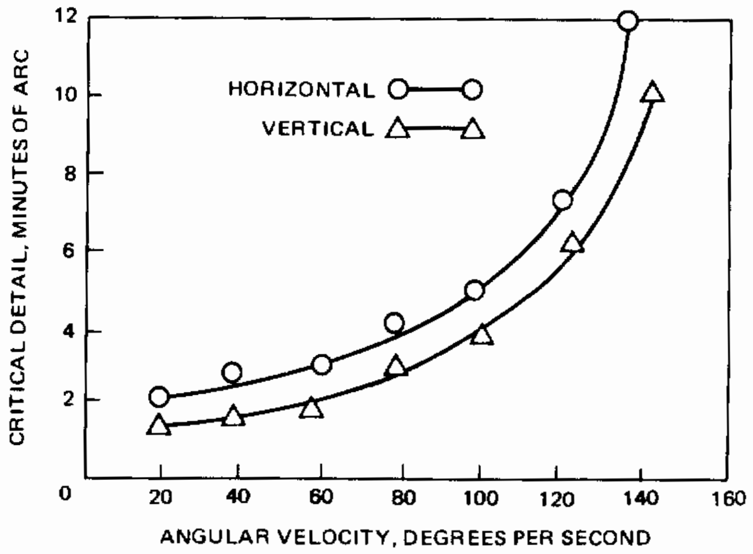


Figure 82. Visual acuity as a function of horizontal and vertical movement.

Studies by Ludvigh (1949) and Miller (1958) indicated that dynamic visual acuity is a function of the luminance level of the display; increasing the luminance level improves dynamic acuity. Semple (1971) presented a summary figure of these results, depicting the effects of illumination and angular velocity on visual acuity (see Figure 83). As can be seen from the figure, dynamic visual acuity deteriorated with increased angular velocity at each of the six illumination levels investigated. The rate of deterioration, however, was greater at the lower luminance intensities than at the higher intensities.

After a review of the relevant material dealing with dynamic acuity Semple (1971) made the following points in summary:

(1) Dynamic acuity shows a predictable impairment with increasing angular velocity, with noticeable deterioration beginning with an angular velocity of about 20 degrees per second.

(2) Generally, peripheral vision is more affected than central vision, especially at higher velocities, but the degradation in acuity is about the same for moving observer or moving target.

(3) Higher dynamic acuity is possible if the head is allowed to move freely than if the head is restrained.

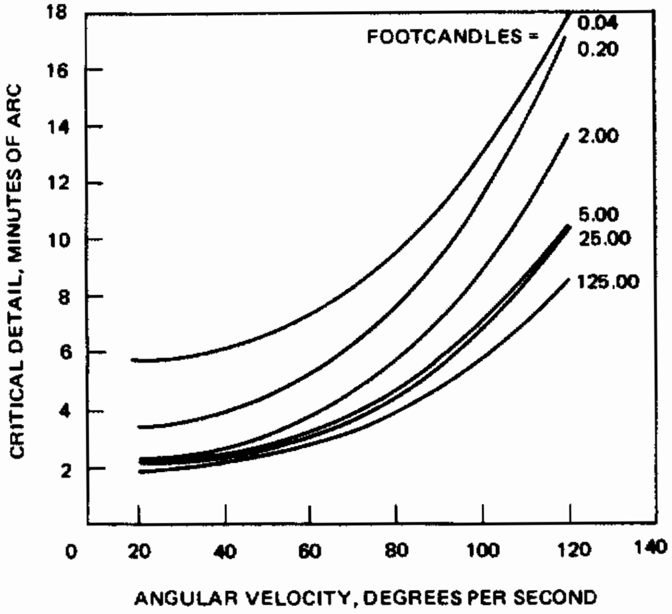


Figure 83. Acuity as a function of illumination level and angular velocity.

(4) Both static and dynamic acuity increase with increasing illumination (up to 1000 fL) and exposure time (up to 16 seconds exposure time).

(5) Dynamic acuity is subject to more rapid deterioration with anoxemia, reduced illumination levels, visual fatigue, and with advancing age.

(6) Horizontal movement produces greater deterioration than vertical movement, and the effect of vibration is about equal on both vertical and horizontal movement.

(7) Certain individuals are 'velocity resistant' (subject to minimal acuity loss with increasing angular velocity) while other individuals are 'velocity susceptible' and suffer severe acuity degradation with slight angular velocity (p. 286).

Lippert (1963) conducted a study to determine the ability of observers to identify vertically moving alphanumeric symbols which were regularly spaced on a moving belt. Targets subtended 39 minutes of arc at the subject's eye (in the vertical dimension). Two hundred and twenty-five symbols were employed, arranged in nine columns (25 symbols in each column). The clear space between columns subtended 51 minutes. Thus the display consisted of densely packed, regularly spaced symbols (the center to center spacing was 1.5 degrees). Alphanumeric symbols were black on white and displayed under high contrast (93 percent between symbol and surround) and ample lighting (3 fL).

The study was intended to establish recognition limits for one class of regularly spaced targets as a function of angular velocity and viewing aperture size. All apertures were 3 degrees wide. Three aperture heights were employed: 3, 13, and 30 degrees. Preliminary tests showed that with small apertures and high angular velocities, symbols appeared to "stream". Thus two thresholds were measured during subsequent investigations: (1) the zero legibility threshold (just a little slower than the streaming phenomenon) where at least one symbol could be detected as such and (2) the 100 percent legibility threshold where all symbols could be identified. Three subjects were used to determine the angular velocities at which the criterion of zero legibility and the criterion of 100 percent legibility could be met for each of the three rectangular apertures.

Study results showed that the mean angular velocity for zero legibility varied from 30 degrees/sec for the 3 degree (2 inch) aperture to 56 degrees/sec for the 30 degree (20 inch) aperture. The mean angular velocity for 100 percent legibility varied from 10 degrees/sec for the 3 degree (2 inch) aperture to 16 degrees/sec for the 30 degree (20 inch) aperture (see Figure 84). The mean angular velocities for zero legibility were approximately three times as great as those required for 100 percent legibility.

A series of experiments by Lippert and Lee (1963) were designed to explore the limiting angular velocities of dynamic vision. A symbol density one-fifth that of the original study by Lippert (1962) was employed. Symbols were 39 minutes high and spaced 7.5 degrees apart. The basic apparatus was the same as that used by Lippert (1963); however, some significant improvements were made. A higher brightness of stimulus material, a larger white surround, and less change of brightness from the experimental viewing time of the subject to the resting state between trials were used.

The results showed that aperture conditions were significantly different. The larger the aperture, the higher was the angular velocity at which the subject could score 100 percent (see Figure 85). Lippert and Lee (1963) also demonstrated that television presentation required the velocity of the

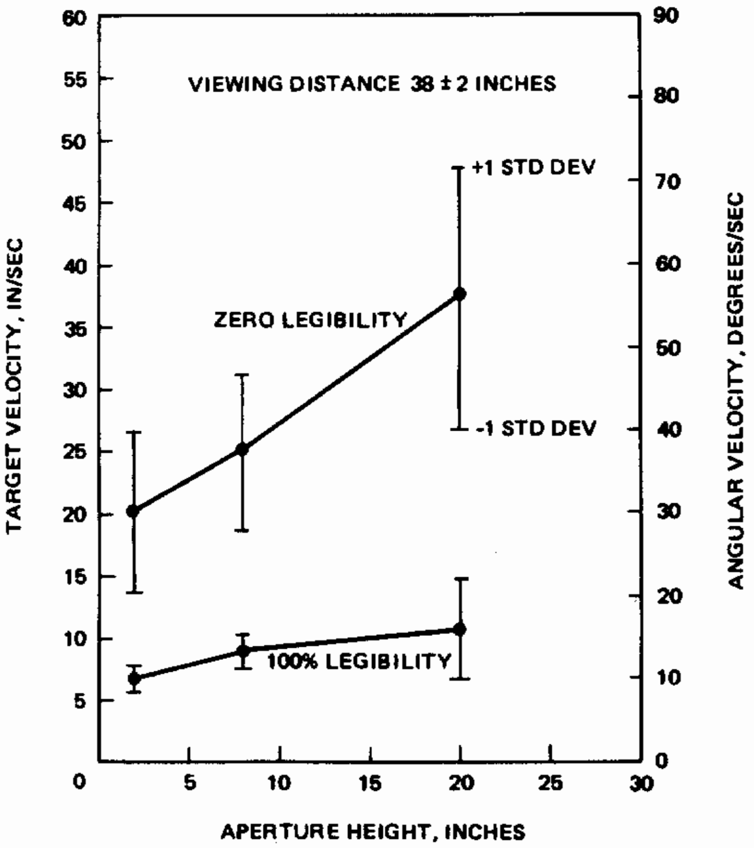


Figure 84. Effect of velocity and aperture size on symbol legibility (from Lippert, 1963)

belt to be decreased approximately 30 percent, on the average, from that of direct viewing to achieve 100 percent legibility.

In considering the effects of motion on matrix symbols, display update rate becomes important. As the symbol is translated in the vertical and horizontal axes, optimum legibility requires that data update rate should be sufficient to provide for as smooth a transition as possible. Inherent in many matrix displays is a "jumpiness" associated with symbol translation caused by the successive addressing of new elements in the direction of motion accompanied by the darkening of elements on the opposite side of the symbol. As information update rate is reduced, larger jumps will occur in symbol motion as several elements are skipped at the advancing edge of the symbol between one information update and the next.

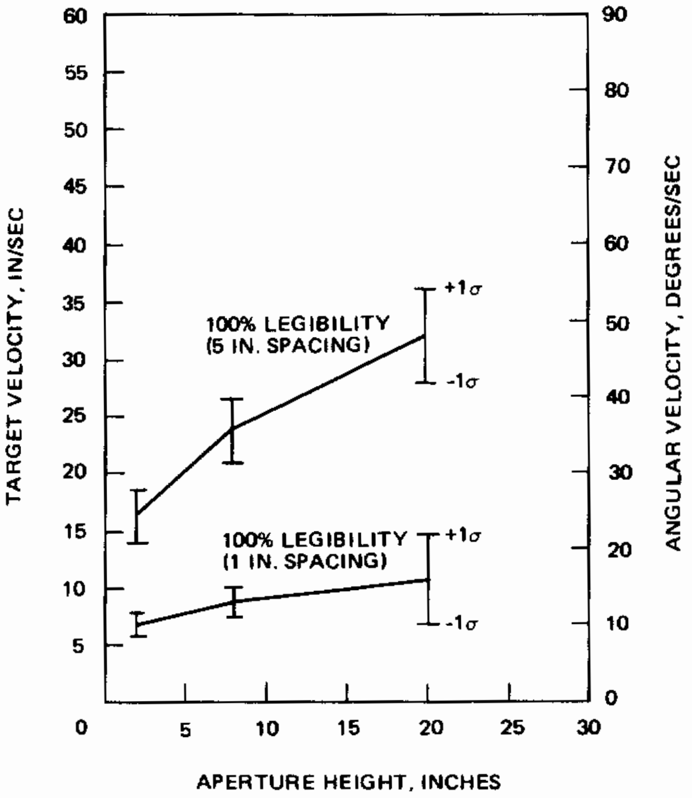


Figure 85. Comparison of 100 percent legibility curves for Lippert and Lee (1962) (symbols spaced 1 inch on center in vertical dimension) and Lippert and Lee (1973) (symbol density 1/5 - i.e., 5 inch spacing on center).

Matrix symbol rotation involves still another problem. As noted earlier, the physical placement of the matrix emitters affects symbol geometry, causing it to change with different symbol orientations. In addition to this phenomenon, symbol rotation is also influenced by update rate as mentioned above. Thus while the above reported data provide some information as to the effects on operator performance of continuous symbol motion, it is not known to what extent these data will be applicable to matrix displays in which symbol movement would occur in discrete steps. No data was found on the effects of symbol motion for dot-matrix displays. However, one might expect a greater decrement in the legibility of translated matrix symbols, compared to solid-stroke symbols, particularly in those cases where long update rates cause large "jumps" in matrix symbol motion.

## A. 10 VIBRATION

Vibration is characterized by the periodic displacement of a mass over time and is defined by the amplitude and the frequency of the displacement. Frequency is typically expressed in terms of number of cycles per second (Hertz). Amplitude (a measure of vibration intensity or magnitude) can be expressed in terms of displacement (i.e., inches or feet per second), or acceleration (expressed in terms of gravitational units "g"). Vibration can be sinusoidal, complex (consisting of two or more sine waves in combination), or random. Most of the research conducted has been with sinusoidal vibration.

Oscillation below 1 Hz is not usually characterized as vibration. At such frequencies, the amplitudes of motion are large with the result being that the whole body follows the motion and the primary sensory stimulation is to the vestibular system. At frequencies above 30 Hz, vibratory energy transmitted to the body is likely to be damped by body-support cushioning as well as by the buttocks, or feet and legs of the subject. Thus the majority of human vibration studies have been conducted at relatively low frequencies - 1 to 30 cycles per second. According to Hornick (1973) not only do major vehicular resonances generally occur in this range, but in addition man's performance capability has been shown to be affected by frequencies in this range.

Semple (1971) pointed out that much of the vibration research relating to visual perceptual tasks has been concerned with measures of visual acuity. After a review of the literature, Semple (1971) offered the following summary of study results: "The presence of vibration in a visual display situation adversely affects visual acuity. The extent of the visual degration is a function of: frequency of the vibration and amplitude of the vibration. With frequencies of vibration up to approximately 4 Hertz, slight visual degradation is observed. The first significant degradation occurs at 5 Hertz (from 10 percent to 20 percent degradation, depending upon amplitude). At frequencies between 8 and 10 Hertz, the result is 20 percent-plus loss of acuity. From 9 to 16 Hertz, approximately 50 percent-plus degradation and symbol blurring occurs. Vibration amplitudes of ±0.5g will increase visual degradation at all frequencies" (p. 516).

Semple also reported a study by Ketchel, Danaher, and Morrissey (1969) in which it was confirmed that adverse effects occur in visual performance when vibration falls within the frequency range of 10 to 30 Hertz. In addition it was reported that the degradation in performance was more pronounced when additional complexities, such as task difficulty, g-level, ambient lighting, insufficient contrast, and workload were added.

Wulfeck, Weisz, and Raben (1958) reported a study in which visual acuity was measured before, during, and after 2-hour exposures to various combinations of frequency and amplitude of vibration. Both subjects and test objects were vibrated. Effects of vibration on visual acuity were related to head vibration not platform vibration (since with subjects seated on a vibrating platform their body tissues absorbed much of the vibratory energy). Figure 86 depicts binocular visual acuity at various frequencies of head vibration for five subjects. Peaks can be seen at certain frequencies where acuity was most affected. The authors proposed that the first peak might be due to difficulty in fixating the vibrating test objects, while the remaining peaks might be due to the effects of complex sympathetic vibrations produced at resonance in the musculature of the eye, compounded with the fundamental vibration of the test object.

While the above reported studies dealt primarily with the influence of vibration on visual acuity, other studies have considered the effects of vibration on the legibility of alphanumerics. Hornick (1973) has provided a good summary of vibration study results, concerning the effects of sinusoidal vibration on the legibility of letters and numerals (see Table 76).

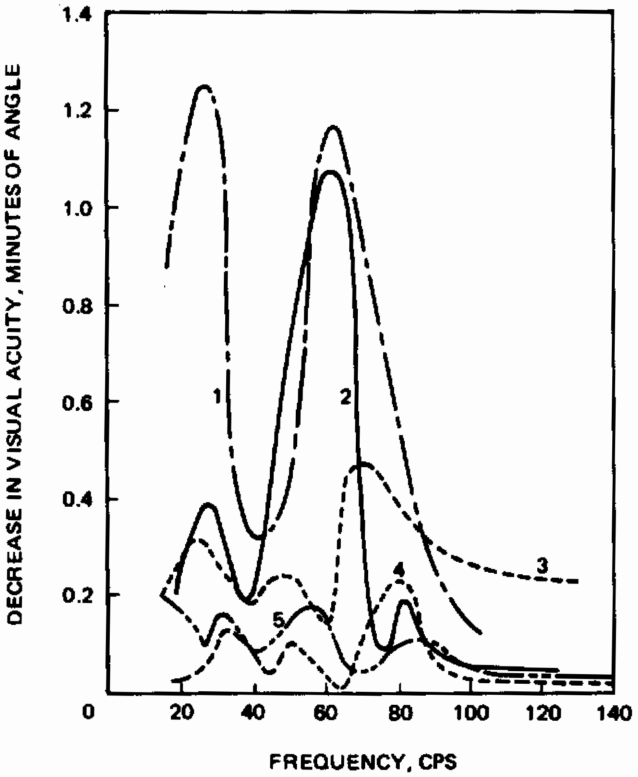


Figure 86. The influence of exposure to vibration on visual acuity. (The five curves are for different subjects).

Hornick (1973) summarized the effects of vibration on visual performance as follows:

> In general, the range of 10 to 25 Hz is most detrimental to visual performance, though occasionally frequencies above and below this band cause decrement. The relationship of subject and display is important in that lower frequencies (below 10 Hz) more readily cause visual decrement if the display alone or the display and man are vibrating. Above 10 Hz, vibration of the human more frequencly results in visual decrement, as compared to the motion of the display alone. Decrement increases as a function of amplitude or intensity level.
>
> Visual performance during vibration can be protected by proper design of displayed matter. Cluttered displays result in relatively greater decrement during vibration than do those which are easier to read. At relatively short distances, vibration can be expected to cause errors in viewed numerals or letters subtending about 9 minutes of arc or less (p. 312).

### TABLE 26. SUMMARY OF VIBRATION EFFECTS ON VISUAL PERFORMANCE

| Vibration Conditions | Visual Task | Effect | Source |
|---|---|---|---|
| Subject static; display vibrated at 5 Hz, 0.063 in. (Double amplitude). | Reading speed. | Speed reduced by about 5.3%. | Tinker, 1948 |
| 1-30 Hz in combinations of vertical, pitch, and roll motion. | Reading printed words, both static and moving display. | Visual acuity worst at 4-7 Hz; pitch motion caused greatest decrement; roll motion least decrement. | Pradko, 1964 |
| 8, 13, 11, 23 Hz at 0.05 and 0.1 in. (double amplitude) and 10, 20, 30, 40, 50 Hz at 0.05 in. | Read 3-digit numbers, 1/4 in. high | Beginning at 8 Hz, errors increase as a function of frequency; no function of amplitude; errors increase to 40 Hz. | Mozell and White, 1958 |
| 1-27 Hz; 4 subjective intensity levels. | Digit reading. | Greatest error in 12-23 Hz range; errors increase with intensity. | Snyder, 1962 |
| 1-27 Hz; 4 subjective intensity levels. | Digit reading; visual angle 6 to 24 min. of arc. | Greatest error in 12-23 Hz range; errors increase with intensity; errors only for 9 and 6 min. of arc digits. | Teare and Parks, 1963 |
| 5-37 Hz; ±0.44-0.51 g's in z axis and 0.83-1.02 g's in z axis; 6 Hz at ±0.13-0.36 $g's_z$; 19 Hz at ±0.16 $g's_z$. | Read printed numbers subtending 4.4 min. of arc; series of studies to compare subject and display motion influence. | Increase in error at 5, 14, and 27 Hz for lower intensity; below 10 Hz, influence of vibrating display greater than vibrating subject; above 10 Hz, the reverse. | Dennis, 1965 |

A study by Carel, McGrath, Hershberger, and Herman (1974) investigated the effects of vibration on the legibility of map alphanumerics. Both subjects and the display were subjected to the vibration spectrum characteristics of the UH-1N helicopter. Upper-case words and numerals were displayed at 2 and 8 line pairs per millimeter (lp/mm) display resolution against both high and low clutter backgrounds. Six combinations of contrast and luminance were tested.

Two performance measures were employed: size of the symbol when it was read or spelled with no subsequent errors, and its size when it was deemed comfortable. Results obtained under vibration conditions were compared with results obtained under similar conditions in a static environment. Figure 87 depicts the effect of vibration on alphanumeric size. As can be seen from Figure 87, visual angle increased from 10.36 arcminutes in a static environment to 14.70 arcminutes under vibration, a 41.89 percent increase in threshold legibility. Similarly, visual angle for comfort legibility increased from 12.59 arcminutes under static conditions to 16.53 arcminutes under vibration, a 31.29 percent increase.

A vibration by contrast/luminance interaction was significant for both threshold and comfort legibility. This interaction is pictured in Figure 88. As can be seen from the figure, vibration increased the visual angle required for threshold and comfort legibility at all six contrast/luminance conditions. However, the detrimental effect of vibration was more severe for some contrast/luminance conditions than others. Table 27 gives the percent increase in visual angle due to vibration for threshold and comfort legibility. The percent increase in visual angle due to vibration was pronounced for the 6.0/0.1 fL, and 0.1/10.0 fL contrast/luminance conditions. These contrast/luminance conditions also resulted in the poorest non-vibration legibility (largest visual angles) of the six contrast/luminance conditions tested. Thus, those contrast/luminance conditions which provided poorest static legibility were most affected by vibration. The authors concluded that the severity of reduced legibility due to vibration depended upon the basic legibility of the displayed map information.

From the above it appears that the detrimental effects of vibration may be minimized by the careful selection of symbol and display parameters.

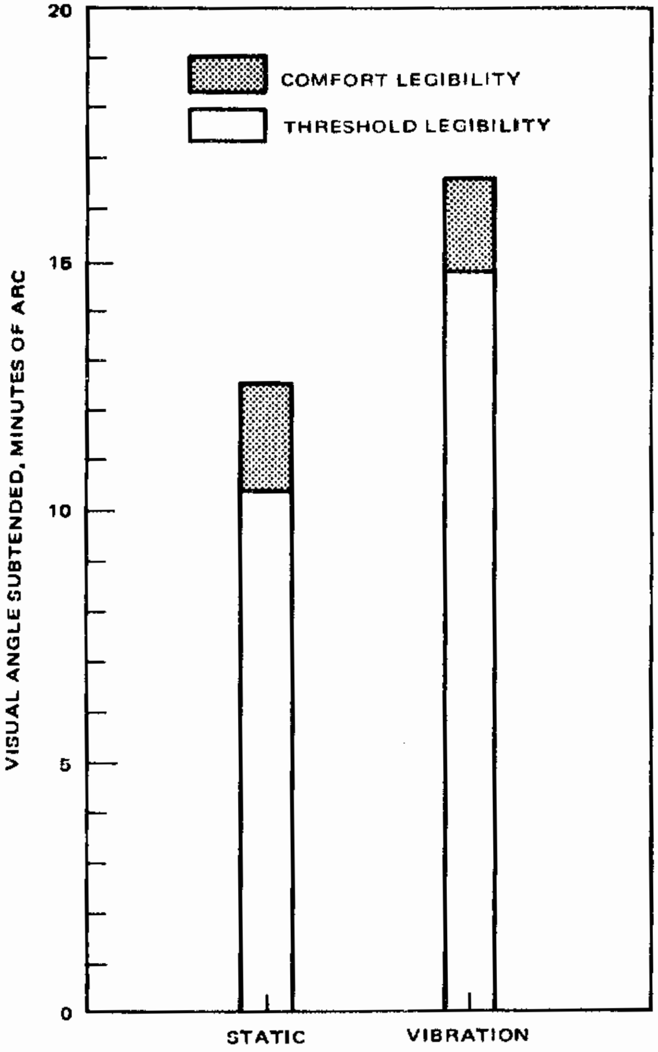


Figure 87. Effect of vibration on alphanumeric threshold and comfort legibility.

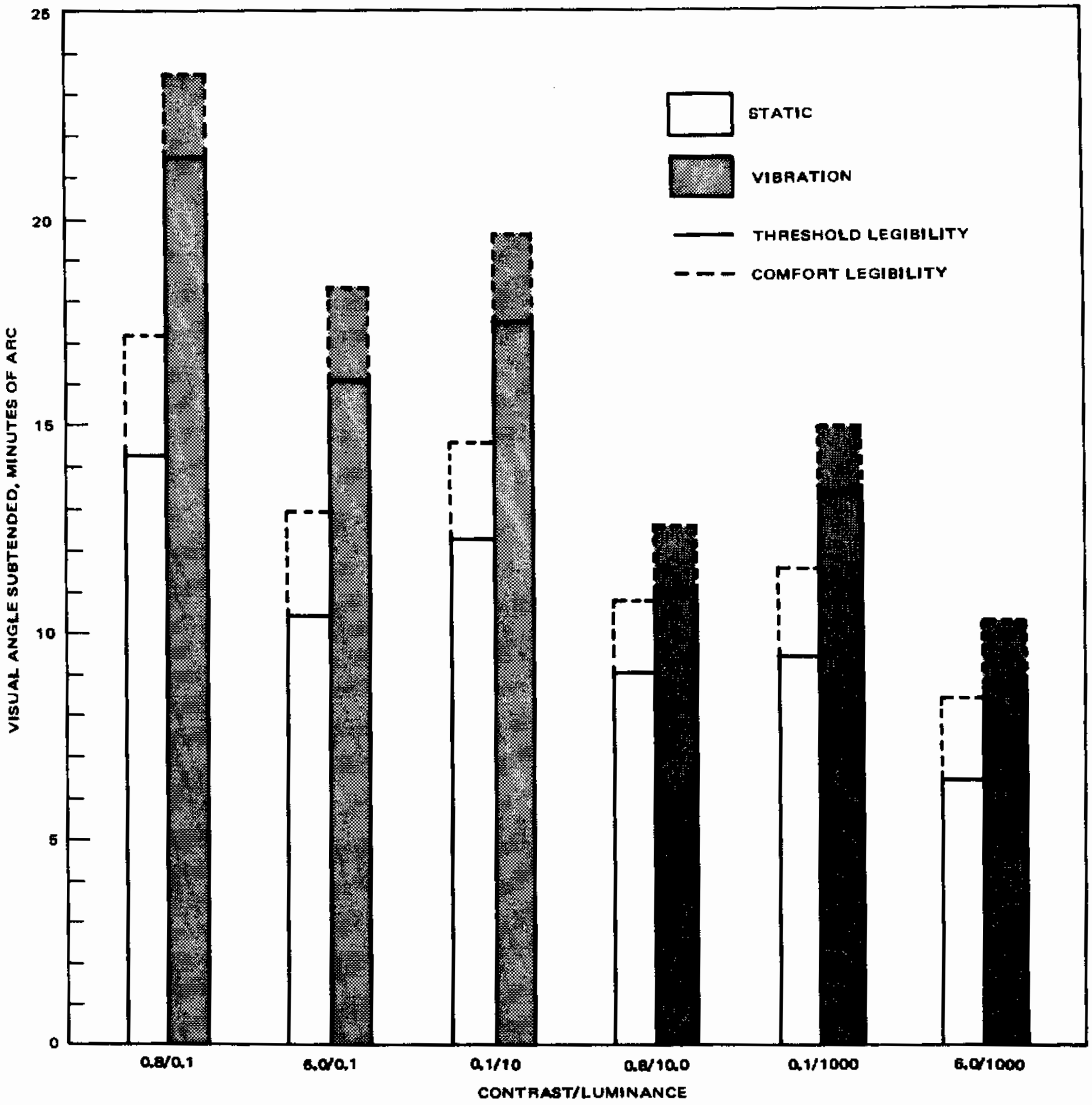


Figure 88. Effect of vibration and luminance contrast on alphanumeric threshold and comfort legibility.

TABLE 27. PERCENT INCREASE IN VISUAL ANGLE DUE TO VIBRATION

| | Percent Increase Visual Angle | |
|---|---|---|
| Contrast/Luminance | Threshold Legibility | Comfort Legibility |
| 0.1/10 | 43.4 | 34.2 |
| 0.1/1000 | 39.3 | 29.7 |
| 0.8/0.1 | 50.3 | 36.6 |
| 0.8/10 | 21.7 | 15.9 |
| 6.0/0.1 | 53.7 | 41.2 |
| 6.0/1000 | 32.3 | 22.0 |

Indeed, Wulfeck, Weisz, and Raben (1958) supported this position stating that "When vibration cannot be avoided, its effects upon visual performance may be reduced by proper design of the visual displays and printed materials which must be viewed" (p. 289). Similarly, Hornick (1973) stated "Visual performance during vibration can be protected by proper design of displayed matter" (p. 312). In addition, he commented that visual impairment is extremely sensitive to the specific vibration/task situation with such factors as illumination level, type of vibration, background clutter, symbol size, and type of visual task all proving to be important.

No data were found regarding the legibility of matrix displays under vibration. However, after a review of the literature, the following expectations appear reasonable. As was pointed out above, those conditions which degrade symbol legibility under static conditions will be most adversely affected by vibration. In reference to matrix displays, it appears that conditions in which symbol definition is low (small number of dots per symbol height) and/or where the symbol is rotated (producing a distorted image) vibration will be most detrimental. In addition, it seems reasonable to predict that the parameters shown to be of importance in determining symbol legibility under vibration in previous studies (i.e., symbol size, illumination level, etc.) will similarly influence matrix display legibility in a vibration environment.

## A. 11 SYMBOL PLACEMENT – THE ELEMENT OF SPATIAL UNCERTAINTY

Visual search is a term applied to the visual acquisition of objects in the field of view when their location is initially unknown. According to Taylor (1973) the important variables in the search process include "size and structure of the field, characteristics of the target object, including its size and complexity, luminance level, contrast, uniqueness, and so on" (p. 652). Thus visual search appears to be influenced by those parameters (i. e., symbol size, luminance, contrast, etc.) which have been shown to affect display symbol legibility. Visual search is also influenced by other factors having little to do with the nature of the symbology, being related instead to the magnitude of the uncertainty of physical target location. Thus, for example, as pointed out by Taylor, the size of the visual field has been shown to affect visual search. Indeed, Honigfeld (1964) commented "generally, detection time increases with the area that must be examined. The effectiveness of search can be increased by reducing spatial uncertainty" (p. 6).

While Honigfeld suggests that detection time typically increases with the amount of area to be searched, this does not imply the existence of a quantitative functional relationship. In other words, increasing search area by a certain percentage does not necessarily increase search time by a constant increment. Increases in detection time occasioned by spatial uncerainty vary greatly depending on individual observer differences (such as differences in search strategy).

Commenting upon search strategy, Ketchel and Jenney (1968) noted that a random spatial arrangement (high spatial uncertainty) makes it more difficult for an observer to keep track of the items which he has sampled and those he has not. Individual differences in this ability appear likely.

Self (see Beiberman, 1973) reported a number of observations relating to the effects of spatial uncertainty on search stragegy and search time:

1. When a target is not quickly found, searchers tend to 'oversearch' (repeatedly search) likely areas and completely avoid areas dismissed as either unsuitable or as suitable but not containing the target. Frequently, targets in contextually unlikely places are not found for minutes even though of adequate size, resolution, and contrast for quick recognition when examined.

2. Despite instructions and training, few observers systematically search a scene until after initial rapid scene-appropriate search fails to find a target. Clearly, search is neither purely systematic nor purely random.
3. Observers sometimes forget which areas have been searched and assume that they have searched an area when they have not. This leads to large time scores when the target is there.
4. Other things being equal, target objects closer to the center of the picture tend to be found quicker.
5. Numerous moving image studies show that subjects under high pressure do hurry to find targets much quicker than those under little or no pressure.
6. Some observers quickly find targets that others with equal training find only after extended search time or do not find at all. Chance factors, such as looking at the right place early in search, are clearly important. However, some subjects are consistently as much as two to three times faster than others over dozens of targets and scenes, and across studies, (p. 80-81).

From the above, it becomes obvious that many of the factors influencing search time under conditions of target spatial uncertainty defy precise experimental control: subject search strategy, subject memory (for which areas have been previously searched), subject motivation, and just plain chance factors (looking at the right place early in search). Thus adding spatial uncertainty as a parameter in the present research designed to assess symbol legibility would serve to increase the variability of experimental results. While an investigation of the effects of symbol legibility on spatial uncertainty may be of interest in itself, the adoption of a spatial uncertainty paradigm in the determination of symbol legibility requirements seemed unwise.

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## APPENDIX B

## INSTRUCTIONS TO SUBJECTS (SCREENING STUDY)

The Hughes Aircraft Company, Display Systems and Human Factors Department is conducting a research study to determine the legibility of dot-matrix symbology under several viewing conditions. You have been asked to serve as a test subject in this laboratory research.

You will be viewing 16 conditions in all, each condition being a particular combination of 10 variables being investigated. Under each viewing condition you will see 10 symbols, presented one at a time and in random order. The 10 symbols are: 1, 3, 8, I, N, Q, U, V, △, □. (As you can see, some of the symbols are easy to confuse). For each trial your task will be to identify the displayed symbol as quickly and as accurately as possible.

During experimental trials you will be seated in a chair facing a cathode ray tube display. Viewing distance will be established by the experimenter prior to each experimental condition. While you will not be required to place your head in a restraint, you are <u>NOT</u> to purposely move your head or body in an attempt to see the display better.

The procedure will be as follows: For each experimental condition the experimenter will set up the proper display conditions, adjust your viewing distance and the angle at which you view the display. After the proper conditions have been established, you will be given a push-button switch which serves to both "turn on" the display (causing a symbol to appear), and "turn off" the display (causing the symbol to disappear). The experimenter will say "READY" when all conditions are set for the start of a trial. When you are ready to begin, push the control button once, and a symbol will appear on the display screen. The symbol may be large or small, bright or dim, rotating or translating across the display. As soon as you are able to identify the displayed symbol, you are to push the control button again. This will remove the symbol from the screen, and your "time-to-recognition" will be recorded by a computer.

At the same time that you push the button (indicating your recognition of the symbol) you are to make a verbal report of the symbol identity to the experimenter who will record your response.

If you have still not recognized the symbol after 10 seconds, the symbol will automatically disappear and that trial will be over. While speed is important, it must be stressed that identification ACCURACY is of greater importance. You are NOT to guess the identity of any symbol. You must be reasonably sure you can identify the symbol before you press the button to extinguish the display. Further, do not anticipate your decision -- that is, do not count on the fact that you will be able to figure out what the symbol was after you turn off the display. You should be sure of the symbol identity BEFORE you extinguish the symbol.

Due to the mechanics of the push button switch, it is essential that after you depress the button, you let it up completely. Do not hold the button down or a symbol will not appear. If you press the button (incorrectly) and a symbol does not appear immediately, the computer teletype will begin to type. DO NOT PRESS THE BUTTON AGAIN to try and activate a symbol. Wait, and the experimenter will reset the symbol for you and then instruct you to continue.

At the end of 10 trials, the experimenter will change the viewing conditions, and another 10 symbols will be presented. For any given set of viewing conditions, the 10 symbols will always be the same ones listed above. Each symbol will be presented only once for a given viewing condition. Do not attempt to anticipate which symbols you will be viewing next.

During experimental trials you will be required to wear a black face mask and a black velvet smock to prevent the occurrence of a reflected image of yourself on the display screen.

The study variables that you will experience are as follows:

1. Static Symbol Orientation: Sometimes the symbol on the display will be presented upright, sometimes it will be rotated a few degrees clockwise. Due to the construction of the symbols by fixed position dots, symbol rotation can cause symbol distortion.

2. Symbol Translation: On some trials the symbol will translate across the display in the X and/or Y axes.
3. Symbol Rotation: Sometimes the symbol will rotate in a clockwise direction. Again due to the fact that symbols are constructed of fixed-position dots, rotation will cause the symbol to distort.
4. Dot Size and Dot Gap: Both the size of the dots used to construct the symbols and the gaps between these dots will be varied.
5. Symbol Definition: The number of dots used to make up the symbols will be varied. In some cases the symbols will be 7 dots high, in others 21 dots high.
6. Display Contrast: The brightness of the dots and ambient illumination will be controlled by the experimenter.
7. Viewing Distance: The experimenter will adjust your viewing distance for each condition to establish a symbol subtense of either 15 or 30 minutes of arc.
8. Viewing Angle: In some conditions the display will be rotated away from you so that you will be viewing it at a $45^{\circ}$ angle.

Prior to the start of the experimental trials, the experimenter will show you photographs of several of the experimental conditions so you will know what to expect. In addition you will be given several practice trials so you may become familiar with the experimental procedures. If you have any questions, please ask them now. You will not be informed of the correctness of your responses during the experimental trials.

# APPENDIX C

## INSTRUCTIONS TO SUBJECTS (ORIENTATION-DEFINITION-ROTATION STUDY)

The Hughes Aircraft Company, Display Systems and Human Factors Department is conducting a research study to determine the legibility of dot-matrix symbology under several viewing conditions. You have been asked to serve as a test subject in this laboratory research.

You will be viewing 32 conditions in all, each condition being a particular combination of the three variables being investigated. Under each experimental condition you will be viewing any one of 36 symbols, presented one at a time and in random order. Some of the symbols you may see more then once, others you may not see at all. For each trial your task will be to identify the displayed symbol as quickly and as accurately as possible.

During experimental trials, you will be seated in a chair facing a cathode ray tube display. Viewing distance will be established by the experimenter prior to each experimental condition. While you will not be required to place your head in a restraint, you are NOT to purposely move your head or body in an attempt to see the display better.

The procedure will be as follows: For each experimental condition the experimenter will set up the proper display conditions and adjust your viewing distance. After the proper conditions have been established, you will be given a push-button switch which serves to both "turn on" display (causing a symbol to appear), and "turn off" the display (causing the symbol to disappear). The experimenter will say "READY" when all conditions are set for the start of a trial. When you are ready to begin, push the control button once, and a symbol will appear on the display screen. The symbol may be stroke written or composed of dots, tilted to the right, or rotating.

As soon as you are able to identify the displayed symbol, you are to push the control button again. This will remove the symbol from the screen, and your "time-to-recognition" will be recorded by a computer. After you have pushed the button indicating your recognition of the symbol, you are to tell the experimenter the name of the symbol you saw.

If you have still not recognized the symbol after 10 seconds, the symbol will automatically disappear and that trial will be over. While speed is important, it must be stressed that identification ACCURACY is of greater importance. You are NOT to guess the identity of any symbol. You must be reasonably sure you can identify the symbol before you press the button to extinguish the display. Further, do not anticipate your decision--that is, do not count on the fact that you will be able to figure out what the symbol was after you turn off the display. You should be sure of the symbol identity BEFORE you extinguish the symbol.

Due to the mechanics of the push button switch, it is essential that after you depress the button, you let it up completely. Do not hold the button down or a symbol will not appear. If you press the button (incorrectly) and a symbol does not appear immediately, the computer teletype will begin to type. DO NOT PRESS THE BUTTON AGAIN to try and activate a symbol. Wait, and the experimenter will reset the symbol for you and then instruct you to continue.

The variables that will be manipulated during the experimental trials are as follows:

1. Static symbol Orientation: Sometimes the symbol on the display will be presented upright, sometimes it will be rotated a few degrees clockwise. Due to the construction of the symbols by fixed position dots, symbol rotation can cause symbol distortion.
2. Symbol Rotation: Sometimes the symbol will rotate in a clockwise direction. Again due to the fact that symbols are constructed of fixed-position dots, rotation will cause the symbol to distort.
3. Symbol Definition: The number of dots used to make up the symbols will be varied. In some cases the symbols will be 7 dots high, in others 11 or 21 dots high. In still other cases the symbols will be continuous (stroke-written).

Prior to the start of the experimental trials, the experimenter will show you pictures of several of the upright symbols so you may become familiar with them. In addition you will be given several practice trials so you may become familiar with the experimental procedures. If you have any questions, please ask them now. You will not be informed of the correctness of your responses during the experimental trials.

# APPENDIX D

## INSTRUCTIONS TO SUBJECTS
## (SUBTENSE STUDY)

The Hughes Aircraft Company, Display Systems and Human Factors Department in conducting a research study to determine the effects of symbol subtense on the modulation required for threshold symbol legibility. You have been asked to serve as a test subject in this research.

You will be viewing eight conditions in all, each condition being a particular combination of the three variables being investigated. These variables are symbol subtense (15 and 30 minutes of arc), symbol construction mode (stroke-written and 5 x 7 dot matrix), and ambient illumination (0.5 and 100 fL). Under each viewing condition you will see one symbol out of eight possible symbols. The eight symbols are: 1, 3, 8, I, Q, U, V, □ . (As you can see, some of the symbols are easy to confuse). For each trial your task will be to identify the displayed symbol. The symbols will be presented in random order and any given symbol may appear more than once.

During experimental trials you will be seated in a chair facing a cathode ray tube display. Viewing distance will be established by the experimenter prior to each experimental condition. While you will not be required to place your head in a restraint, you are <u>NOT</u> to purposely move your head or body in an attempt to see the display better.

The procedure will be as follows: For each experimental condition the experimenter will set up the proper display conditions and adjust the distance from which you view the display. After the proper conditions have been established, the experimenter will cause a symbol to appear on the display, at an initial brightness level so low that you will not be able to see the symbol. Nevertheless, he will ask you to guess the identity of the symbol. Then the experimenter will increase the brightness of the symbol slightly and again ask you to identify it. You are to keep identifying the symbol each time the experimenter instructs you to do so until you are told to stop. You should <u>guess</u> any time you are unsure of the symbol identity.

During experimental trials you will be required to wear a black face mask and a black velvet smock to prevent the occurrence of a reflected image of yourself on the display screen.

Prior to the start of the experimental trials, the experimenter will show you photographs of several of the experimental symbols so you will know what to expect. In addition you will be given several practice trials so you may become familiar with the experimental procedures. If you have any questions, please ask them now. You will not be informed of the correctness of your responses during the experimental trials.

## APPENDIX E

## INSTRUCTIONS TO SUBJECTS (ACTIVE AREA-SURROUND LUMINANCE STUDY)

The Hughes Aircraft Company, Display Systems and Human Factors Department is conducting a research study to determine the effects of percent active area and ambient illumination on the modulation required for threshold symbol legibility. You have been asked to serve as a test subject in this research.

You will be viewing 35 conditions in all, each condition being a particular combination of the levels of the two variables being investigated. Under each viewing condition you will see one of 10 possible symbols. The 10 symbols are: 1, 3, 8, I, N, Q, U, V, Δ, □. (As you can see, some of the symbols are easy to confuse). For each trial your task will be to identify the displayed symbol. Symbols will be displayed in a random order, and each symbol may appear more than once.

During experimental trials you will be seated in a chair facing a cathode ray tube display. Viewing distance will be established by the experimenter prior to each experimental condition. While you will not be required to place your head in a restraint, you are NOT to purposely move your head or body in an attempt to see the display better.

The procedure will be as follows: For each experimental condition the experimenter will set up the proper display conditions and adjust the distance from which you view the display. After the proper conditions have been established, the experimenter will cause a symbol to appear on the display at an initial brightness level so low that you will not be able to see the symbol. The experimenter will increase the brightness of the symbol slightly and ask if you can identify it. As soon as you see anything on the display (other than a flat field) you are to GUESS the identity of the symbol. The experimenter will continue to increment the symbol luminance by small steps, pausing after each increment to ask you to identify the symbol. After your first response you should continue to respond at each subsequent step. You should guess any time you are unsure of the symbol identity.

Prior to the start of the experimental trials, the experimenter will show you several of the target symbols on the display so that you may become familiar with them. In addition you will be given several practice trials so you may become familiar with the experimental procedures. If you have any question, please ask them now. You will not be informed of the correctness of your responses during the experimental trials.

# APPENDIX F

## INSTRUCTIONS TO SUBJECTS (MODULATION SENSITIVITY STUDY)

This is an experiment to find out how our ability to see patterns depends upon various viewing conditions. The specific pattern that will be employed in the study is one consisting of both horizontal and vertical rows of dots forming a pattern of squares or "patches." The size of the pattern you are viewing will be changed during the experiment. The spatial frequency, or number of dots making up the pattern will also be varied.

At the beginning of each trial, there will be enough contrast on the display for you to see the pattern. You will be given a knob by which you can both increase and decrease contrast. Clockwise increases contrast; counterclockwise decreases contrast. Your task will be to adjust the contrast on the display in order to determine what we will term your "minimum detectable" threshold.

When asked to set your minimum detectable threshold for a given condition you are to adjust the contrast on the display until you can just see that there is a pattern on the screen. In other words you should be able to see that the screen is other than a flat field. However, when setting minimum detectable thresholds, it is all right if the pattern appears to fade in and out of view. We are looking for the lowest modulation setting for a given condition where you can see that there is a pattern on the display and can identify the pattern, but the pattern need not remain visually stable as you view it. You will be asked to set two minimum detectable thresholds in succession for any given condition.

In setting your minimum detectable threshold you may overshoot and use the control to bracket the threshold region until you are certain of your setting.

After each setting you are to hand the contrast control knob to the experimenter who will record the setting, change the knob, and then hand it back to you for your next threshold setting.

Finally, while finding your thresholds, it is necessary that you do not move your head laterally from side to side as much motion makes the pattern perception easier.

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