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THE EFFECTS OF DISPLAY FAILURES AND SYMBOL ROTATION ON VISUAL SEARCH AND RECOGNITION PERFORMANCE

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U.S. ARMY HUMAN ENGINEERING LABORATORY

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This study was conducted to investigate the effects of display failures and rotation of dot-matrix symbols on visual search and recognition performance. The type of display failure (cell, horizontal line, vertical line), failure mode (ON, failures matched the symbols; OFF, failures matched the background), percentage of cells failed (0, 1, 2, 3, 4%), and rotation angle (0°, 70°, 105°) were the variables examined. Results showed that displays that exhibit ON cell failures greater than 1% significantly affect search time performance. Cell failures degrade performance more than line failures. Search time and accuracy are best when symbols are oriented upright. The effects of display failures and rotation angle on search time were found to be independent. Implications for display design and suggestions for quantifying the distortion caused by rotation are discussed.

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THE EFFECTS OF DISPLAY FAILURES AND SYMBOL ROTATION ON VISUAL SEARCH AND RECOGNITION PERFORMANCE

INTRODUCTION

This research is part of a series of experiments investigating the presentation of information on matrix-addressed displays. As outlined by Decker, Pigion, and Snyder (1987), the research focuses on alphanumeric and cartographic-symbolic information-presentation tasks and includes the effects of display failures on user visual task performance. Prior research in this series has been conducted to examine the variables of font, character and matrix size, modulation, negative and positive contrast (Decker, Kelly, Kurokawa, & Snyder, 1991), symbol rotation (Decker, Lloyd, Kurokawa, & Snyder, 1991; Kurokawa, Decker, & Snyder, 1991), as well as display failures often found in matrix-addressed technologies, including line and cell failures (Dye & Snyder, 1991; Lloyd, Decker, & Snyder, 1991). As a logical extension of the previous research, this study was designed to determine the combined effects of symbol rotation and display failures on visual search and symbol recognition performance.

Symbol Rotation

A current application of visual displays is the presentation of cartographic and symbolic information, for example, moving map displays for both commercial and military usage. With these applications, the displayed symbolic information may require rotation as the operator changes direction, tracks targets, or perhaps changes viewpoints. When symbols and alphanumerics are created within a dot-matrix format (typical of matrix-addressed displays), rotating the matrix pattern causes distortion of the symbols because the relative positions of the dots are changed. While it is possible to enhance rotated patterns through the use of gray scale (Crow, 1978) or dithering, these techniques are often complicated and expensive to implement. Furthermore, limited research has been conducted to determine the extent to which operator performance is actually affected by the distortion caused by rotation and the extent to which enhancement would improve performance beyond non-enhanced patterns.

Vanderkolk (1976) investigated symbol orientation (0° and 15°) as one of many variables in a fractional factorial design. Two levels of character definition were used: 7 or 21 dots per character height. An interaction between character definition and orientation was found. Reaction time for identifying characters was significantly slower for the seven dots per character height condition when rotated 15° off the upright orientation. Conclusions regarding rotation are difficult to make from this study since only two levels of orientation were investigated, and analysis of higher order interactions was not possible.

Kurokawa, Decker, and Snyder (1991) investigated the effects of screen rotation, direction of rotation (clockwise and counterclockwise), and target distance from the center of screen rotation on the identification of dot-matrix alphanumerics in a search task. In this study, a random pattern of letters and numerals was created on a 1024- by 1024-pixel cathode-ray tube (CRT) display. After the pattern was created in the upright orientation (0°), the entire pattern was rotated about the center of the display screen. The screen pattern was rotated at 5° intervals between 0° and 180°. With the inclusion of the clockwise and counterclockwise direction variable, rotation angles around a full 360° were included. Rotating the screen pattern necessarily resulted in a distortion of the dot-matrix characters. When the matrix was rotated, a dot could fall between two dots (or pixels) on the display, and an approximation to the closest pixel was required. Figure 1 illustrates the distortion of the character B with changes in rotation angle.

In addition to the distortion caused by rotation angle, distortion is also a function of the distance from the rotation center, based on the rotation strategy. A new *x,y* position is determined as follows:

$$X_{rotated} = \text{round}(X_{original} \cos \Theta - Y_{original} \sin \Theta), \text{ and}$$
$$Y_{rotated} = \text{round}(X_{original} \sin \Theta + Y_{original} \cos \Theta),$$

in which $X_{original}$ and $Y_{original}$ are the original *x,y* coordinates of a point, and $X_{rotated}$ and $Y_{rotated}$ are the *x,y* coordinates of a new, transformed position, while round is defined as a function to round the real number value inside the parentheses to the nearest integer.

As can be seen in these equations, the new *x,y* coordinates are determined by the original *x,y* coordinates and the angle of rotation. To determine a new *x* coordinate, the difference between the product of the original *x* coordinate and the cosine of the angle to be rotated, Θ, and the product of the original *y* coordinate and the sine of the angle is calculated and rounded to the nearest integer. Similarly, a new *y* coordinate is determined by combining the original *x,y* coordinate components weighted by the sine and cosine functions. The weights vary from -1 to 1 and act to "pull" the dot position differentially to a new rotated position. When rounding the product of the weight and the coordinate component and keeping the weight constant, the larger number the coordinate component is, the closer the rounded value of the product will be to the actual product. In other words, the larger value of a coordinate component provides better "resolution." The greater distance from the center of rotation, that is, the larger valued *x* and/or *y* coordinates, the closer the dot position would be to the ideal position and the less the distortion of a dot-matrix pattern.

Therefore, *x,y* coordinates farther from the center result in new dot positions similar to the original position, and in less distortion (Kurokawa et al., 1991). Figure 2 is an example of the distortion resulting from a distance change in the *x* coordinate (keeping the *y* coordinate constant) for a 45° angle of rotation. Four distance zones were determined relative to the center of the screen (0,0). These zones were incremented by 100 dots along the radii of four concentric circles.

Kurokawa et al. (1991) used upper case 7 x 9 dot-matrix alphanumerics created in the Lincoln/MITRE font. The target set consisted of B, C, I, K, V, 0, 2, and 7. The dependent variable was the response time required to locate the target. Results indicated significant effects of angle of rotation and distance. Figure 3 illustrates the effect of angle. The results appear to be nonsystematic. A best fitting line indicated a quadratic fit, and post hoc test results indicated no apparent pattern or grouping of angles. The response time was shortest at 0° and 25° and longest at 115° and 105°.

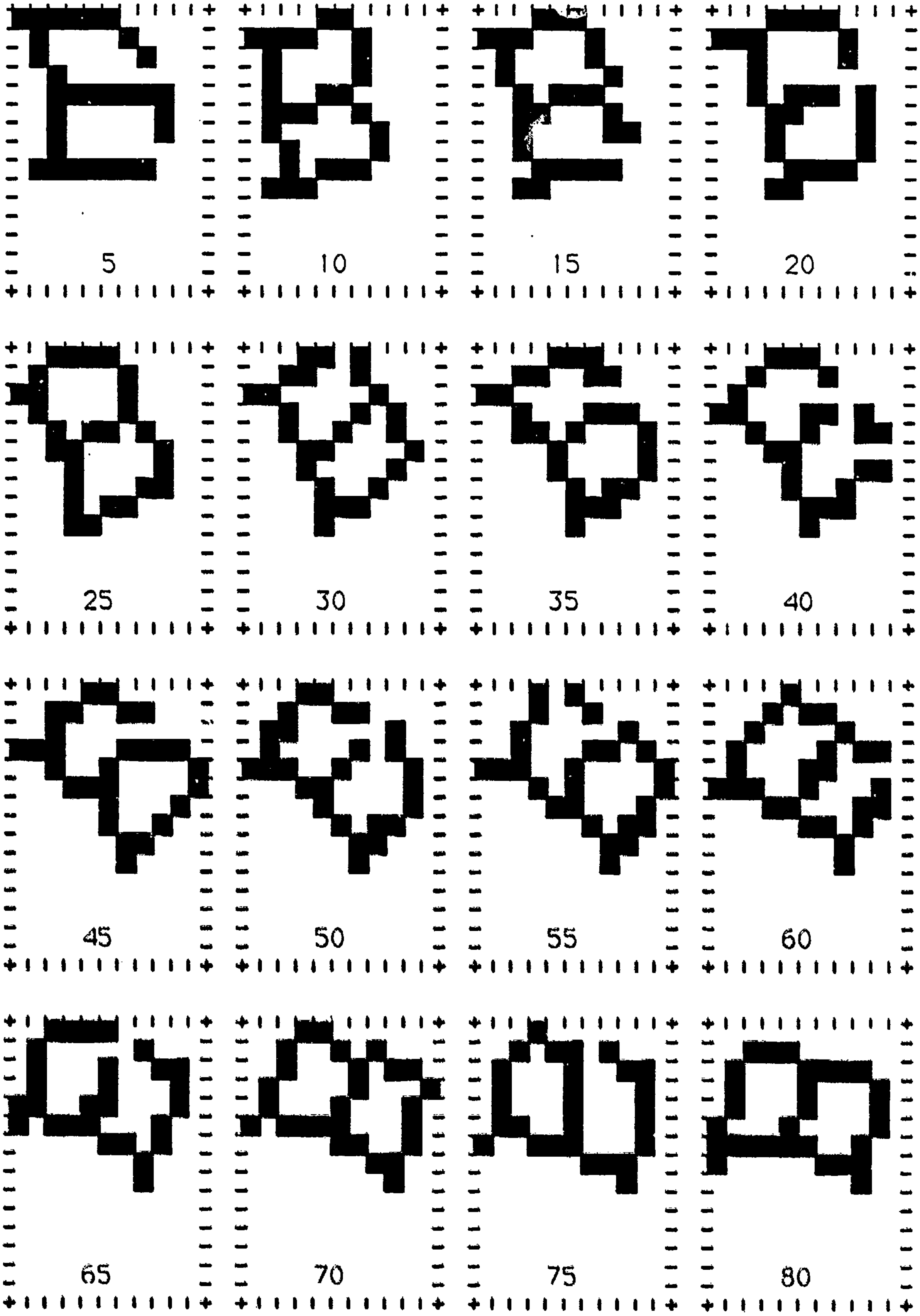

Figure 1. Distortion of upper case B with changes in rotation angle.

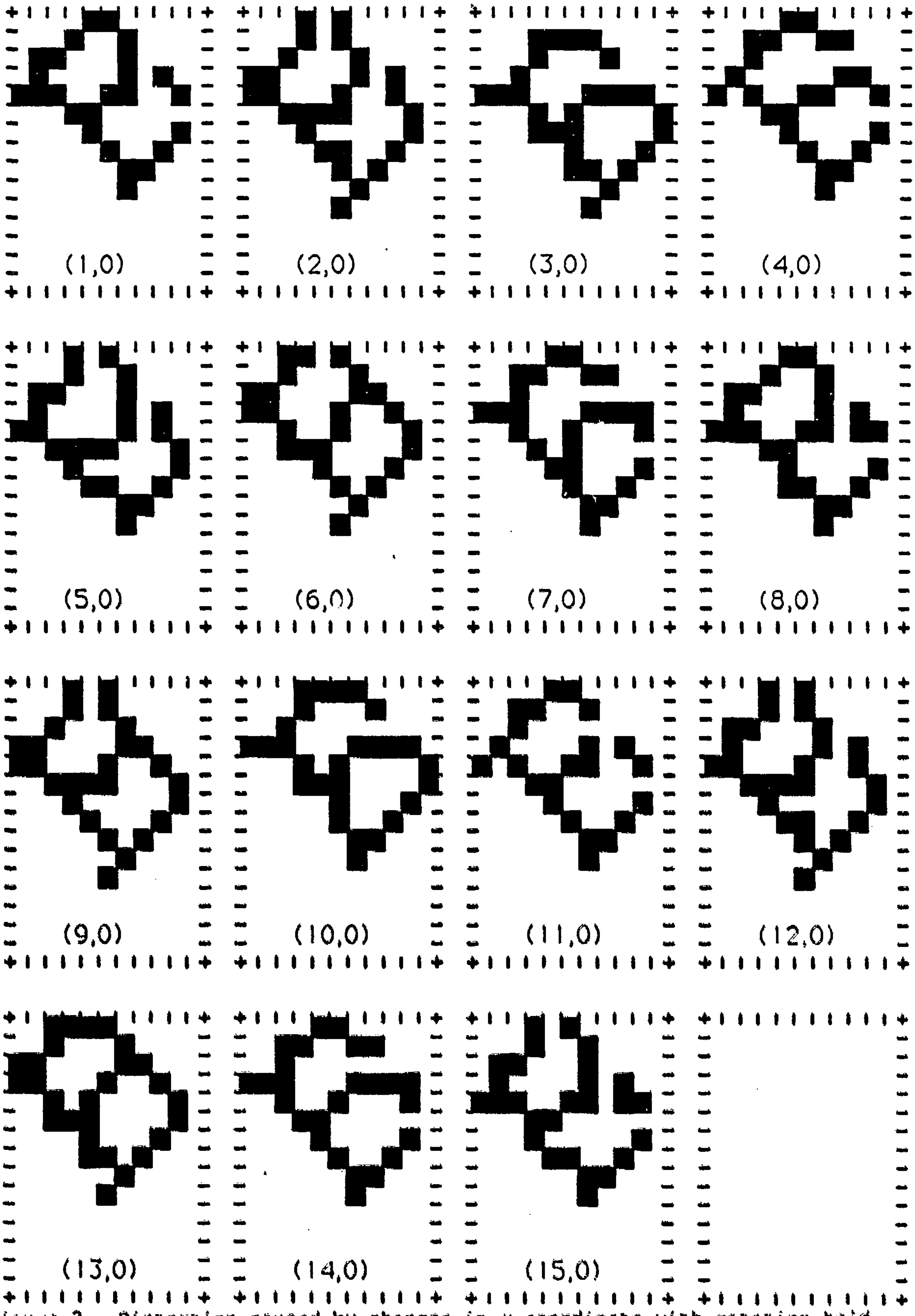

Figure 2. Distortion caused by changes in x coordinate with rotation held constant at 45°.

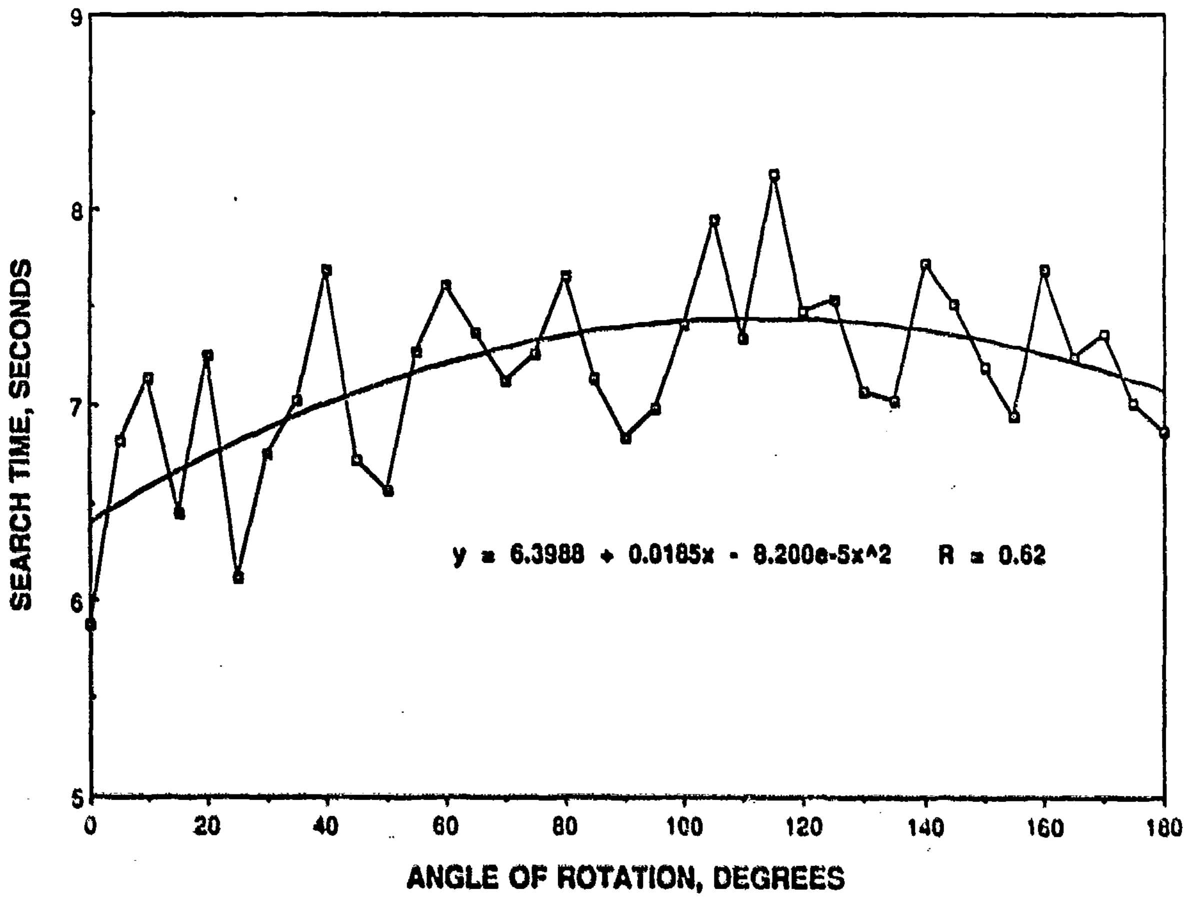

Figure 3. Mean response time as a function of angle of rotation (from Kurokawa et al., 1991).

Kurokawa et al. (1991) also found a significant effect of distance that indicated that when targets were within Zone 1, response time was fastest, with increases in response time as the target moved outward toward Zone 4. However, it was hypothesized that response speed would be faster for zones farther from the center because of less distortion. The results are best explained by considering the subject's search strategies. The subject's eyes fixated on the center of the screen at the beginning of each trial. If the target was within Zone 1, it was identified very rapidly. When subjects did not find the target within the center, they began looking outward, probably in a circular fashion. This strategy was mentioned by many subjects during the course of the experiment.

Further analysis was conducted to determine the effects of each character. The numeral 2 resulted in significantly faster search times than did any other target. These results are possibly caused by the unusual shape of this character in the Lincoln/MITRE font.

An effort was made by Kurokawa et al. (1991) to quantify the distortion. For each angle, the distance between the dot position after rotation and the ideal dot placement position (if it were unconstrained) was determined and summed across all dots composing the character B. This measure was termed "pixel deviation by angle." An additional measure, pixel deviation by distance, was also calculated. For this latter measure, the x coordinate was varied from 0 to 16 pixels while keeping the y coordinate constant at 0, and the pattern was rotated 45°. The sum of the dot deviations was again calculated as previously described. These quantitative measures as well as other descriptors were entered into a regression analysis to predict search speed (the reciprocal of response time). Results indicated that these descriptors do not adequately describe performance ($R^2 = 0.2184$).

An alternate form of analysis, which has been used to characterize symbols on flat panel dot-matrix displays, is the use of two-dimensional fourier analysis. With this technique, the spatial frequency components of each character at various rotations can be determined, may provide a better description of the characters, and may be more useful for predicting performance. Unfortunately, this technique is very time-consuming and requires extensive analysis because each character at each angle has to be analyzed separately. Maddox (1979) used this technique to characterize three different dot-matrix fonts and correlated the results with user performance data. For the Maddox study, results of the two-dimensional fourier analysis did not correlate well with human performance. Maddox concluded that the benefits did not justify the intensive analysis this technique requires. Maddox also used a nonparametric phi (ϕ) coefficient to analyze the similarity between characters and found moderate correlations with performance. Perhaps this latter technique should be attempted for characterizing the difference between upright and rotated symbols.

It is difficult to draw conclusions regarding distortion and performance from the Kurokawa et al. study, although the attempt was very beneficial. The authors concluded that the lack of orthogonality between the distortion caused by rotation angle and the distortion caused by distance is perhaps the best explanation for the nonsystematic results.

Mental Rotation

Distortion effects may be confounded with the possibility that subjects mentally rotated the symbol before identification could be made. However, this explanation is unlikely. Support for theories of mental rotation are found throughout the literature when subjects are required to determine whether stimuli are presented in a "normal" version or as "mirror images" (Cooper & Shepard, 1973; Corballis & Nagournay, 1978; Corballis, Zbrodoff, Shetzer, & Butler, 1978; Eley, 1982; Koriat & Norman, 1985; White, 1980). Research also indicates that mental rotation is not required to identify or classify a shape or alphanumeric (Corballis & Nagournay, 1978; Corballis et al., 1978; Eley, 1982; Koriat & Norman, 1985; White, 1980). One theory for this latter finding is that familiar stimuli such as alphanumerics can be identified through extraction of feature information, such as the curve in the letter R, regardless of orientation. One might argue that when a character was rotated and therefore distorted, the character is no longer highly familiar to the subject.

Eley (1982) evaluated the feature extraction theory against mental rotation for identifying novel symbols rather than overlearned alphanumerics. Subjects were trained to high and low familiarity criteria (minimal versus extensive familiarity with the symbol set). The number of symbols in a set was also varied. No effect of orientation on reaction time was found regardless of familiarity or symbol set size. Using the same symbol sets, the experiment was repeated requiring subjects to determine "normal" or "mirror image," and orientation effects were found. Mental rotation does not appear to be performed during identification type tasks.

Research also indicates that it is possible to eliminate the effects of mental rotation on performance. Cooper and Shepard (1973) examined the effects of advance information on reaction time to determine whether an alphanumeric character was "normal" or "mirror image." Subjects either received (a) no prior information, (b) knowledge of the character's identity, (c) knowledge of the orientation, (d) knowledge of identity and orientation in sequence, or (e) knowledge of identity and orientation simultaneously. With no advance information, response time increased in a concave function from 0° to 180° and is symmetrical about 180° and 360° (when reaction times for both normal and mirror-image responses are pooled). When previous information about the character's identity or the character's orientation was given, reaction time decreased; however, the shape of the function was similar to that with no information. When both orientation and identity were known in advance (either as sequential information or simultaneously), there was no effect of orientation. The advance information of identity and orientation appears to allow the subject to prepare for the stimuli by creating a mental image in memory and then comparing the image to the stimulus to determine if the image is a match or a mismatch. Similar results were found by Cooper (1975) and cited by Cooper and Shepard, (1973).

Decker et al. (1991) conducted a study similar to the one conducted by Kurokawa et al. (1991). The variables investigated were rotation angle (0°, 15°, 45°, 70°, 95°, 105°, 140°, and 170°), matrix size (7 x 9, 9 x 11, and 11 x 15), direction of rotation, and distance from rotation center. Two distance zones were specified, 0 to 200 pixels and 250 to 350 pixels from the screen center. Stimuli consisted of 26 upper case letters of the alphabet, the numerals 0 through 9 created in the Lincoln/MITRE font, and 26 Army symbols redrawn as dot-matrix symbols. Targets included 26 Army symbols and the alphanumerics A, B, C, F, J, L, P, 1, 5, and 8. The search pattern was created in upright orientation (0°) and then rotated around the center of the screen. To eliminate the need for subjects to perform mental rotation, the target symbol and an arrow that indicated the orientation in which the symbols would appear were presented to the subject in advance. The subjects were allowed to view the target symbol and orientation prompt as long as they wanted before initiating a search trial. It was assumed that with this prior information, as well as the fact that an identification task was being used, subjects would not be required to mentally rotate during search.

The results of this experiment indicated significant main effects of character and matrix size and rotation angle, as well as an interaction between these variables. Performance was slowest for the 7 x 9 matrix size, followed by the 9 x 11 and 11 x 15 matrix sizes, respectively. There were significant differences among angles for the 7 x 9 and 9 x 11 matrix sizes, although results were inconsistent in terms of order among angles. For the 11 x 15 matrix size, there were no significant differences among angles. These results are perhaps explained by the differences in the number of dots in each matrix. With more dots to define a symbol, less distortion would be expected. This logic is supported by the fact that there are no differences in performance among the 7 x 9, 9 x 11, and 11 x 15 matrices at the 0° condition, and greater differences among angles for the 7 x 9 size than for the 9 x 11 size. As previously noted and consistent with these results, Vanderkolk (1976) found an interaction between matrix size and angle, with degraded performance with the smaller character size at 15° rotation.

Search performance was found to be significantly faster when symbols were not rotated. There were no significant differences among any other angles. There was a noticeable (although nonsignificant) drop in response time at 95°. This result may possibly be attributed to the fact that at 90°, there is no symbol distortion, and perhaps at 95°, there is little distortion. This result was supported by an increase in accuracy at 95° beyond that found for several other rotations.

Display Failures

With matrix-addressed display technologies, there is the possibility of both line and cell failures, in which a pixel or line may remain on or off, regardless of the intended state. These failures have been found to have an impact on legibility and readability (Decker et al., 1987). Riley and Barbato (1978) systematically added or removed dot elements from 5 x 7 alphanumeric characters and found that the removal, addition, or simultaneous addition and removal of dots did not differentially affect character identification. However, identification was significantly faster when characters were not degraded. Pastor and Uphaus (1982) found a linear relationship between dot loss and identification accuracy for losses as great as 2%. Laycock (1985) systematically added failures to text and subjectively concluded that cells that failed ON were more degrading than those that failed OFF. Laycock concluded that less than 0.01% of ON cell failures was tolerable, while 1.0% of OFF cell failures was tolerable. Results are Laycock's opinion, and it was noted that performance data should be collected.

Abramson, Mason, and Snyder (1983) investigated the effects of line and cell failures on reading speed using a plasma display. The variables studied were font, case, failure mode (failed ON or OFF), failure type (cell, vertical, or horizontal line failures), and percent failures (0, 4, 8, 12, 16, and 20%). Failures were randomly placed on the screen. In general, their results indicated that cell failures degraded reading performance more than line failures; ON failures were more degrading than OFF failures; and as the percentage of failures increased above 2%, reading speed decreased. There were many interactions, and readers are referred to Abramson et al. (1983) for detailed information.

Lloyd et al. (1991) conducted a similar study in which they investigated both reading speed and visual search performance. In addition to the variables of failure type, failure mode, and percent failure (0, 4, 8, and 12%), polarity (dark symbols on a light background or light symbols on a dark background), and matrix size (7 x 9, 9 x 11, or 11 x 15) were also included. Stimuli consisted of the 26 upper case letters of the alphabet, the numerals 0 through 9, and 26 Army symbols. Subjects participated in two tasks, a speed of reading task and a random search task.

The results were similar for both tasks and verified the findings of Abramson et al. (1983). Cell failures impacted performance more than line failures did, and ON failures (those that match the luminance of the symbols) were more degrading than OFF failures were. The random search task was more sensitive to failures than the reading task was. At 4% failures, search time is increased by 27% and errors by 34%, while reading time is increased by only 4% from the no-failure (0%) condition.

Objectives of the Present Study

Display failures and the distortion caused by symbol rotation affect task performance. Because it is possible that both rotation and failures will occur on a display, it is of interest to determine the subsequential combined effects on performance. It was hypothesized that the combination of the two would be compounded in some way. This experiment assesses these combined effects in a visual search and recognition task that is similar to those tasks used in previous studies, thereby permitting comparison of results.

METHOD

Experimental Design

The variables investigated were angle of rotation (0°, 70°, and 105°), failure type (cell, vertical line, and horizontal line), failure mode (ON, failure luminance matched the symbol luminance; OFF, failure luminance matched the background luminance), and percent failure (0, 1, 2, 3, 4%). Previous research simulated higher percentages of failures. In this study, lower levels were investigated to determine minimum cutoff levels for quality assurance. A 3 x 3 x 2 x 5 within-subjects factorial design was used.

Subjects

Twelve students (eight males, four females) from Virginia Polytechnic Institute and State University were paid $5.00 per hour to participate. Subjects were tested for normal or corrected 20/22 near and far point visual acuity, lateral phoria, and vertical phoria using a Bausch and Lomb Orthorater. Subjects were also tested for normal near and far contrast sensitivity using a Vistech system.

Apparatus

Stimuli were presented on a Tektronix Model GMA201 high resolution achromatic CRT with a 48-centimeter (cm) diagonal screen. Although the CRT had the capability of displaying 2048 x 2048 pixels, the active area was constrained to 1024 x 1024 pixels within an area of 27.9 cm^2 because of bandwidth limitations of the graphics controller. The GMA201 has a 0.19-millimeter (mm) spot size, which is sufficiently small to simulate a high resolution flat panel display device.

An eight-bit plane PEPE graphics controller by Vectrix Corporation was installed on an IBM personal computer (PC-AT). The PC controlled stimulus generation, presentation, and data collection. A mouse input device (Mouse Systems) was used for subjects' responses. Responses were timed using the time-of-day clock, which had a resolution of ±55 milliseconds (ms), built into the PC.

Subjects were seated in an hydraulic dentist's chair adjustable in height and distance from the CRT. Subjects were positioned 50.8 cm from the CRT, and the angle of their gaze below horizontal was 15°. The display was tilted upward 15° so that viewing was normal to the display surface.

Stimuli

Stimuli consisted of the 26 upper case letters of the alphabet, the numerals 0 through 9, and 26 Army symbols. For each stimulus presentation, all 62 symbols were presented on the screen; however, only 36 symbols were used as targets. Targets included the 26 Army symbols and 10 of the alphanumerics (A, B, C, F, J, L, P, 1, 5, and 8). Stimuli were drawn in 11 x 15 dot matrices subtending 18 x 25 arcminutes of visual angle. The alphanumerics were drawn in the Lincoln/MITRE font. The Army symbols were standard Army symbols redrawn as dot-matrix symbols. Figures 4 through 6 illustrate the alphanumerics and symbols. Stimuli were presented in three orientations: 0° (vertical), 70°, and 105°. For each trial, all stimuli were rotated the same amount.

A search pattern was created by randomly selecting *x,y* screen coordinates for each of the 62 symbols, characters, and numerals including the target, so that no symbols would overlap. The entire random pattern was rotated around the center of the pattern. A new random pattern was created for each trial.

Failures were simulated by turning individual pixels or lines on or off. Failures that matched the symbol luminance are termed ON failures, and those matching the background luminance are termed OFF failures. The locations of the cell and line failures were randomly selected for each trial.

The stimuli were presented on the CRT in negative contrast (dark symbols on a light background) at a luminance modulation of 0.83. Negative contrast was chosen based on previous research that concluded that performance was better with negative contrast displays (Decker et al., 1991; Lloyd et al., 1991). The background luminance was approximately 35 candelas per square meter (cd/m^2).

Photometric Measurements

Luminance and modulation levels were set using a photometric system that consisted of a Gamma Scientific GS-2110 scanning telemicroscope, with a 10- by 3000-micron slit aperture and a 1X power objective lens, a photomultiplier tube (Gamma Scientific, Model D-46), and an intelligent radiometer (Gamma Scientific, Model GS-4100). The photometric system was controlled by an IBM PC-XT computer.

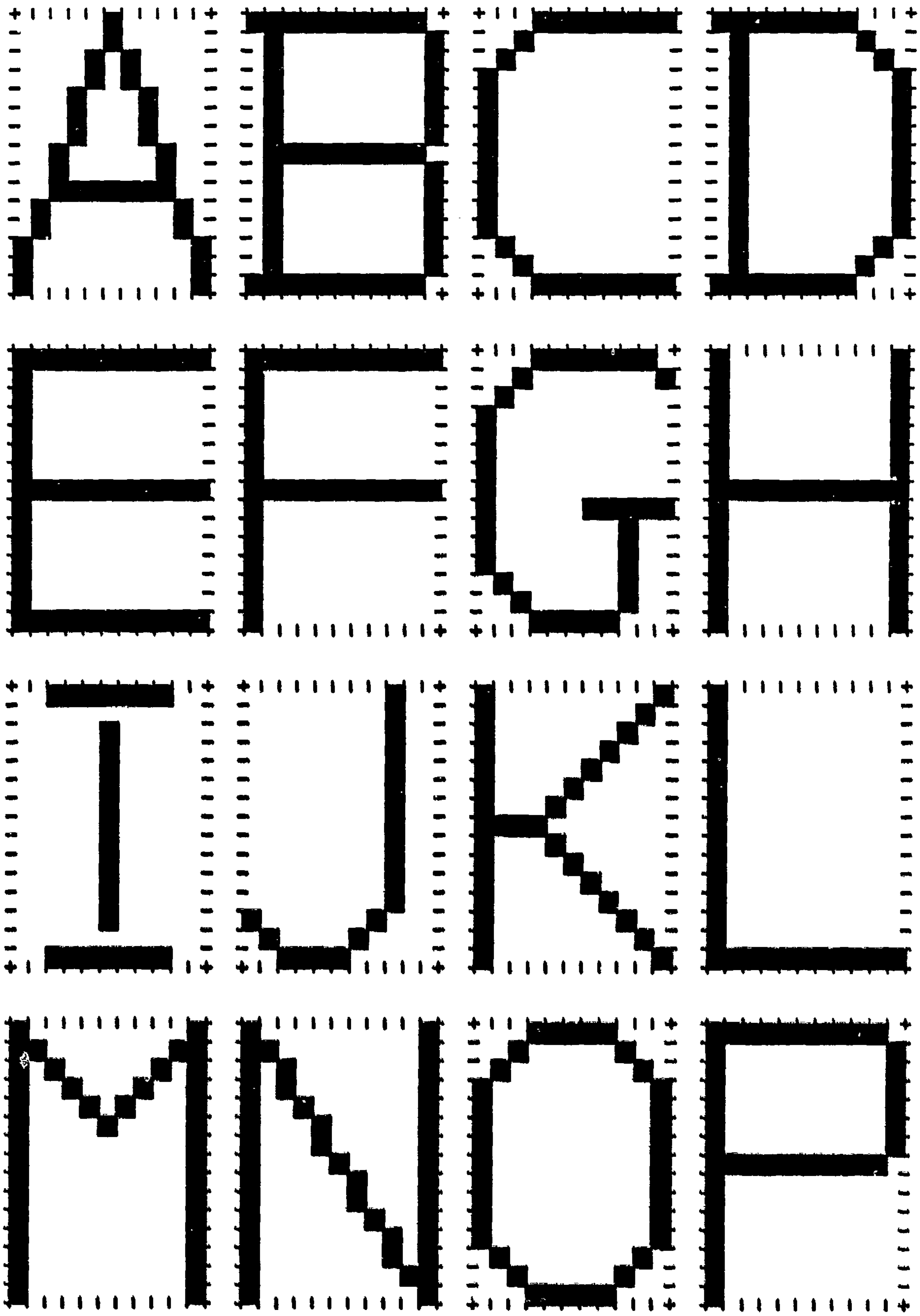

Figure 4. Letter stimuli used in the experiment.

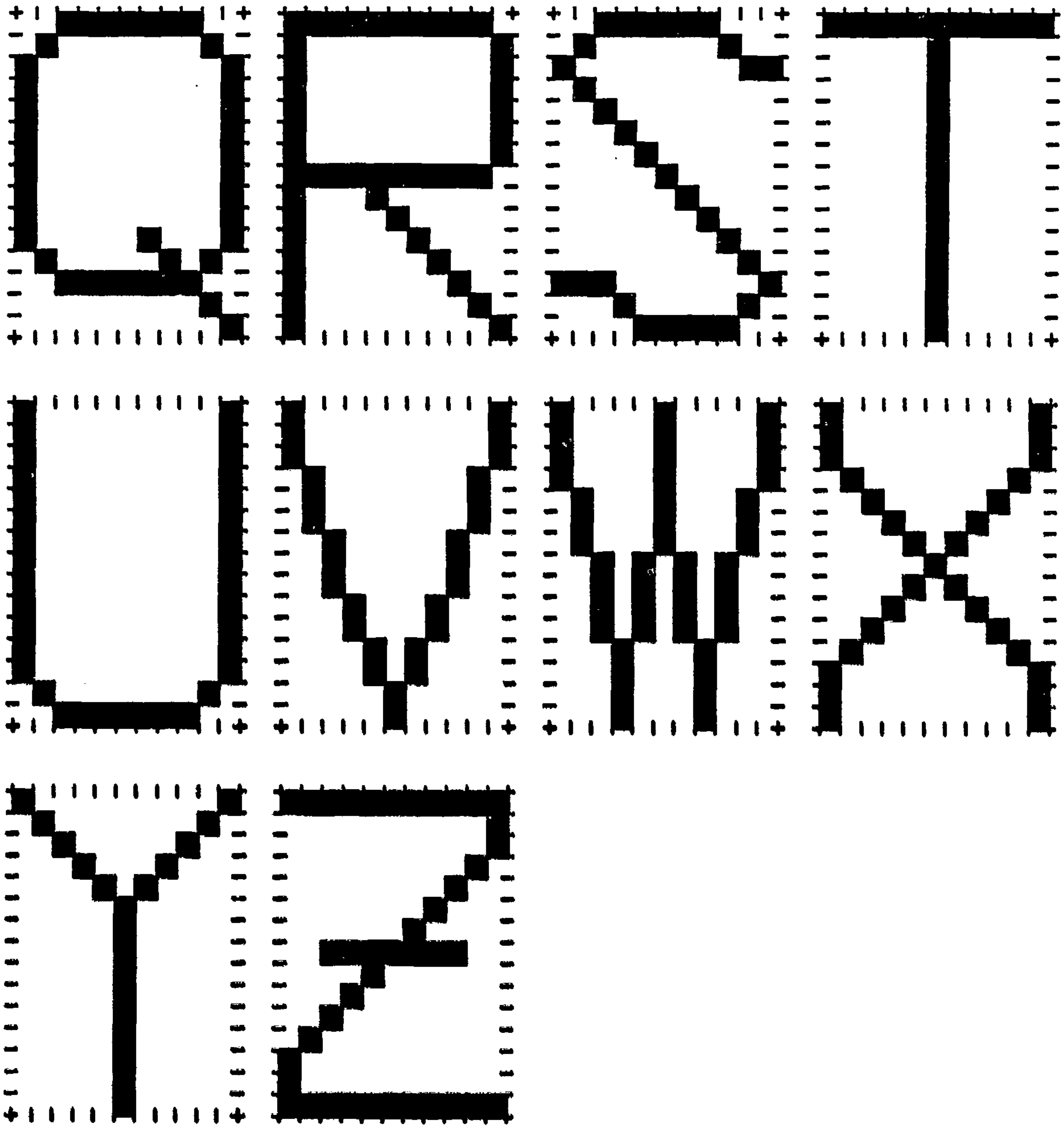

Figure 4 (continued).

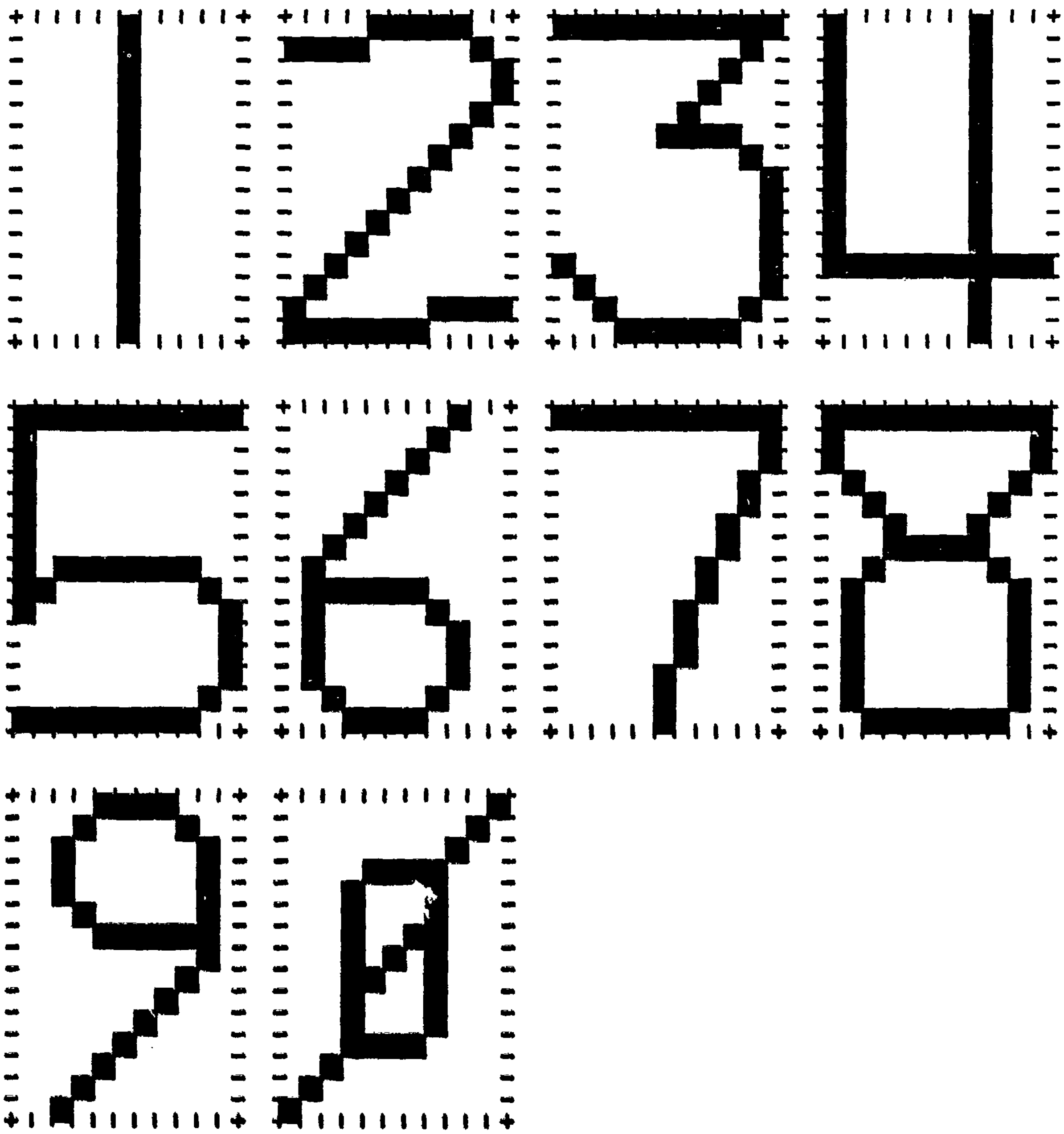

Figure 5. Numeral stimuli used in the experiment.

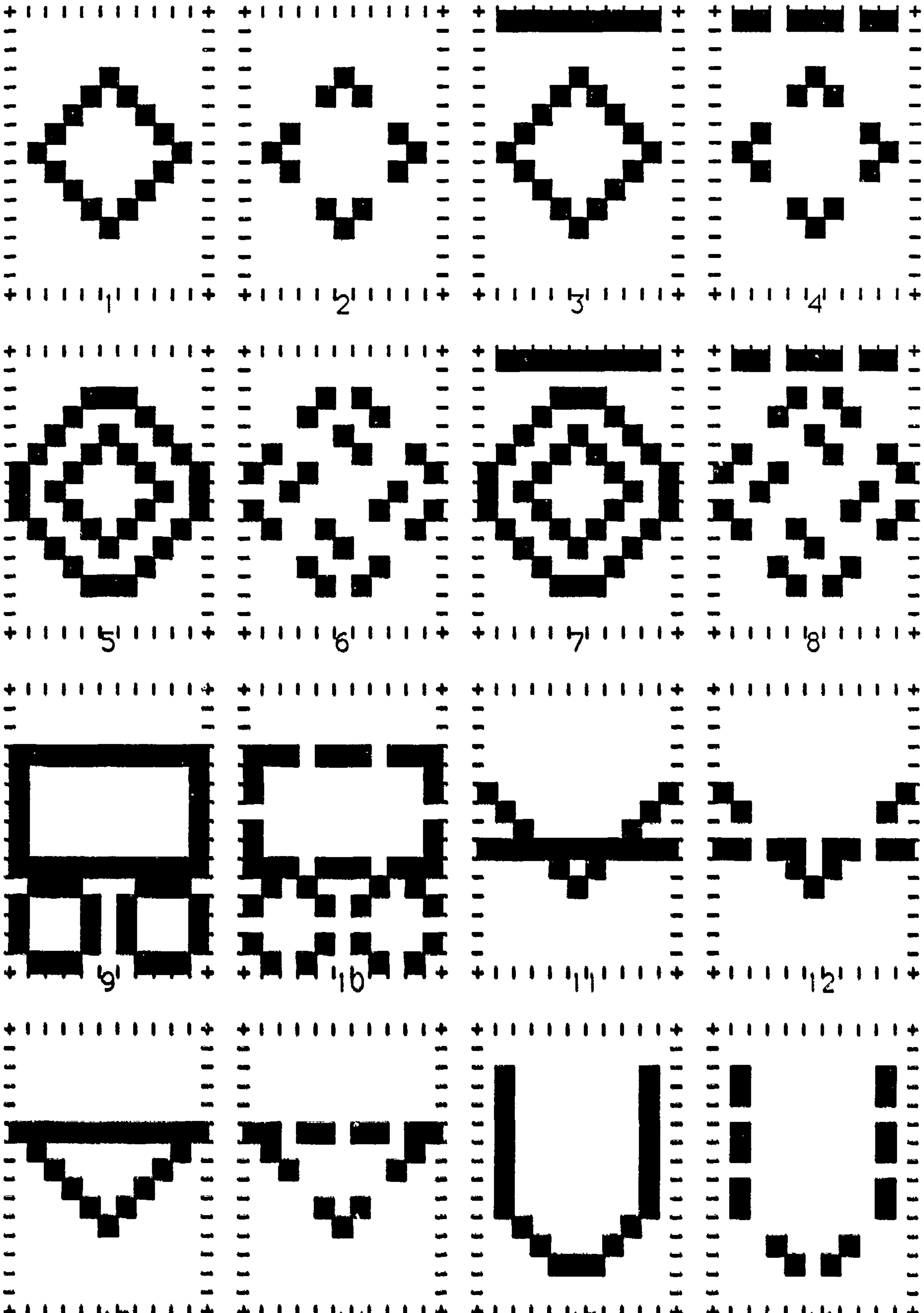

Figure 6. Army symbols used in the experiment.

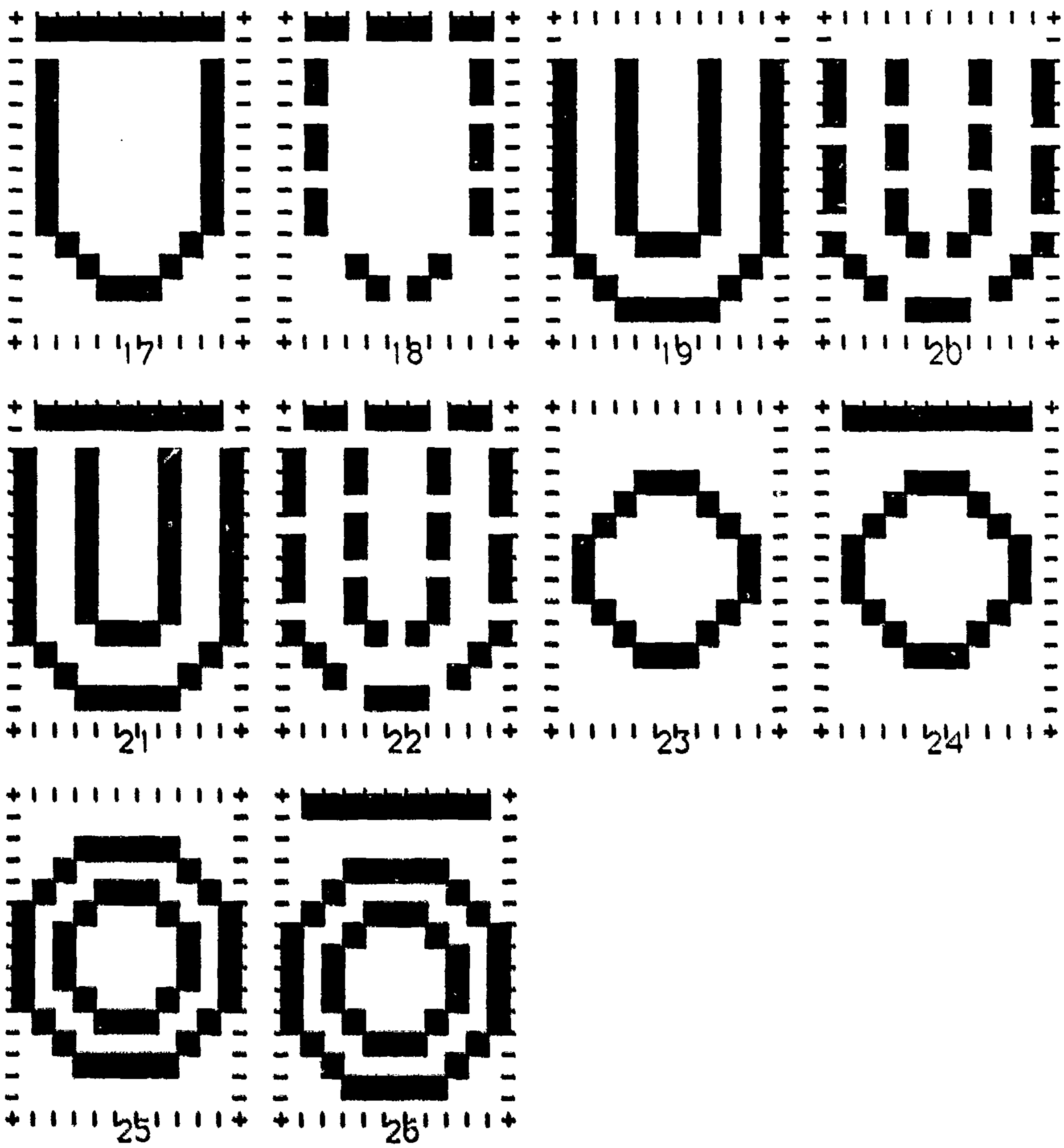

Figure 6 (continued).

Calibration was as follows. The display luminance was first set using the display brightness control so that the luminance level of an all-on field (255 bits) was 49.4 cd/m^2. This hardware brightness control was kept constant, and screen luminance was varied by varying bit levels.

The background luminance was set as closely as possible to 35 cd/m^2 by making vertical scans across several columns of pixels. A dark vertical line was tnen displayed against the background and the line was scanned. The line luminance level was varied until a modulation of 0.83 was reached. The bit levels for the luminance levels of the background and symbols were programmed into the experimental software.

Procedure

At the beginning of each experimental session, the CRT was warmed up for at least 30 minutes. The CRT was calibrated to a luminance of 49.4 cd.m^2 with an all-on field (255 bits). Indirect illumination was set to provide 15 cd/m^2 luminance on the wall directly behind the CRT.

Each of the 90 conditions was presented randomly to each subject 12 times in two blocks of 6 trials, for a total of 1,080 trials per subject. The two blocks of trials were administered on separate days. The direction of rotation was clockwise for one block and counterclockwise for the other, with the order counterbalanced across subjects. Targets were thus assigned to be used 360 times each in the entire design with the constraints that (a) across all 12 subjects, each target was viewed 4 times per condition; and (b) each subject searched for each target a total of 30 times.

On the first day of the experiment, the subjects read a description of the experiment and signed an informed consent form. Subjects were seated in the hydraulic chair, and the height and distance for the subject were adjusted. Subjects were given written instructions and were asked to read them silently as the experimenter read them aloud (see Appendix). Subjects were then given 5 minutes to become familiar with the 26 Army symbols. The symbols were presented on the CRT and on a sheet of paper. Subjects were instructed to pay particular attention to the differences among the symbols. All the subjects stated that they were completely familiar with all symbols at the end of the 5 minutes.

Subjects participated in 18 practice trials to familiarize themselves with the experimental procedure. At the beginning of each trial, the subjects were prompted with a ready message that stated "Ready, the next target is ____." An arrow that designated the rotation angle for that trial was also displayed. This advance information regarding orientation was presented so that subjects were not required to perform mental rotation while searching. Subjects initiated a trial by pressing the right button on the mouse input device, thereby starting the timer. The screen was filled with a random pattern of the symbols, the target, and the appropriate failures. Subjects searched the screen for the target. Upon location of the target, subjects pressed the left button on the mouse input device, which stopped the timer and erased the screen. A blocking pattern was then displayed followed by a nine-cell grid resembling a tic-tac-toe pattern. Each of the nine cells was numbered, and the subject was asked to report the number of the cell in which the target appeared. The experimentor entered the subject's response into the computer after each trial. Search time and accuracy were calculated and recorded by the PC for subsequent analysis.

RESULTS

Search Time

An analysis of variance (ANOVA) was performed on the search time data. A summary of the results is given in Table 1. Because all main effects and their interactions in this experiment are within-subjects effects, significant ($p < .05$) results were evaluated against violations of the assumptions of sphericity using the minimum degrees of freedom for the F tests (Winer, 1971). For those effects not significant with minimal degrees of freedom, Greenhouse and Geisser (1959) ε values were calculated, and the degrees of freedom were adjusted accordingly. Such calculations are footnoted on the ANOVA tables. Post hoc Newman-Keuls tests were performed on significant main effects, and simple effect F tests were conducted on significant interactions.

Rotation angle

As illustrated in Figure 7, search time is shortest at the 0° (nonrotated) position, and about 22% longer at the 70° and 105° rotations, which do not differ from each other ($p > .05$). This expected result agrees with data obtained by Kurokawa et al. (1991), Vanderkolk (1976), and Decker et al. (1991).

Failure mode

Also as expected, ON failures required longer search times than OFF failures (see Figure 8), confirming the results of Abramson et al. (1983), Lloyd et al. (1991), and Dye and Snyder (1991). The failure mode effect is consistent across the rotation angles, as indicated by the nonsignificant mode-by-angle interaction.

Failure type

As reported by others, cell failures require longer search times than do line failures (see Figure 9). A Newman-Keuls test indicated no significant difference between horizontal and vertical line failures, although the small difference in line failure mean search times is in the same direction as that found by others (Abramson et al., 1983; Lloyd et al., 1991), namely, that vertical line failures interfere with performance more than horizontal line failures do.

Figure 10 shows that cell failures are more sensitive to failure mode ($p < .01$) than are line failures. The mode differences are not statistically significant for either type of line failure ($p > .05$). In fact, OFF failures of cells lead to performance as good as either type of line failure, whether the line is failed ON or OFF.

Percent failure

As the percent of cells failed increases, search time increases. Illustrated in Figure 11, the best (and perfect, $R^2 = 1.00$) fit to the means is a positive exponential, indicating that increases in percent cells failed causes disproportionately larger increases in search time. A Newman-Keuls test showed that there are no significant differences among failure rates of 0, 1, and 2%, but that the search time at 3% is significantly greater than at 0%, as is the difference between 4% and 1% ($p < .01$).

Table 1

Analysis of Variance Summary Table for Search Times

Source of Variance	df	MS	F	*p*
Subjects (S)	11	90.07		
Angle of rotation (A)	2	147.54	30.28	0.0001*
S x A	22	4.87		
Failure mode (M)	1	53.07	10.54	0.0078
S x M	11	5.03		
Failure type (T)	2	13.25	5.87	0.0090
S x T	22	2.26		
Percent failure (P)	4	38.08	14.94	0.0001
S x P	44	2.55		
A x M	2	6.23	2.15	0.1409
S x A x M	22	2.90		
A x T	4	5.50	2.08	0.1002
S x A x T	44	2.65		
A x P	8	2.50	1.05	0.4046
S x A x P	88	2.38		
M x T	2	40.76	13.94	0.0001
S x M x T	22	2.92		
M x P	4	10.02	4.33	<.05**
S x M x P	44	2.32		
T x P	8	6.21	1.66	0.1191
S x T x P	88	3.74		
A x M x T	4	1.22	0.49	0.7746
S x A x M x T	44	2.49		
A x M x P	8	1.80	0.65	0.7337
S x A x M x P	88	2.77		
M x T x P	8	7.64	2.62	<.05***
S x M x T x P	88	2.91		
A x T x P	16	3.35	1.37	0.1599
S x A x T x P	176	2.44		
A x M x T x P	16	2.82	0.90	0.5724
S x A x M x T x P	176	3.14		
TOTAL	1,079			

*$p < .01$ with Greenhouse and Geisser (1959) lower bound correction
**Greenhouse and Geisser (1959) $\varepsilon = 0.7912$, adjusted $p < .05$
***Greenhouse and Geisser (1959) $\varepsilon = 0.7729$, adjusted $p < .05$

The effect of percent failure is greater for ON failures than OFF failures (see Figure 12). Differences between failure modes are significant ($p < .01$) at 2% and 4% failure rates, although all differences are in the same (and expected) direction.

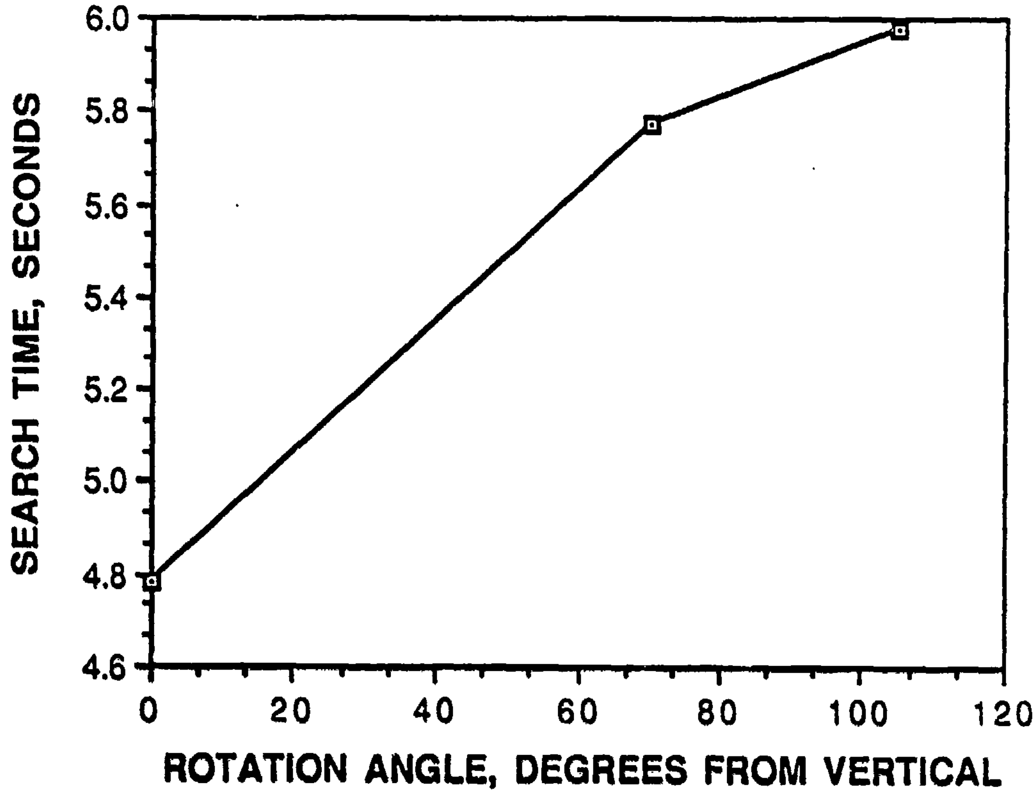

Figure 7. The effect of rotation angle on search time.

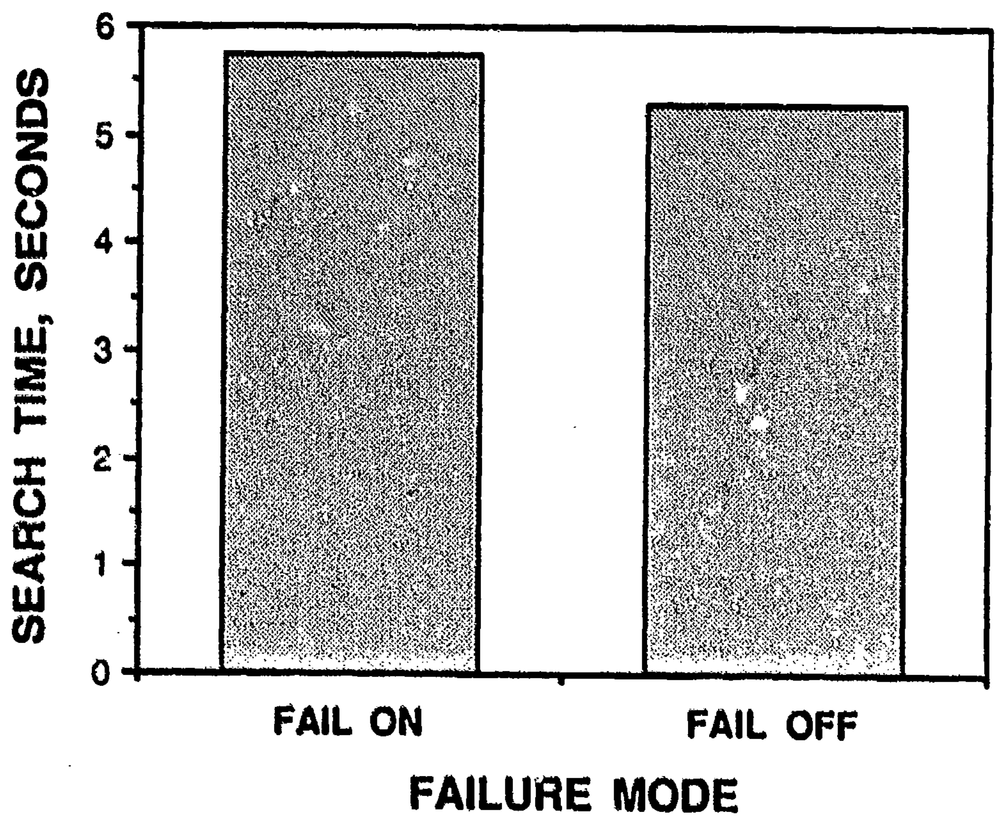

Figure 8. The effect of failure mode on search time.

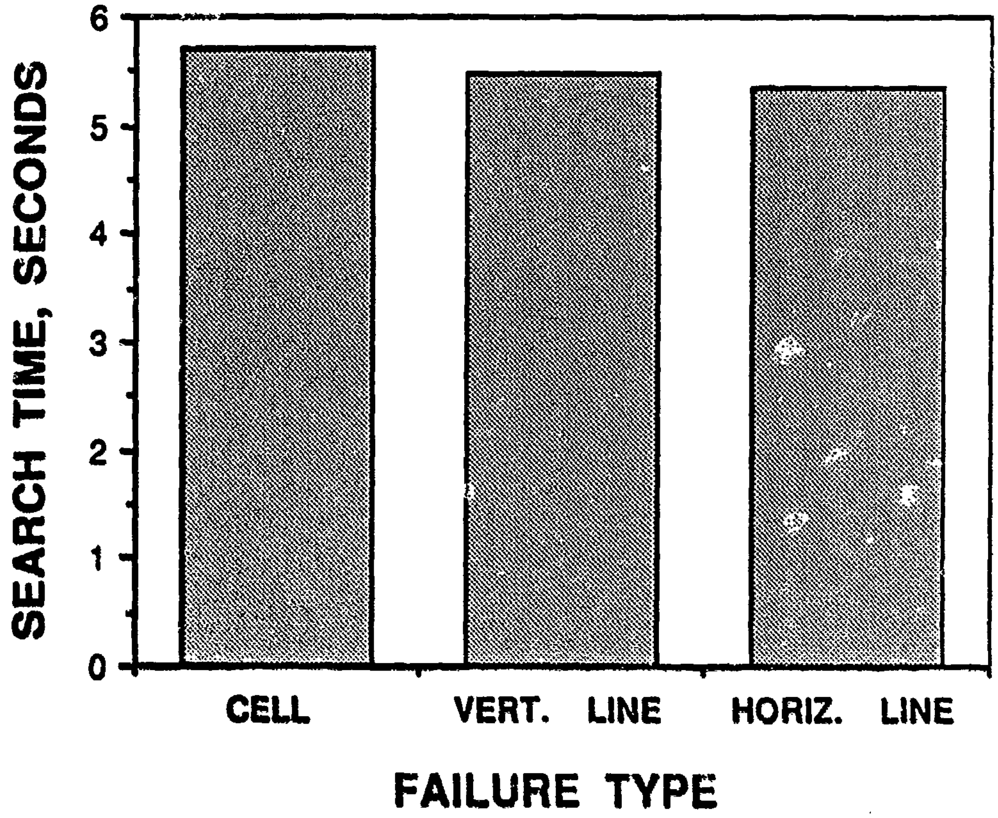

Figure 9. The effect of failure type on search time.

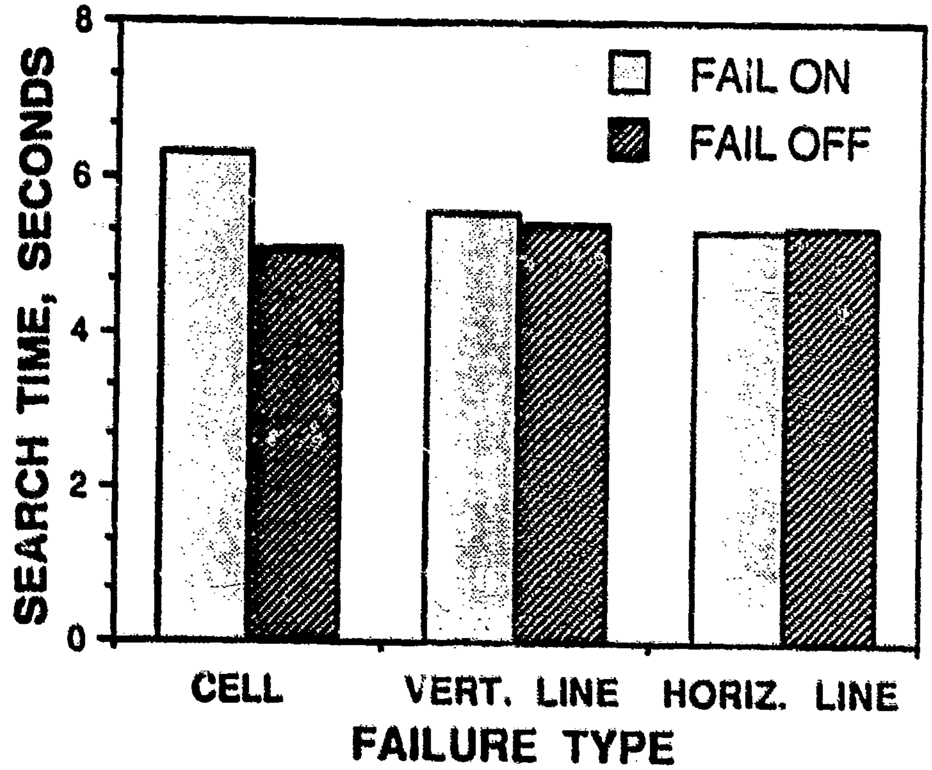

Figure 10. The effect of failure type by failure mode interaction on search time.

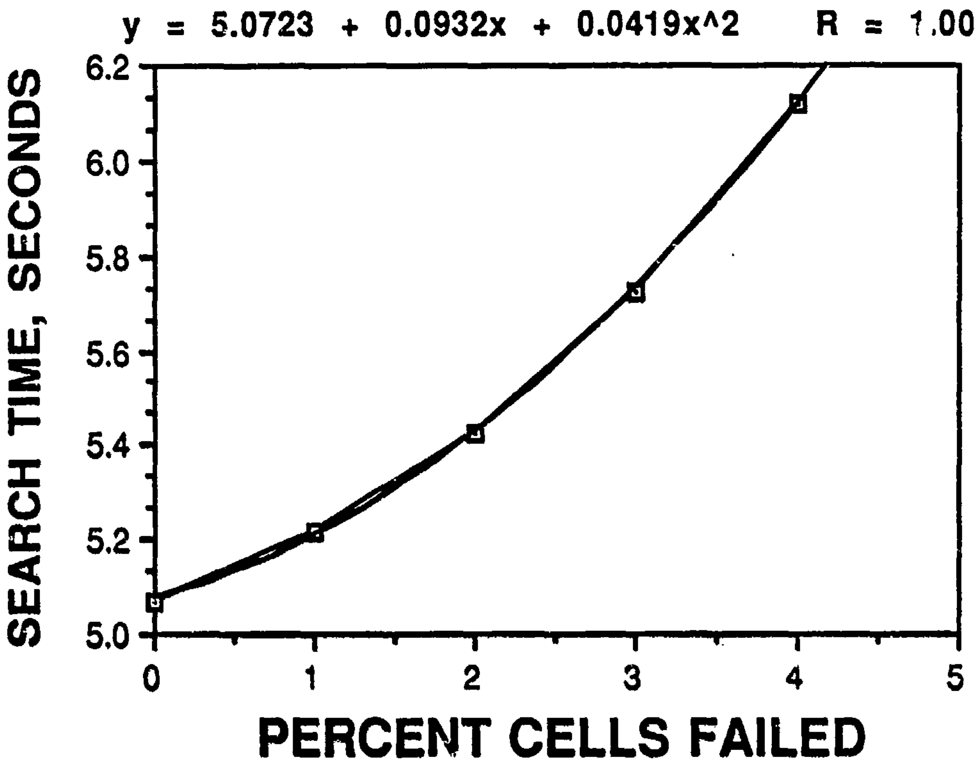

Figure 11. The effect of percent failure on search time.

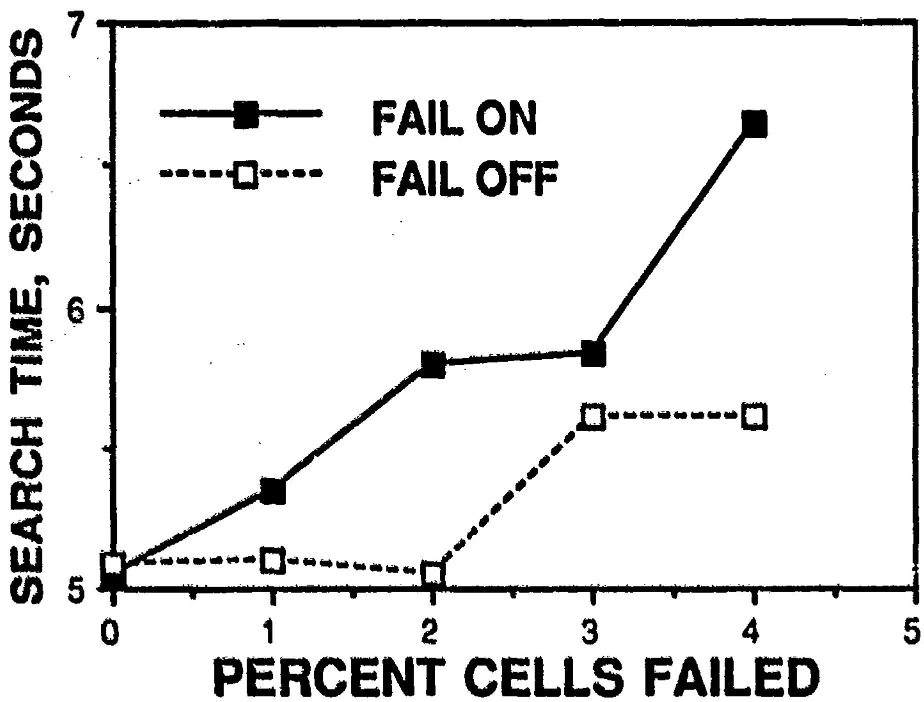

Figure 12. The effect of percent failure by failure mode interaction on search time.

Mode by type by percent failure interaction

The three-way interaction among failure mode, failure type, and percent cells failed is both interesting and meaningful, as it further points out the importance of whether the display fails ON or OFF.

As illustrated in Figure 13 (top), when cells fail ON above a 1% rate, search time increases significantly ($p < .01$). For horizontal and vertical line failures in the ON mode, failure rates from 0% to 4% have no significant effect.

Conversely, when cells fail OFF (see Figure 13, bottom), there is no interaction among failure type and percent failure and no significant effect of either variable. Thus, it is quite clear that most of the significant changes in search time in this experiment are caused specifically by ON cell failures that occur in at least 2% of the cells.

Search Accuracy

An ANOVA of the accuracy data was performed. For each experimental condition, the average number of correct responses was calculated, and the percentage of correct responses was used as the dependent measure. Evaluation of the assumption of sphericity was done as in the ANOVA of search times. Results of this analysis are summarized in Table 2.

Rotation angle

Figure 14 shows that fewer errors were made at 0° (nonrotated) than at either 70° or 105°. There is no difference in accuracy between the two rotations ($p > .05$).

Failure mode

Although the OFF failure conditions produced significantly fewer errors in a statistical sense, the difference is very small (see Figure 15) and would be of no consequence were it not in agreement with other studies showing that OFF failures are less detrimental to performance than ON failures.

Of perhaps more interest is the rotation angle by failure mode interaction illustrated in Figure 16. There are no significant failure mode differences at 0° or 105°, but the OFF failures produced greater accuracy than ON failures at 70° of rotation.

Percent failures

As illustrated in Figure 17, search accuracy generally decreased as the percent of failed cells increased. A Newman-Keuls test showed no differences between 0% and 1% failure rates, or among 2%, 3%, and 4% rates ($p > .05$). Thus, these data clearly indicate that failures of 2% or greater significantly impact performance.

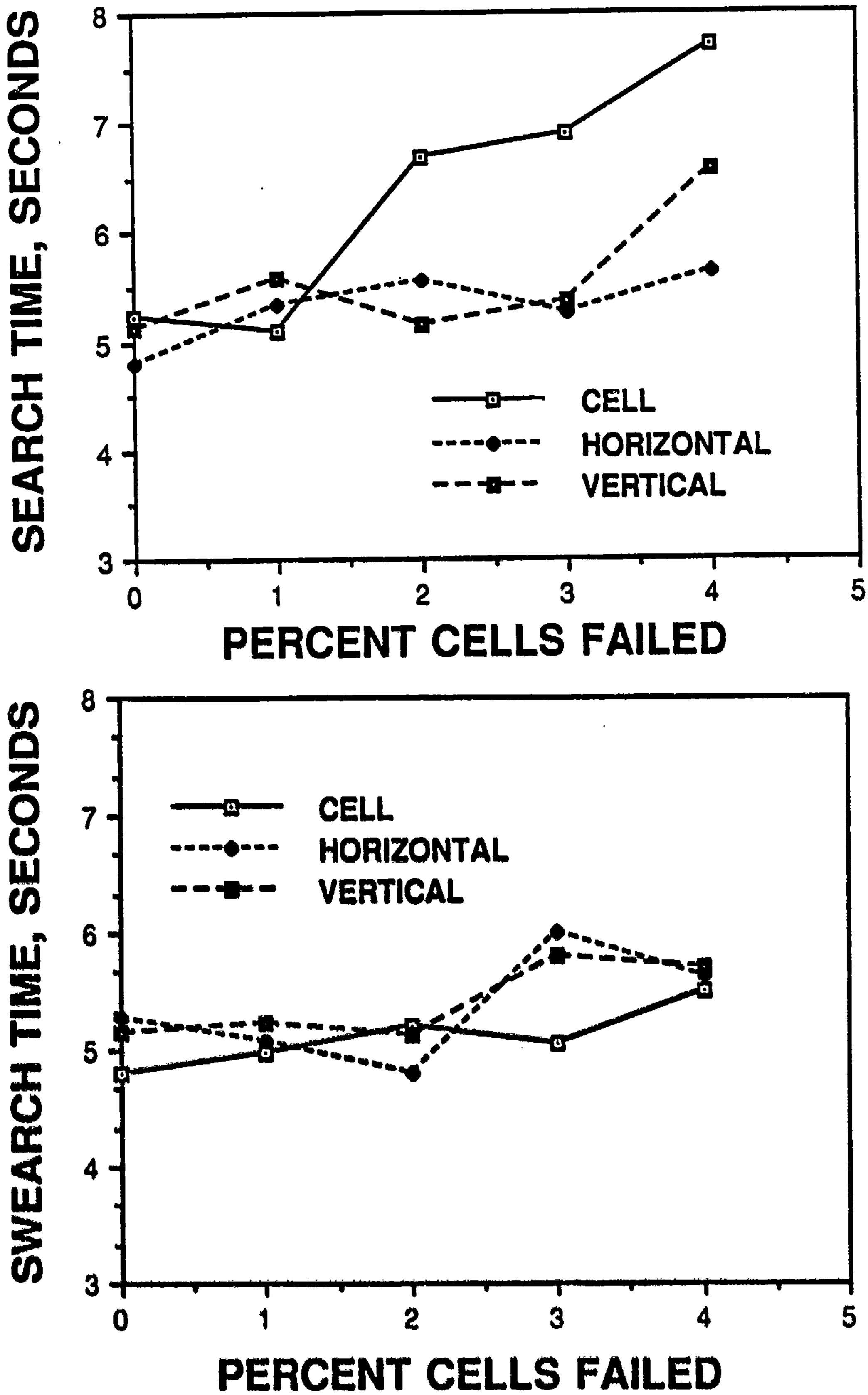

Figure 13. Percent failure by failure type interaction for ON failures (top) and OFF failures (bottom).

Table 2

Analysis of Variance Summary Table for Search Accuracy

Source of Variance	df	MS	F	*p*
Subjects (S)	11	0.2681		
Angle of rotation (A)	2	0.5770	37.62	0.0001*
S x A	22	0.0153		
Failure mode (M)	1	0.0209	10.55	0.0078
S x M	11	0.0020		
Failure type (T)	2	0.0101	1.78	0.1923
S x T	22	0.0057		
Percent failure (P)	4	0.0238	4.15	0.01**
S x P	44	0.0057		
A x M	2	0.0450	8.25	0.0021***
S x A x M	22	0.0054		
A x T	4	0.0085	1.62	0.1852
S x A x T	44	0.0053		
A x P	8	0.0098	1.23	0.2903
S x A x P	88	0.0080		
M x T	2	0.0232	4.87	0.0178***
S x M x T	22	0.0048		
M x P	4	0.0095	1.26	0.3004
S x M x P	44	0.0075		
T x P	8	0.0109	1.29	0.2589
S x T x P	88	0.0084		
A x M x T	4	0.0173	2.33	0.0707
S x A x M x T	44	0.0074		
A x M x P	8	0.0058	0.60	0.7744
S x A x M x P	88	0.0097		
M x T x P	8	0.0153	1.91	0.0686
S x M x T x P	88	0.0080		
A x T x P	16	0.0124	1.50	0.1025
S x A x T x P	176	0.0082		
A x M x T x P	16	0.0073	0.96	0.5036
S x A x M x T x P	176	0.0076		
TOTAL	1,079			

*$p < .01$ with Greenhouse and Geisser (1959) lower bound correction
**Greenhouse and Geisser (1959) $\varepsilon = 0.7649$, adjusted $p < .01$
***$p < .05$ with Greenhouse and Geisser (1959) lower bound correction

Failure mode by failure type interaction

Although the overall effect of failure type is not significant, this variable does have a small but statistically significant interaction with failure mode, as illustrated in Figure 18. Post hoc simple effect F tests indicate no significant differences among the three failure types for OFF failures ($p > .05$), but that the cell failures led to more errors than did horizontal line failures for the ON mode ($p < .05$). Again, while these differences are small, they point out the combined effects of ON cell failures on performance.

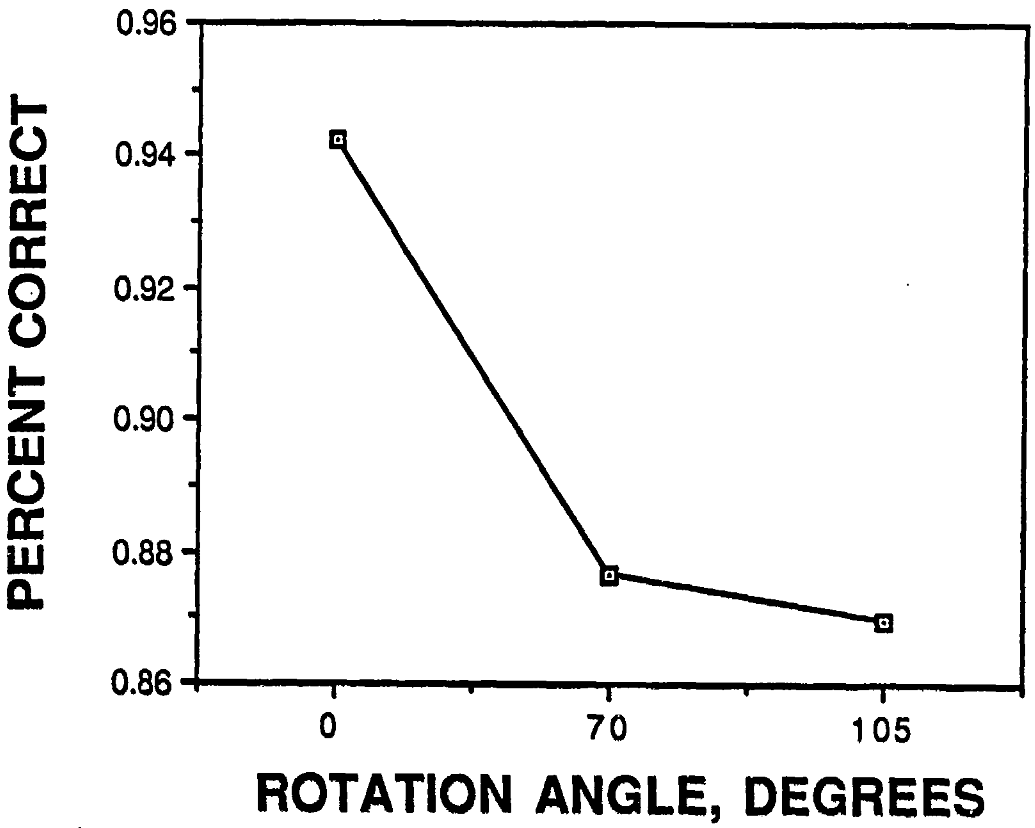

Figure 14. The effect of rotation angle on search accuracy.

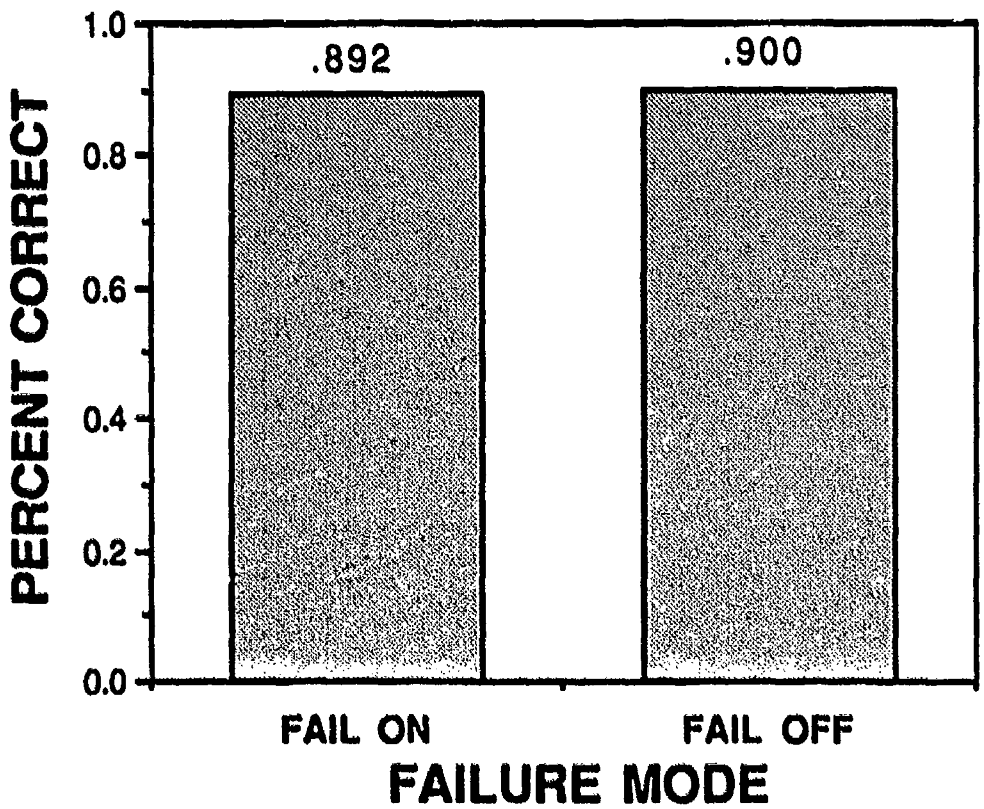

Figure 15. The effect of failure mode on search accuracy.

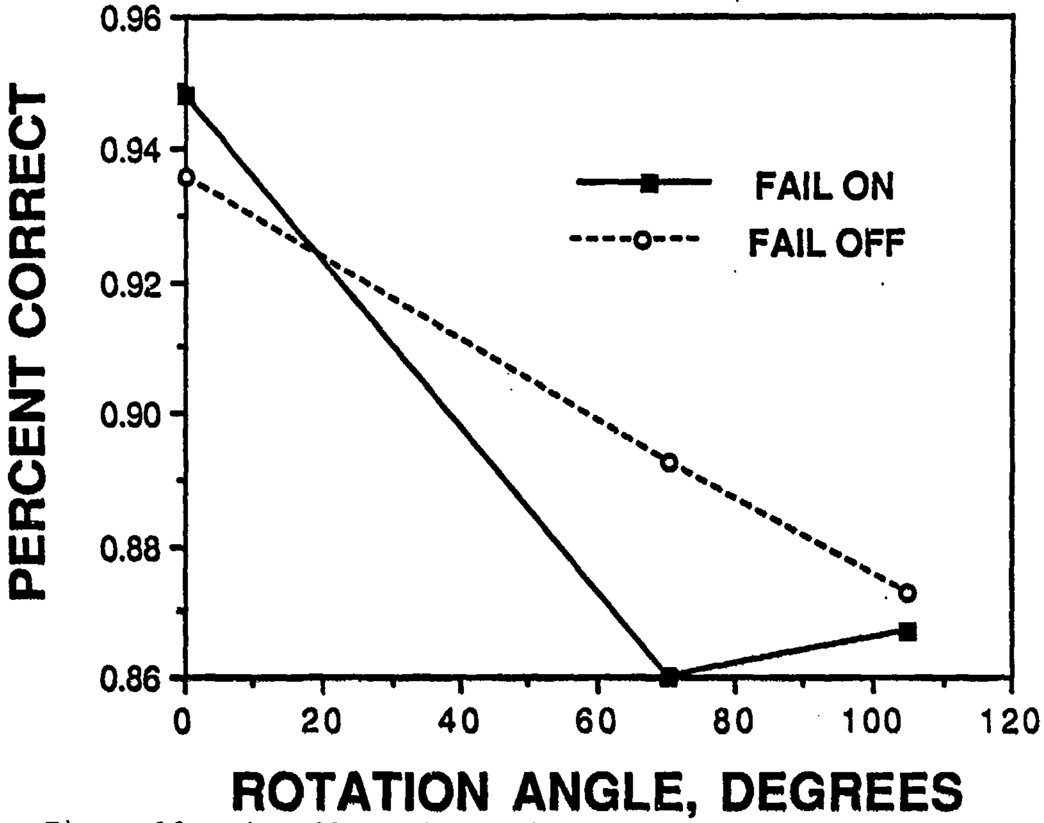

Figure 16. The effect of rotation angle on search accuracy.

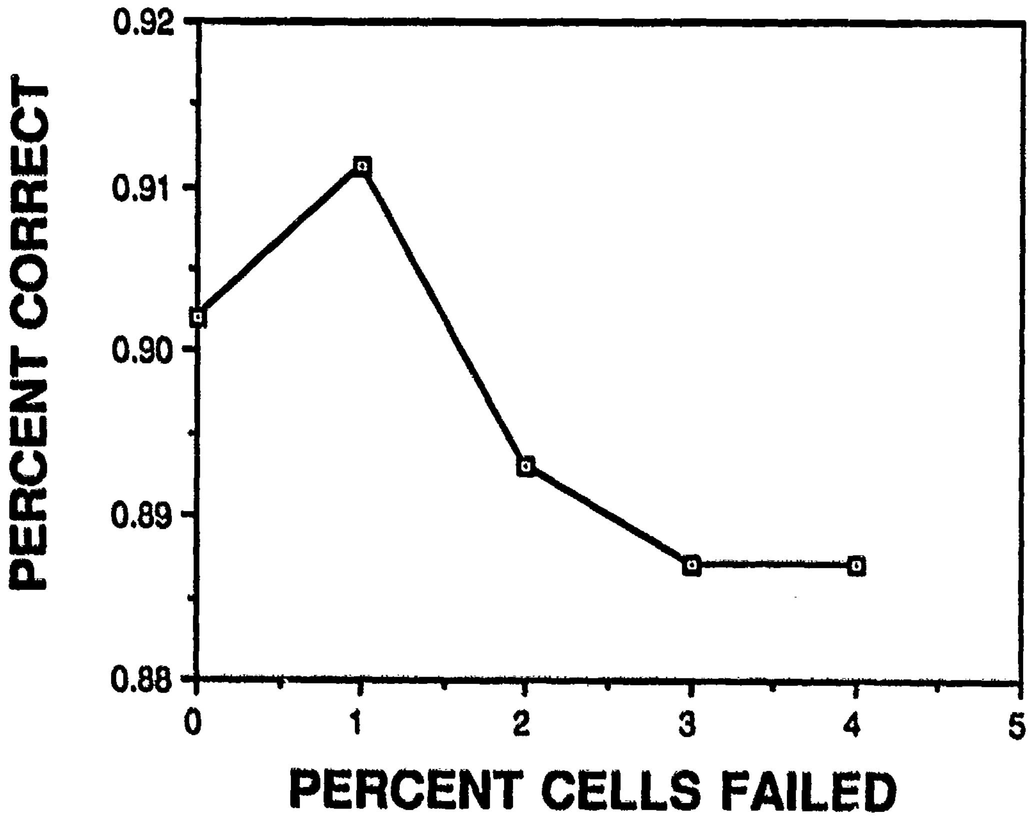

Figure 17. The effect of percent failure on search accuracy.

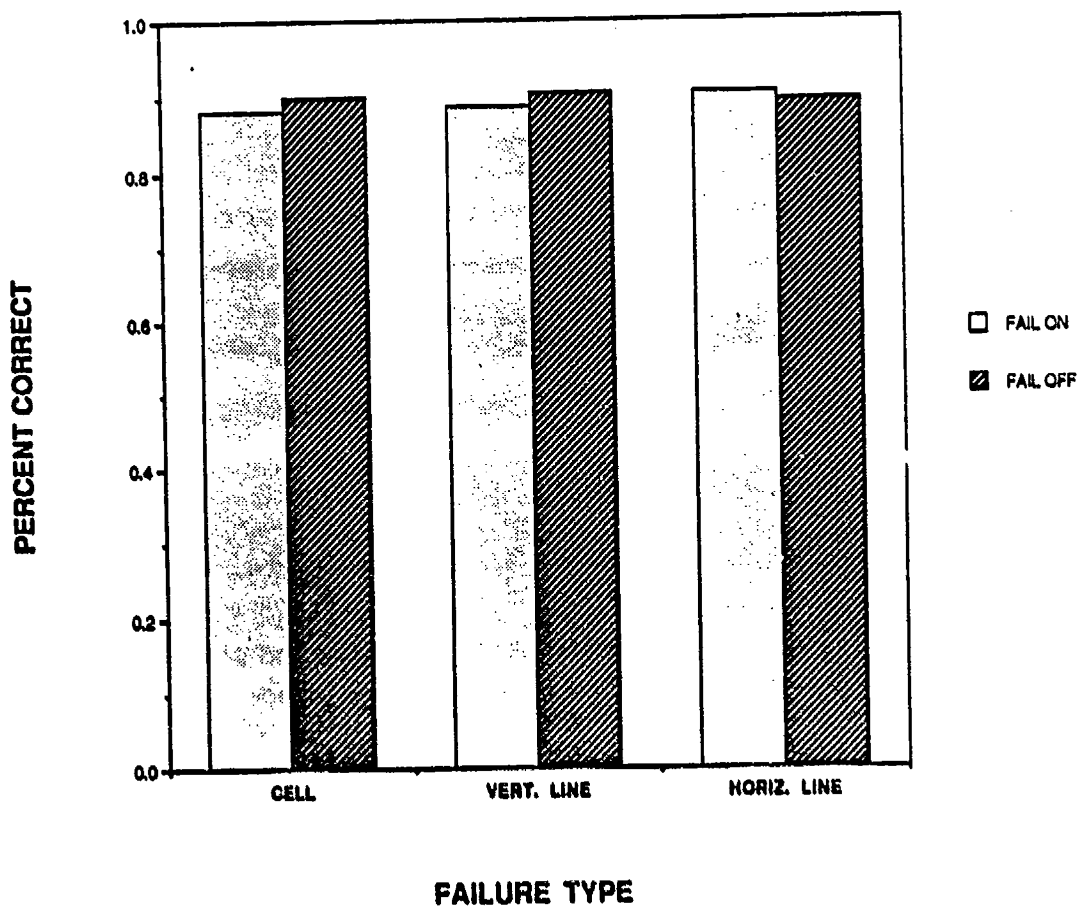

Figure 18. The effect of the failure type by failure mode interaction on search accuracy.

Symbol Analysis

The purpose of this analysis was to examine which dot-matrix symbols may have been more difficult to identify than others and to determine whether there is a need to redesign some of the Army dot-matrix symbols for more stable performance. The mean search times for each target symbol were determined and plotted by angle in Figures 19 through 21 and indicate that symbols 17 and 18 took the longest to find.

The accuracy data (not illustrated) show that search accuracy was below 80% for these two symbols when they are rotated. All symbols except one were above 85% at 0° (symbol 12 had 82% accuracy) with most being above 90%.

Symbols 15 and 16 are very similar in appearance to 17 and 18, and search times also tended to be longer for these symbols. Symbols 3 and 24 had the two longest search times (after 17 and 18) when oriented at 0° and 105°. At 70°, these symbols had search times within the same range, although other symbols took longer. Fastest search times and best accuracy scores tended to be for alphanumerics, as would be expected because of their greater familiarity. The numeral 1 and the letter L had the fastest search times.

Although this analysis is somewhat descriptive, results can be used to determine which symbols to avoid or redesign for future studies. It was not possible to construct a confusion matrix or to conduct a more quantitative statistical analysis because of the experimental procedures used.

DISCUSSION AND CONCLUSIONS

Failure Mode

This experiment again confirms the major impact of failure mode on visual task performance. Cells or lines that fail ON have greater impact on search time than do those that fail OFF. If the failures are cell failures, rather than line failures, the detrimental effect is magnified, and failure rates beyond 1% significantly increase search time. Consistent with the above, accuracy is also less for ON cell failures than for horizontal line failures.

Thus, the results of this study confirm the recommendation made by Lloyd et al. (1991) that displays be designed to minimize ON failures, those that match the symbology, not the background. If a particular display technology were to have such a propensity, polarity inversion might be considered as a technique to reduce the magnitude of the effect. For example, using light characters on a dark background rather than dark characters on a light background would cause an otherwise ON failure to become an OFF failure if the failure were caused by a cell or line to be nonilluminated.

Percent Cells Failed

In this experiment, an effort was made to quantify the effects of failure rates below 4% by using 1% increments. It is highly unlikely that users would accept 4% failure rates, since such a display is quite unattractive and distracting, even though the decrement in search performance is not very great.

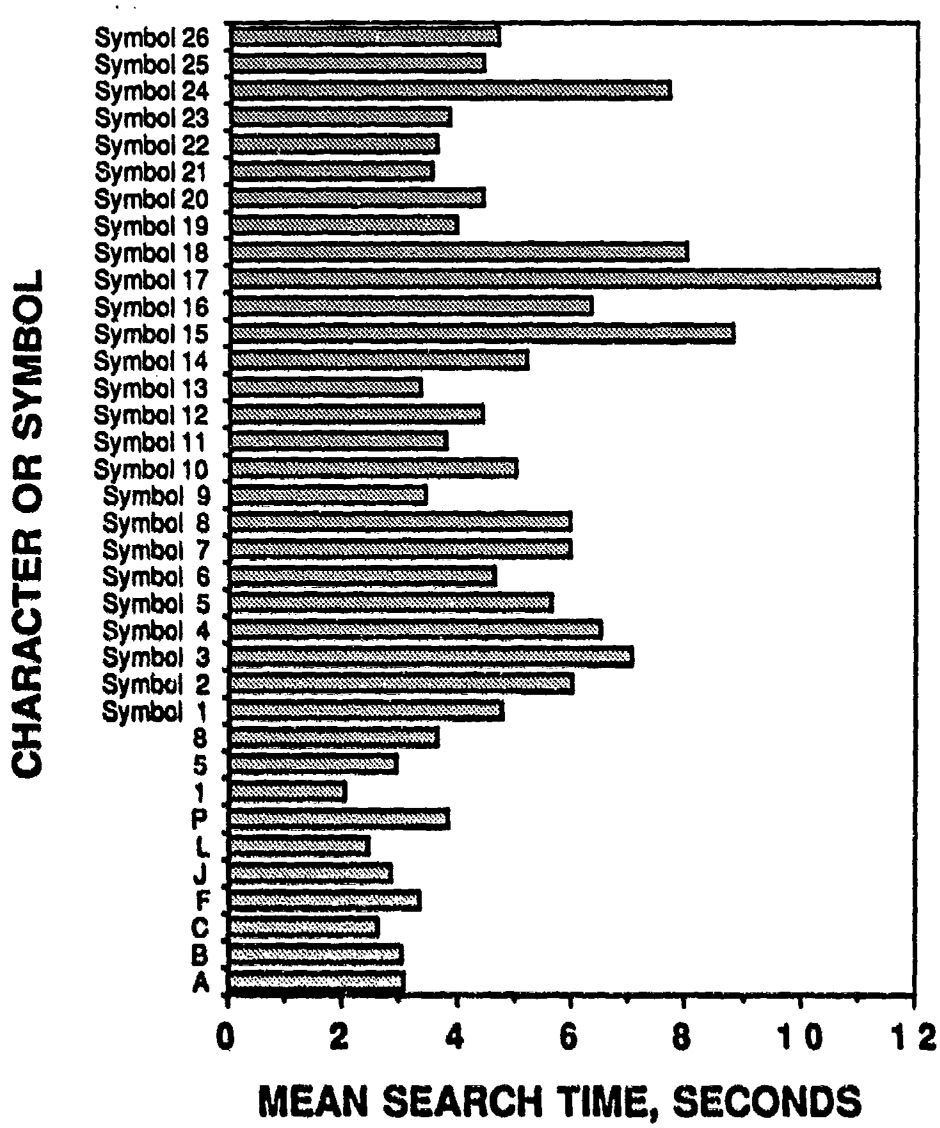

Figure 19. The effect of character or symbol on search time, 0° rotation.

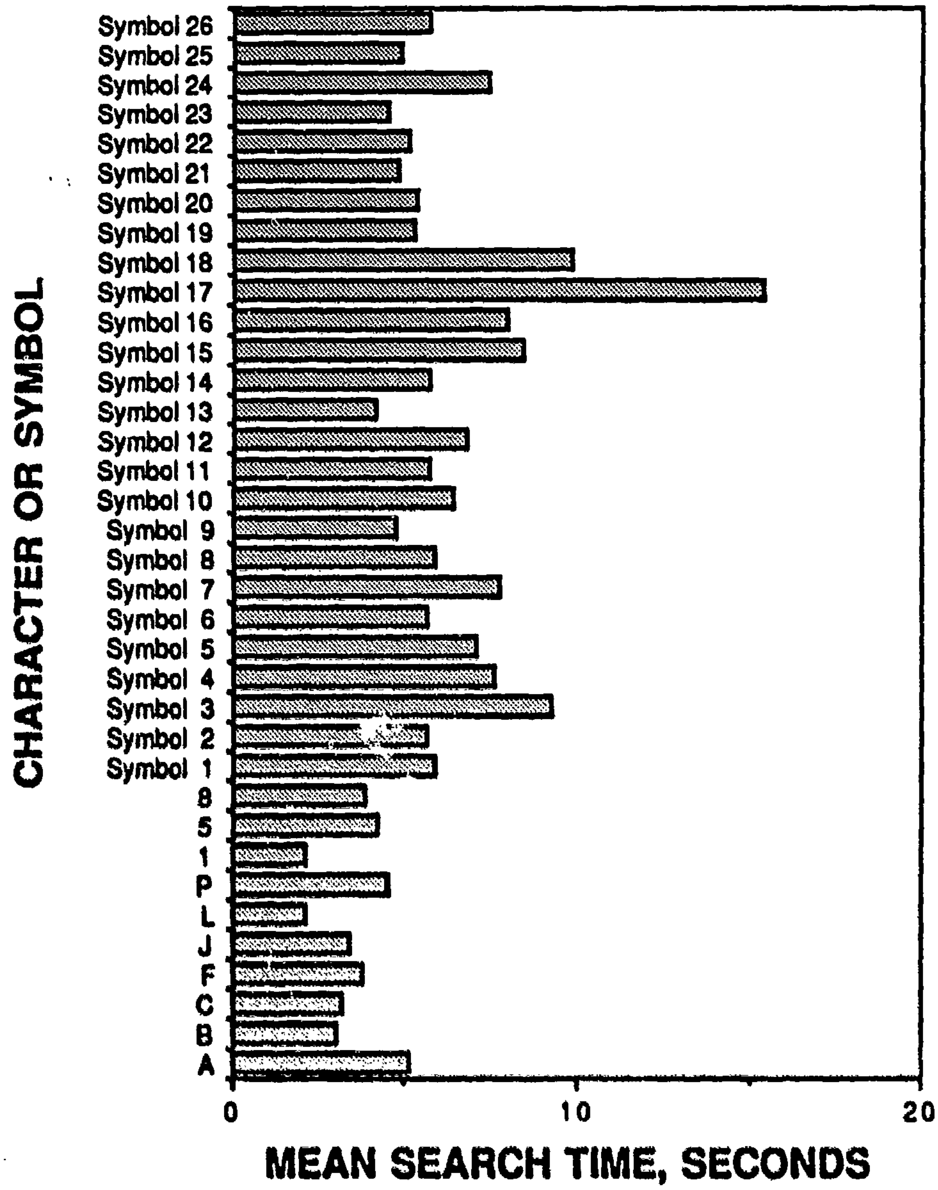

Figure 20. The effect of character or symbol on search time, 70° rotation.

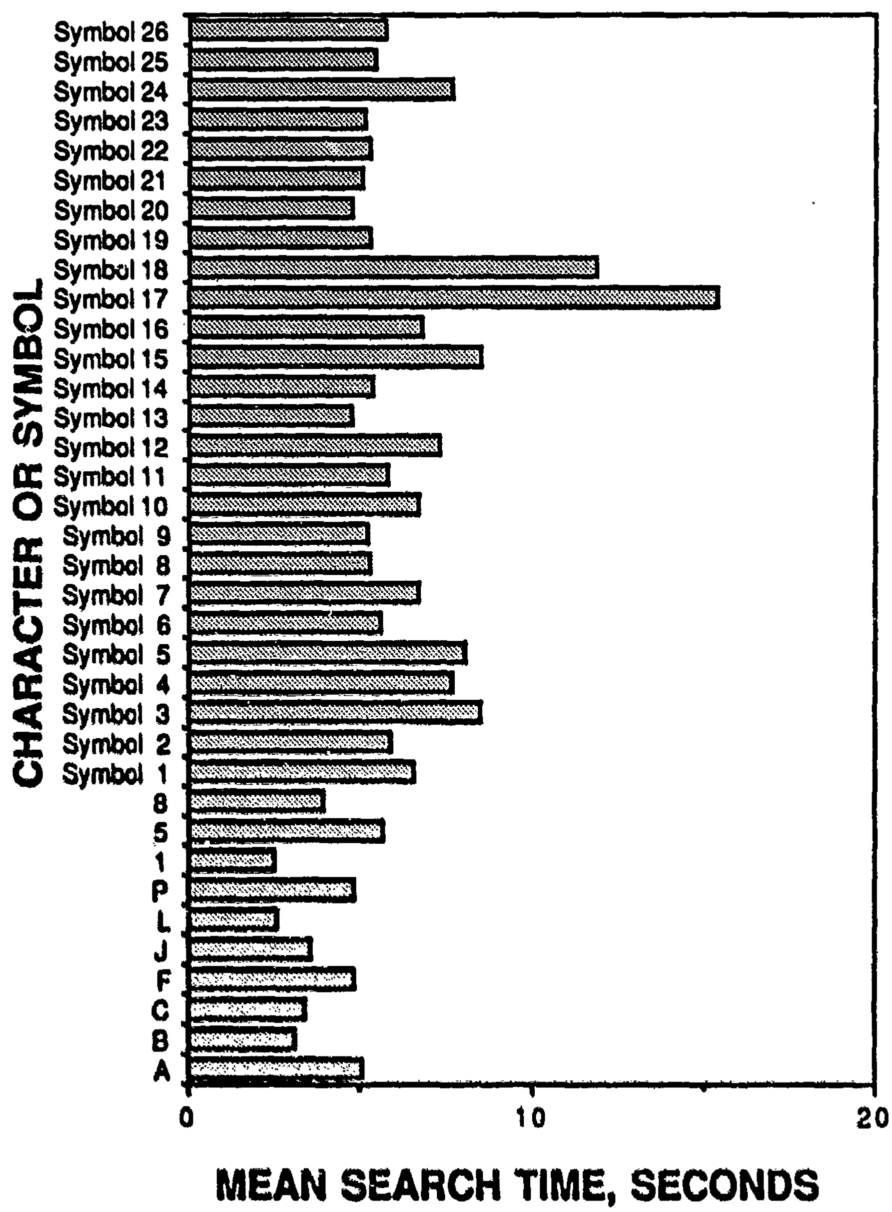

Figure 21. The effect of character or symbol on search time, 105° rotation.

As these data show, the effect of failure rate on search time is positively exponential and well behaved. Increments beyond 1% therefore produce disproportionally greater search times. Moreover, the accuracy data lead to the conclusion that performance degrades significantly beyond the 1% failure rate.

Accordingly, displays having failure rates exceeding 1% must be assumed to cause user performance decreases, particularly in search and recognition tasks. As an upper limit, then, failure rates beyond 1% should be considered unacceptable, particularly for ON cell failures.

Display Rotation

Although the effects of display rotation and failure rate were expected to be compounded, they were not. One reason for this lack of interaction may be that the symbols were created in an 11 x 15 matrix size, which minimizes the effect of rotation angle (Decker et al., 1991). While rotated positions in this study resulted in increased search times and decreased accuracy, the multiplicative effects of rotation with ON failures or cell failures were avoided.

Thus, the relative advantage of the larger character and matrix size is once again demonstrated in that it reduces the impact of other variables, such as cell failures and ON failures, on performance. As in other experiments (Decker et al., 1991; Snyder & Maddox, 1978), a strong recommendation was made for the use of 11 x 15 (or larger) matrix sizes when search tasks are to be performed with rotated displays.

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APPENDIX

INSTRUCTIONS TO SUBJECTS

INSTRUCTIONS TO SUBJECTS

In this experiment, you will be asked to search for an alphanumeric character (letter or number) or cartographic symbol from among other characters and symbols on the screen. The placement of your target character will be random. At the beginning of each trial you will see the words, "Ready, the target character is ______." This will be your target character for that trial. It will appear in only one position on the screen. During the trials, noise may be introduced onto the screen and you will be required to search for the targets which are embedded in the noise.

When you are ready to begin searching, press the right button on the mouse input device. The screen will then fill with a random pattern of letters and numbers. When you locate the target, press the left button on the mouse. You will be asked to identify which of the nine areas the target character fell. After you press the left button on the mouse, a "tic-tac-toe" pattern will appear. Each of the areas in the pattern is numbered. You will then tell the experimenter the number corresponding to the area in which the target appeared. You should keep your eyes fixated where the target appeared on the screen so that when the grid appears, you will be able to remember its exact location. If you allow your eyes to drift, you might lose the position and not be able to identify the area on the grid in which it appeared. If you wish, you may use your finger to help you remember the location of the target on the screen, **after** you press the left mouse button and the random pattern is removed. Please be sure not to start moving your hand to point before you press the left button. The screen will then be erased so that you can initiate a new trial.

During the experiment, we want you to respond **as quickly and as accurately as possible**--both are important. Please keep your head in a straight and upright position while searching; otherwise, your eyes may move from the intended position. We will begin the session with 36 practice trials. If you have any questions, please ask. If you are comfortable with the procedure, we will begin the experiment. The session will last approximately 3 hours. You will be offered the opportunity to take short breaks at various intervals during the session.

Before beginning the experiment, please examine the hard copy of the symbols. It is important that you learn these symbols before we begin. The symbols as well as the alphanumeric characters are also drawn on the CRT screen in front of you. The symbols are very similar; therefore, please pay attention to the differences between the symbols.

(Subjects were shown the set of symbols appearing in Figure 6 on hard copy while the same symbol set appeared on the CRT. The following comments were made by the experimenter, and the various features of the symbols were pointed out on the hard copy.)

The top line is a stroke drawing of the symbols, that is, how they would appear when drawn on paper.

The next three rows are these same symbols in three different sizes. Notice that they are made from dots. This is how they would appear on the CRT screen.

For every symbol type one symbol is drawn with all dots (e.g., diamond symbol #0) and one is missing some dots (e.g., diamond symbol #1). These should be considered as separate symbols.

The U in the alphabet is very similar to the U symbol #14. Examine these differences.

Diamond symbols (#4, 5, 6, and 7) are similar to circular symbols (#22, 23, 24, and 25) when drawn on the CRT. Examine these differences.

You will be given 5 minutes to learn these symbols and their differences.