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THE EFFECTS OF SYMBOL ROTATION AND MATRIX SIZE ON VISUAL SEARCH PERFORMANCE

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U.S. ARMY HUMAN ENGINEERING LABORATORY

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This experiment is one of a series of studies about visual task performance with dot-matrix displays. In this study, the variables of matrix size and symbol rotation are evaluated for their effects on visual search time for familiar alphanumerics as well as for dot-matrix-formed U.S. Army symbols. The results show that increasing the size of the matrix from 7 x 9 to 9 x 11 or even to 11 x 15 dots significantly improves performance for alphanumerics as well as Army symbols, particularly for the more difficult and confusable symbols. Search accuracy improves in much the same manner as search time does.

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INTRODUCTION

Symbol Rotation

A current application of visual displays is the presentation of cartographic-symbolic information about 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), rotation of 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 or 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 (matrix size) 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 from this study regarding rotation are difficult to make since only two levels of rotation 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- x 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:

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

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,

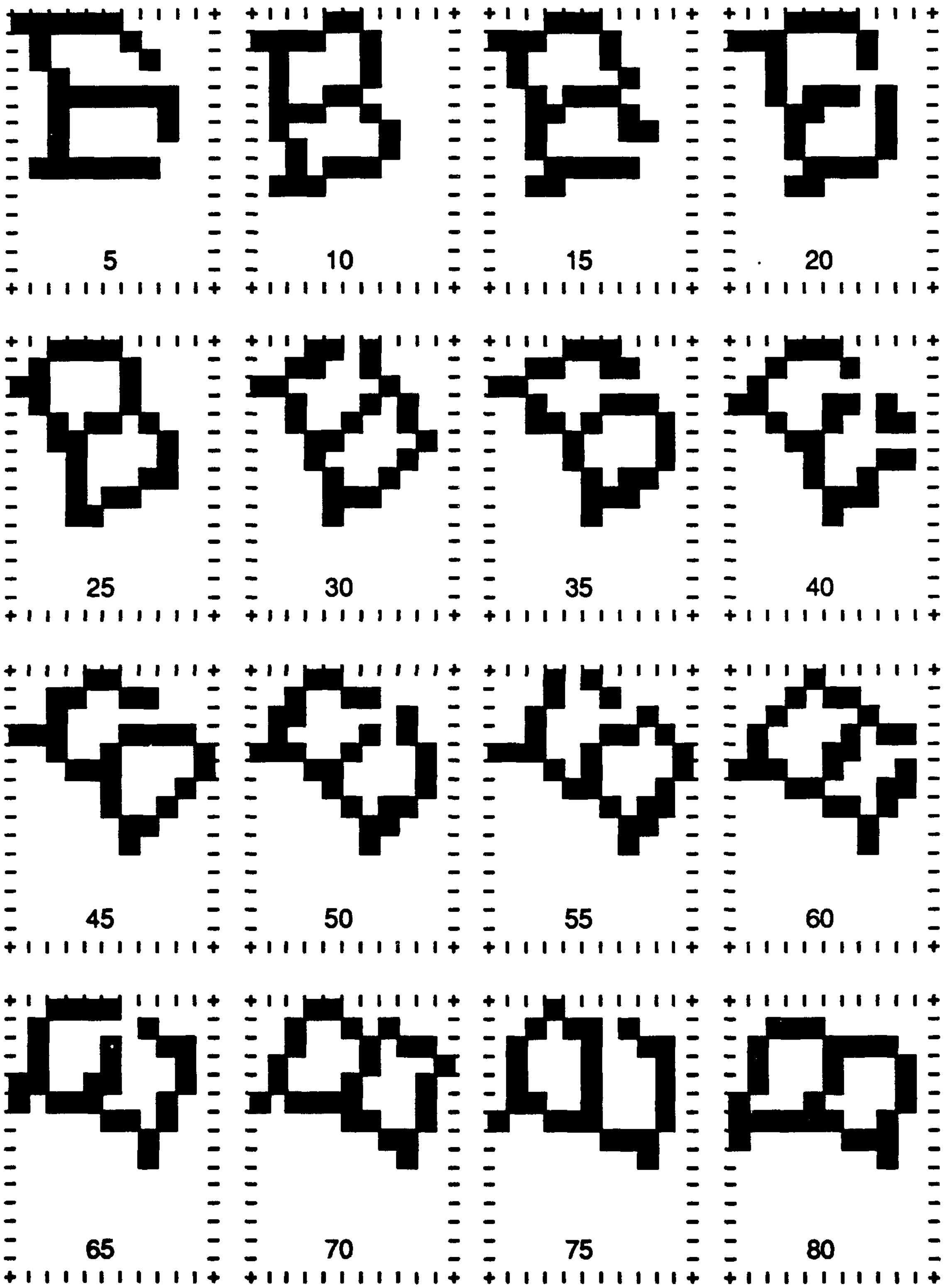

Figure 1. The effect of angle of rotation on character distortion.

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 are 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, 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 (i.e., the larger valued x and/or y coordinates) would therefore provide a dot position closer to the ideal position and less 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 caused by 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 fastest at 0° and 25° and slowest at 115° and 105°.

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 center because of less distortion. The results are best explained by considering subjects' search strategies. The subjects' eyes were fixated at 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 near 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.

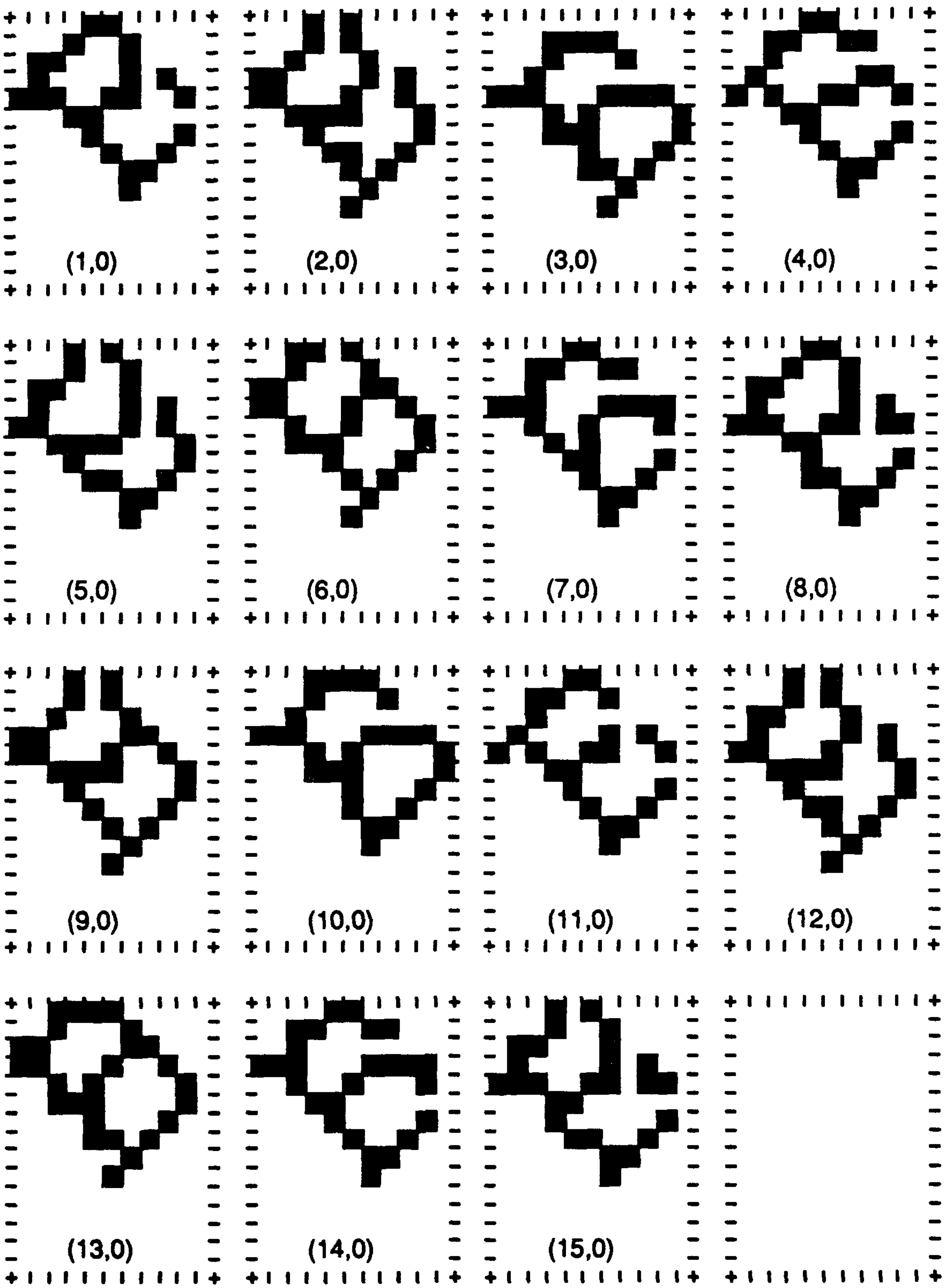

Figure 2. The effect of x distance from the center of rotation on character distortion.

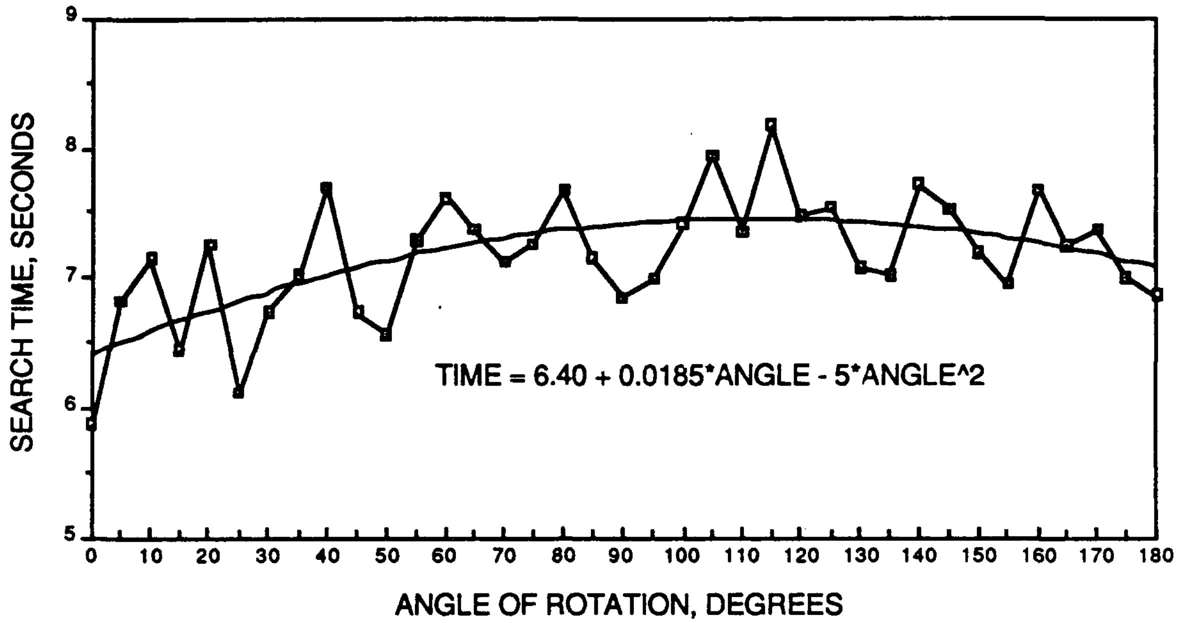

Figure 3. Mean response time as a function of angle of rotation (from Kurokawa et al., 1991).

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, 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 two-dimensional fourier analysis (Maddox, 1979). With this technique, the spatial frequency components of each character at various rotations could be determined and may provide a better description of the characters and 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 two characters and found moderate correlations with performance. Perhaps this latter technique should be attempted to characterize the difference between upright and rotated symbols.

It is difficult to draw conclusions regarding distortion and performance from the Kurokawa et al. (1991) 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 is 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 is 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 meet high and low familiarity criteria. 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 the subjects were given previous information about the character's identity or the character's orientation, 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 Shepard and Kuhn (1971, cited by Cooper & Shepard, 1973).

Matrix Size

The prior study (Kurokawa et al., 1991) clearly demonstrated the adverse effects of image rotation on visual search with dot-matrix displays. The design issue then becomes one of reducing (or eliminating) such effects. One candidate technique is that of processing the image by gray scale pixel modification to eliminate the "stair-stepping" or "scalloping" found in lines written at other than vertical, horizontal, and 45° to the vertical. As noted above, this approach is resource-intensive, requiring considerable processing as each image is rotated, however slightly. Other alternatives may be more desirable.

A well-established tradeoff in display legibility is that of using larger characters and/or matrices with greater numbers of dots to define the characters and symbols (e.g., Snyder & Maddox, 1978). In fact, current display standards (e.g., Human Factors Society, 1988) require a minimum character size as well as a matrix size of at least 7 x 9 dots when upper and lower case alphanumerics are used. As recognized in this body of research, increases from a minimum matrix size of 5 x 7 to as many as 15 x 21 dots tend to improve search performance for non-rotated characters, although minimum improvement is typically found beyond 11 x 15 dot matrix sizes. Nonetheless, this research clearly suggests that the use of larger matrices may reduce the adverse effects of character rotation.

OBJECTIVES

In keeping with the experimental plan for this program (Decker, Pigion, & Snyder, 1987), the objective of this experiment was to gain further understanding of the effects of image rotation on the use of dot-matrix characters and primarily to determine if the use of larger character matrices might reduce the distortion effects found by Kurokawa et al. (1991). Further, a second objective was to evaluate any particular effects caused by a larger target set which included standard U.S. Army symbols.

METHOD

Experimental Design

The experimental design was an 8 x 3 x 2 x 2 within-subjects factorial design. The variables being investigated were angle of rotation (0°, 15°, 45°, 70°, 95°, 105°, 140°, and 170°), matrix size (7 x 9, 9 x 11, and 11 x 15), direction of rotation (clockwise and counterclockwise), and distance from rotation center (0 to 200, 201 to 350 pixels).

For each of the 96 combinations of the four independent variables, each of 10 subjects participated in nine trials, for a total of 864 trials per subject, or 8,640 trials in the entire experiment. To assure uniform exposure to each of the 36 targets (described below), each subject searched for each target 864/36 = 24 times. These 24 trials per target per subject were assigned to the 24 angle-by-size combinations.

The 24 replications of each target per subject were randomly assigned among the four rotation-by-distance combinations, with the constraint that each subject had the required nine trials per factorial combination of all independent variables. That is, each subject received each target equally often (24 times), specifically once per angle-by-size combination, with that target assigned to one rotation-by-distance combination within the angle-by-size combination. Across all 36 targets, each subject thus received 36/4 or nine different targets for each of the rotation-by-distance combinations.

Across all 10 subjects, this design provided 90 trials per factorial combination of the four independent variables, with an average of 2.5 replications per target per factorial combination. (The assignment was constrained to assure either two or three replications.)

As a result, collapsing across targets, and assuming equivalent difficulty of the combinations of targets assigned per experimental condition, this design permits a full factorial analysis of the four independent variables. Any analysis of the target (character and symbol) effect and its interactions with other variables requires pooling the components of the interactions between subjects and the four independent variables.

Subjects

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

Apparatus

Stimuli were presented on a Tektronix GMA201 high resolution achromatic CRT with a 48-centimeter (cm) diagonal screen. Although the CRT had the capability to display 2048 x 2048 pixels, the active area was constrained to 1024 x 1024 pixels within an area 27.9 cm^2 because of bandwidth limitations of the graphics controller. The GMA201 has a nominal 0.19-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 $\pm$55 ms, built into the PC.

Subjects were seated in a dentist's hydraulic chair adjustable in height and distance from the CRT. Subjects were positioned at a distance of 50.8 cm from the CRT, and the angle of their gaze to the center of the display was 15° below the horizontal. The monitor was also tilted back 15° so that viewing was perpendicular to the display.

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). The alphanumerics were drawn in the Lincoln/MITRE font. The symbols were standard Army symbols redrawn as dot-matrix symbols. Figures 4 through 12 illustrate the letters, numerals, and symbols at each matrix size.

A search pattern was created by randomly selecting x,y screen coordinates for each of the 62 symbols, letters, and numerals, including the target, so that no symbols would overlap. The random pattern was then rotated around the center of the pattern. A new random pattern was created 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, Kelly, Kurokawa, & Snyder, 1991; Lloyd et al., 1991). The background luminance of the display was approximately 35 candelas per square meter (cd/m^2).

Photometric Measurements

Luminance and modulation levels were set using a photometric system which consisted of a GS-2110 scanning telemicroscope by Gamma Scientific with a 10- by 3000-micron slit aperture and a 1X 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.

Calibration

The display luminance was first set using the display brightness control so that the luminance level of an all-on field (255 bits) was 49.40 cd/m^2. This hardware brightness control was kept constant, and screen luminance was subsequently 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 vertical line was then 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 at least 30 minutes to provide luminance stability. The CRT was calibrated to a luminance of 49.4 cd/m^2 with an all-on field (255 bits). Ambient illumination was set to provide a uniform 15 cd/m^2 on the wall directly behind the CRT.

The experimental task was one of visual search for one randomly placed target among 61 randomly placed nontargets. This task was used because it was previously demonstrated to be sensitive of the variables of interest (Decker et al., 1987) and because of its relevance to operational situations.

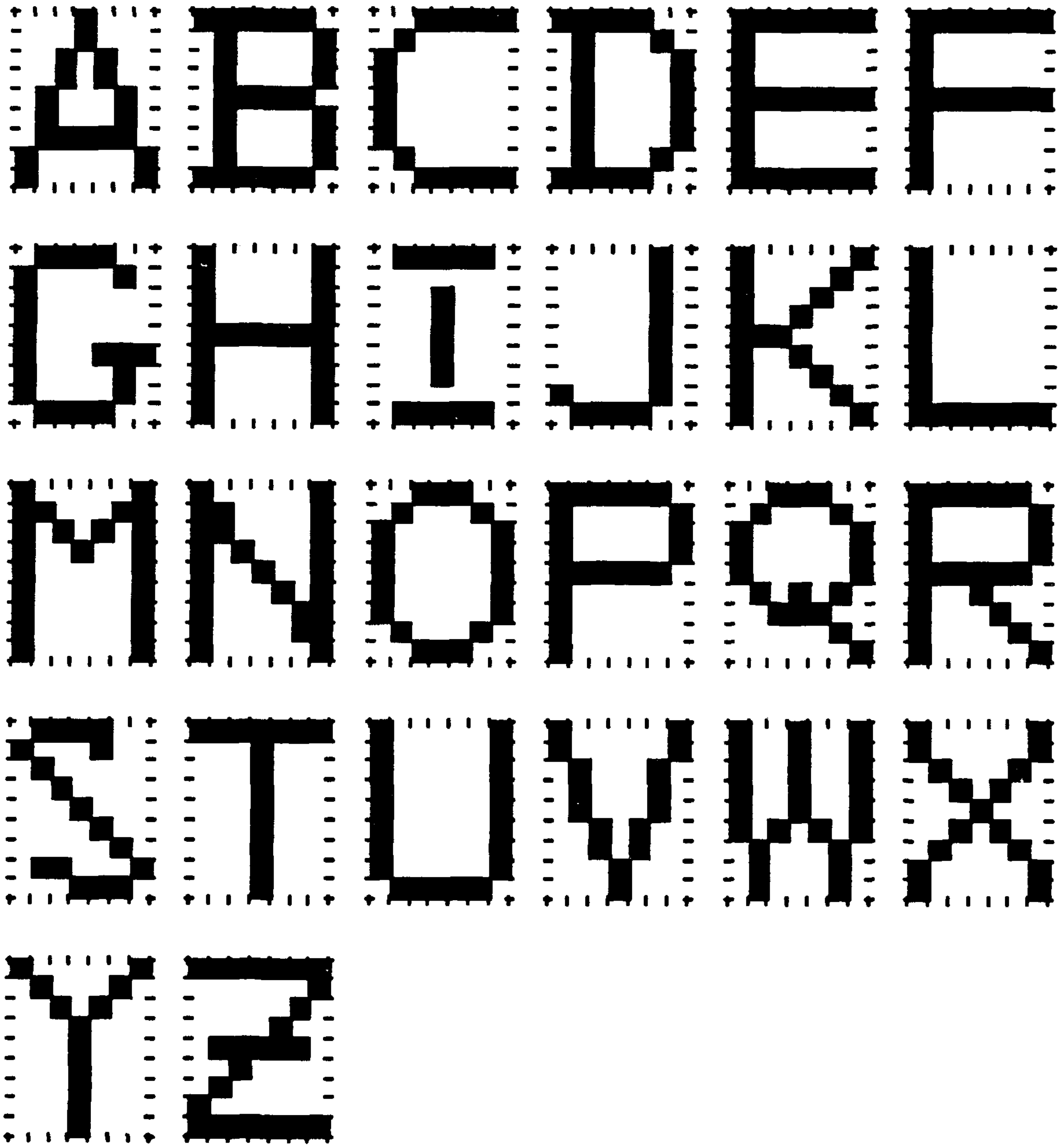

Figure 4. The letters at 7 x 9 matrix size.

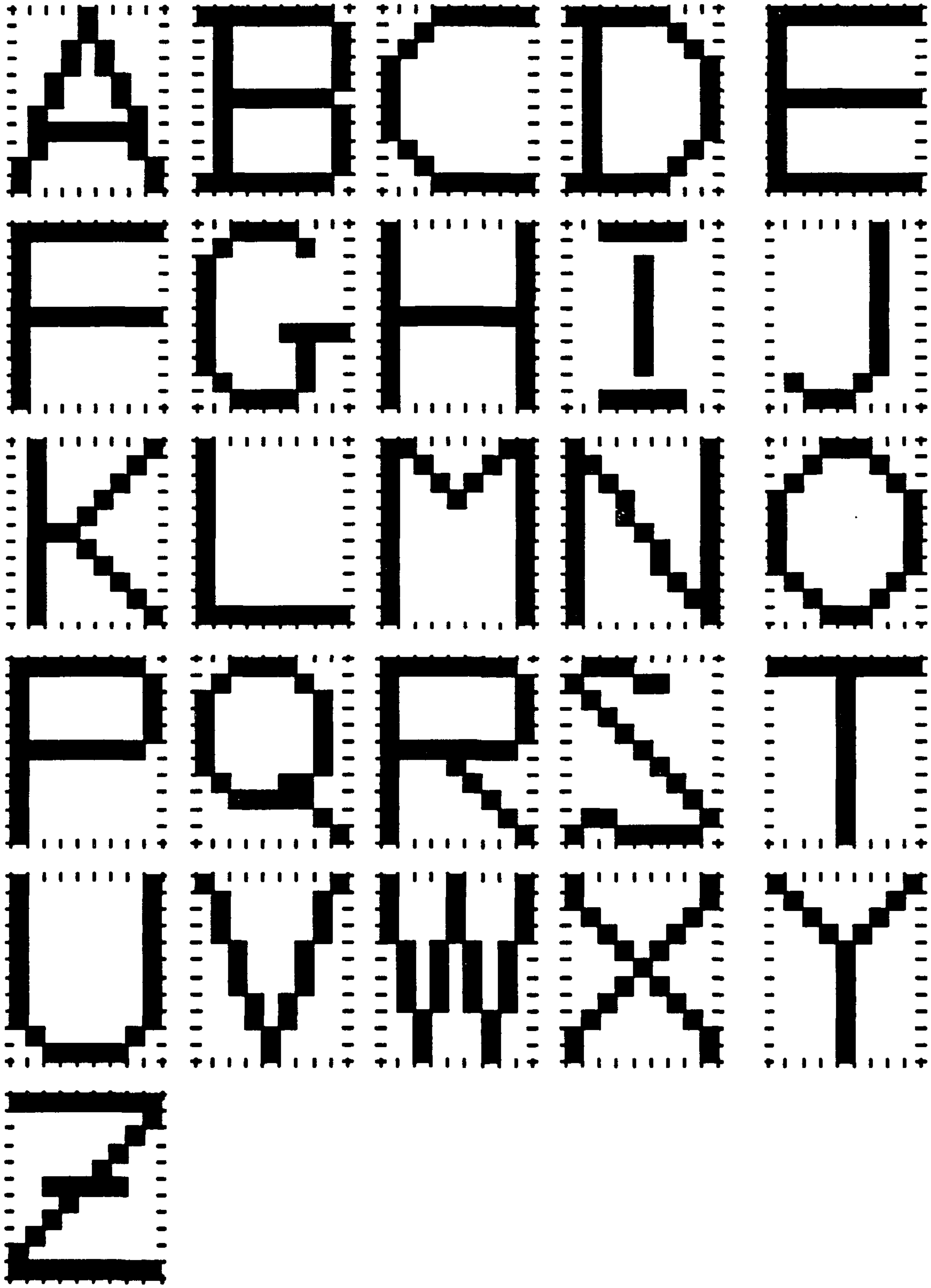

Figure 5. The letters at 9 x 11 matrix size.

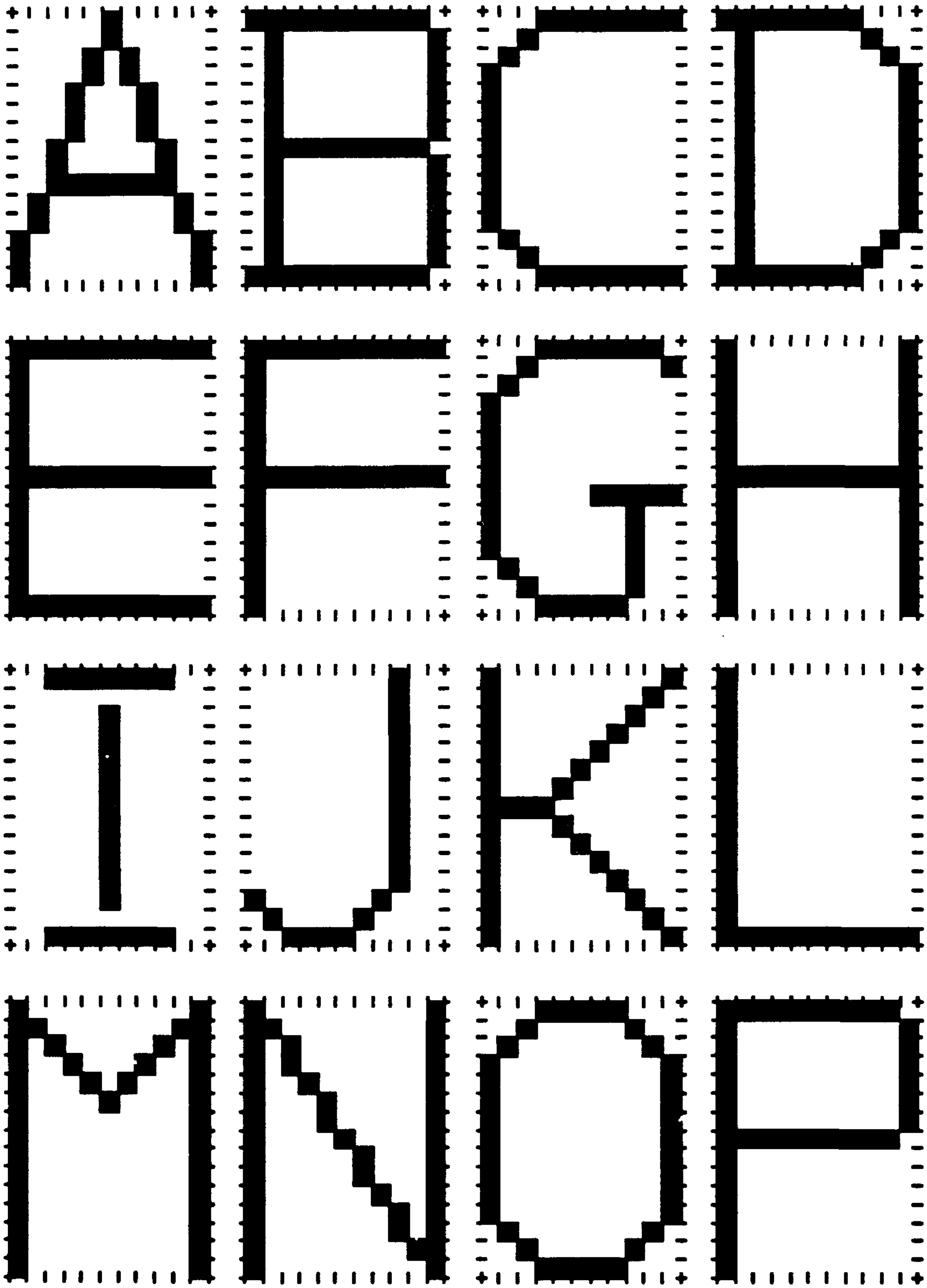

Figure 6. The letters at 11 x 15 matrix size.

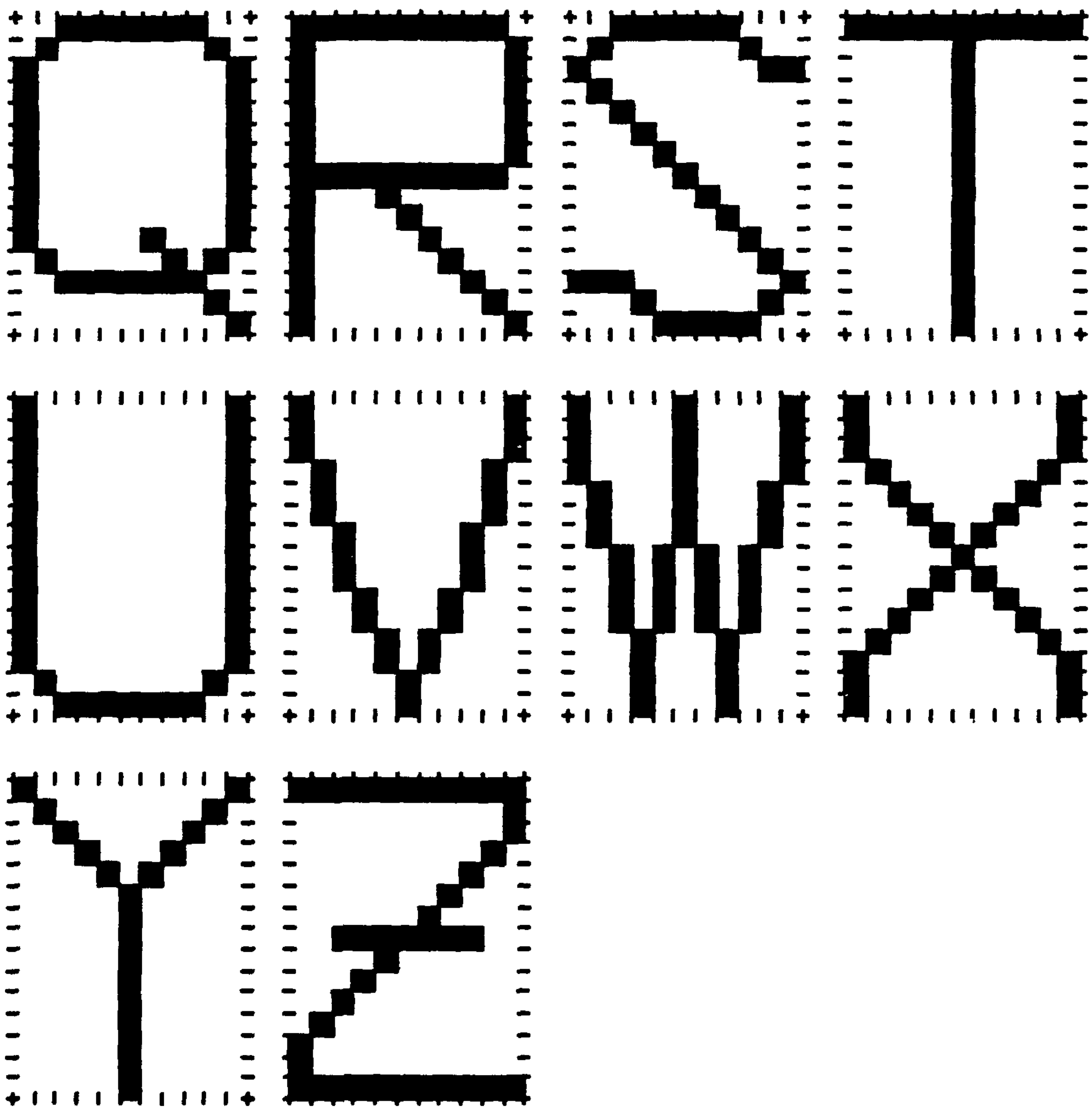

Figure 6 (continued).

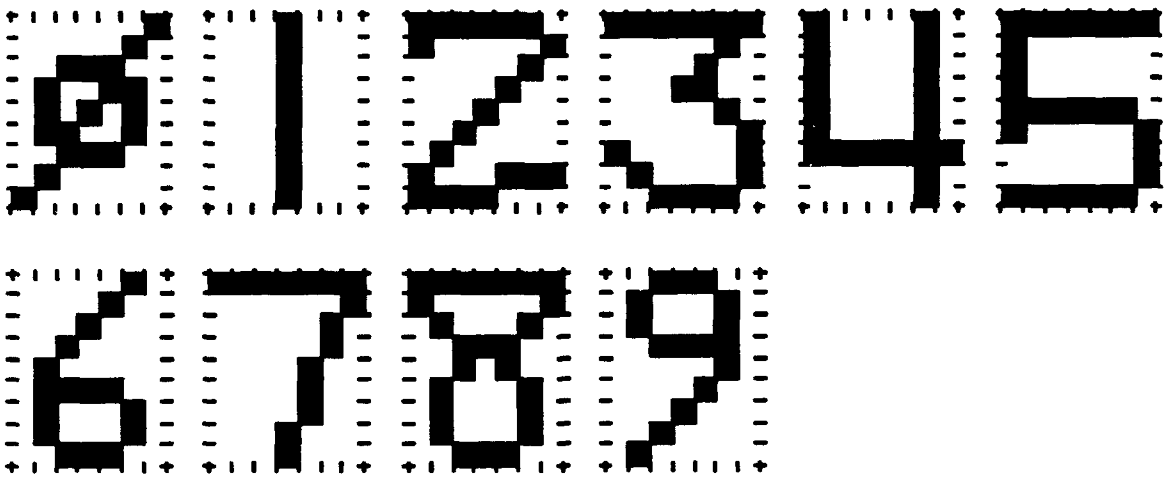

Figure 7. The numerals at 7 x 9 matrix size.

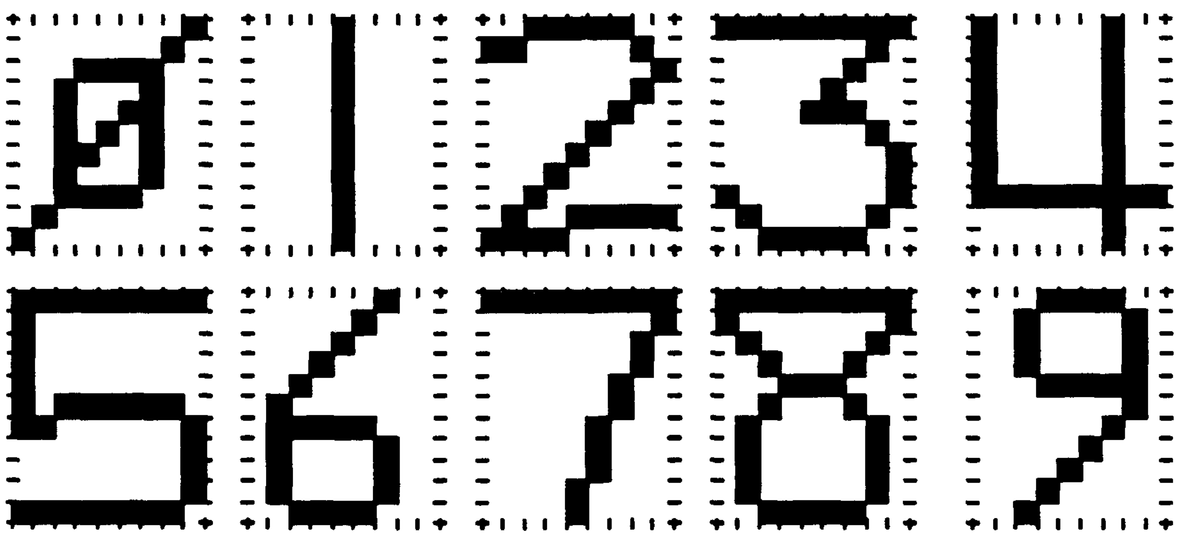

Figure 8. The numerals at 9 x 11 matrix size.

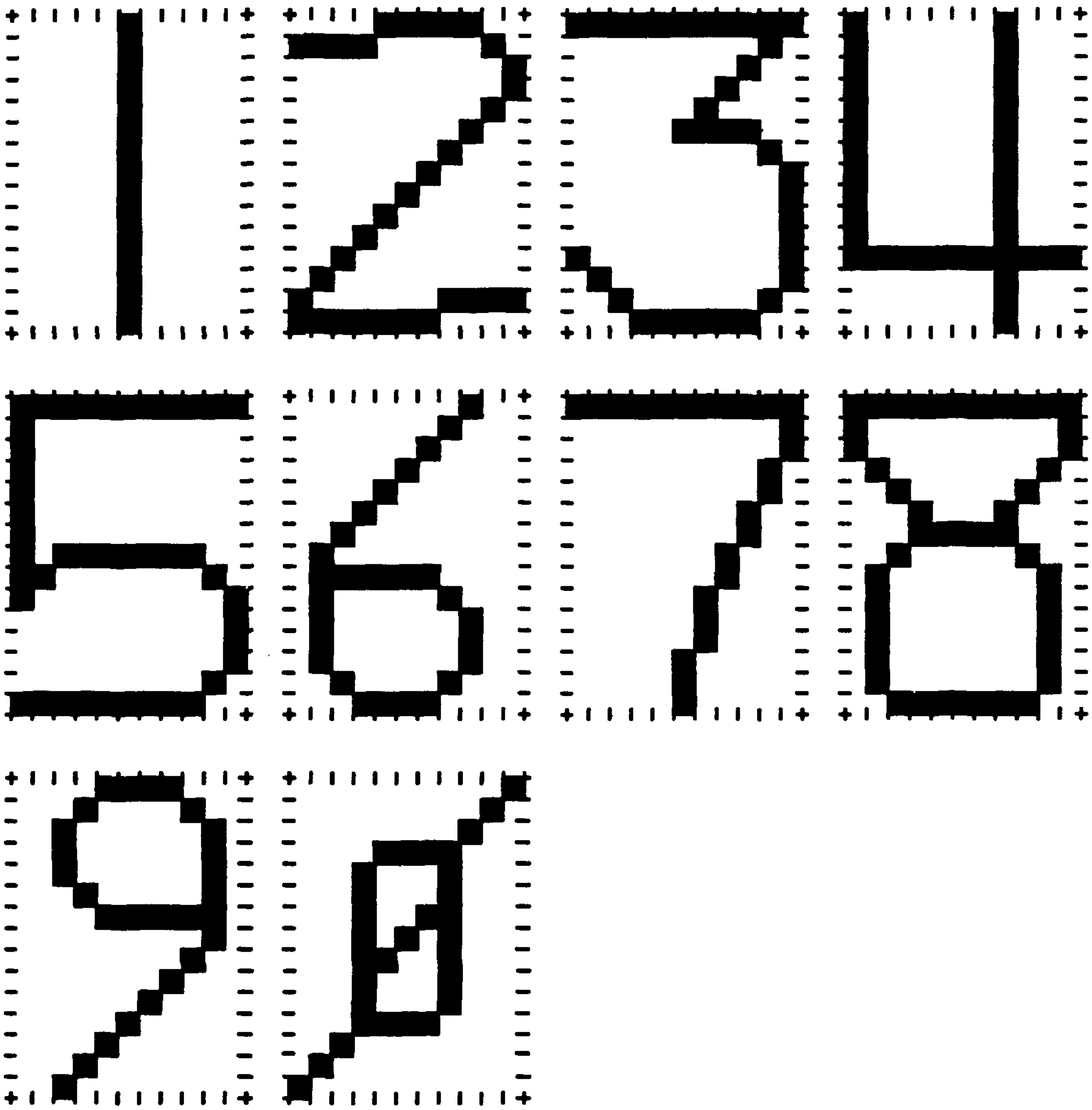

Figure 9. The numerals at 11 x 15 matrix size.

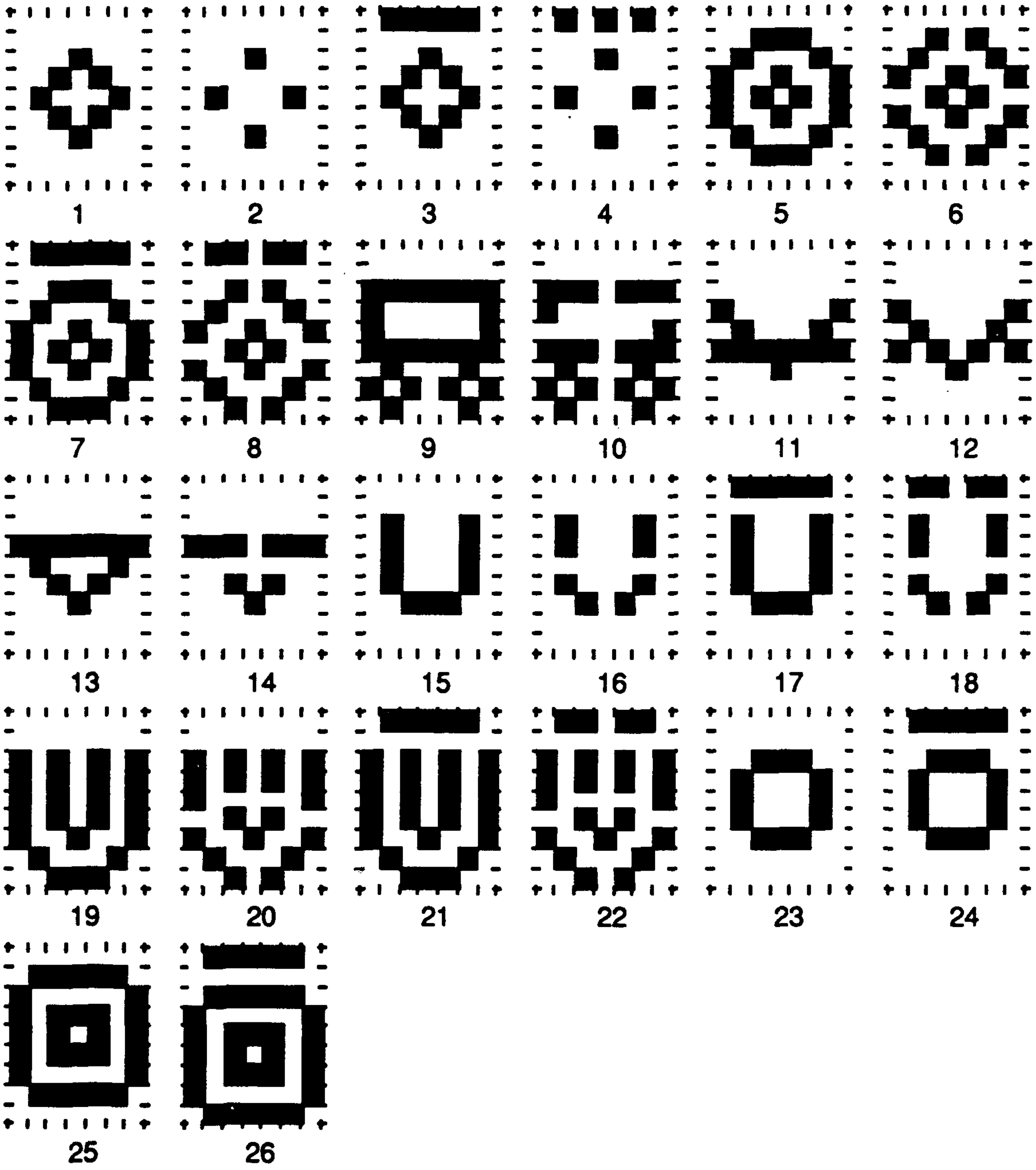

Figure 10. The 26 Army symbol targets at 7 x 9 matrix size.

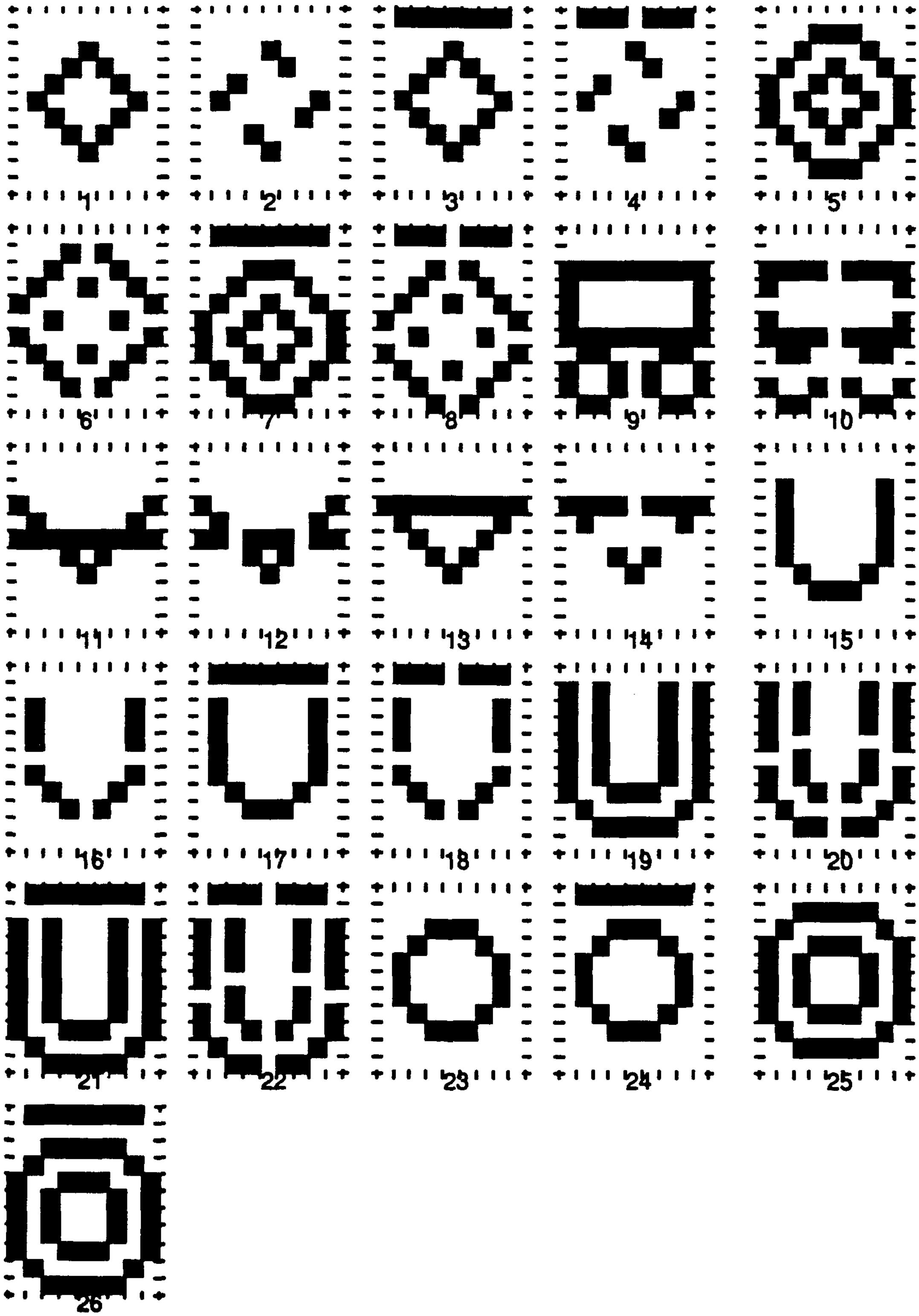

Figure 11. The 26 Army symbol targets at 9 x 11 matrix size.

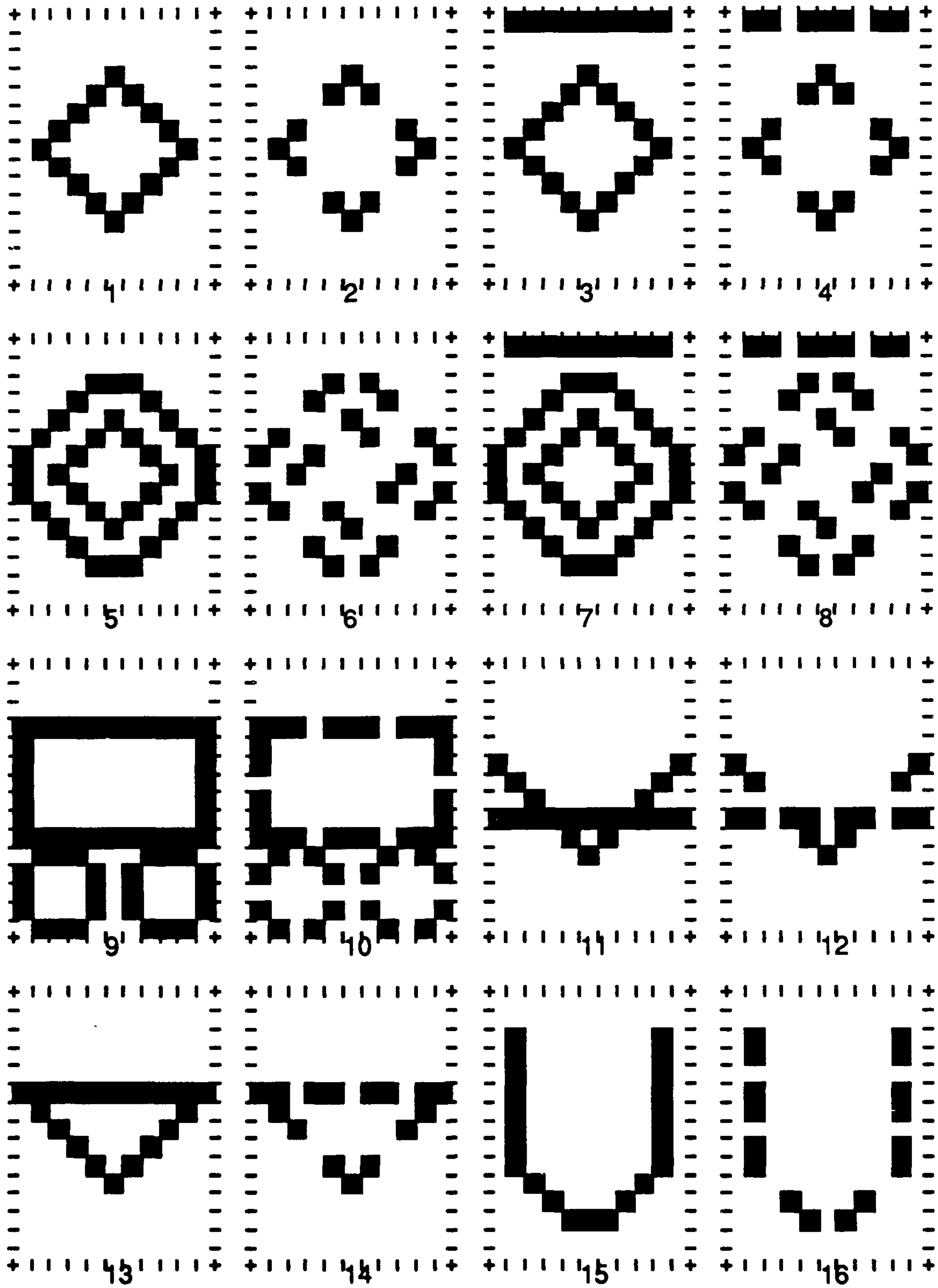

Figure 12. The 26 Army symbol targets at 11 x 15 matrix size.

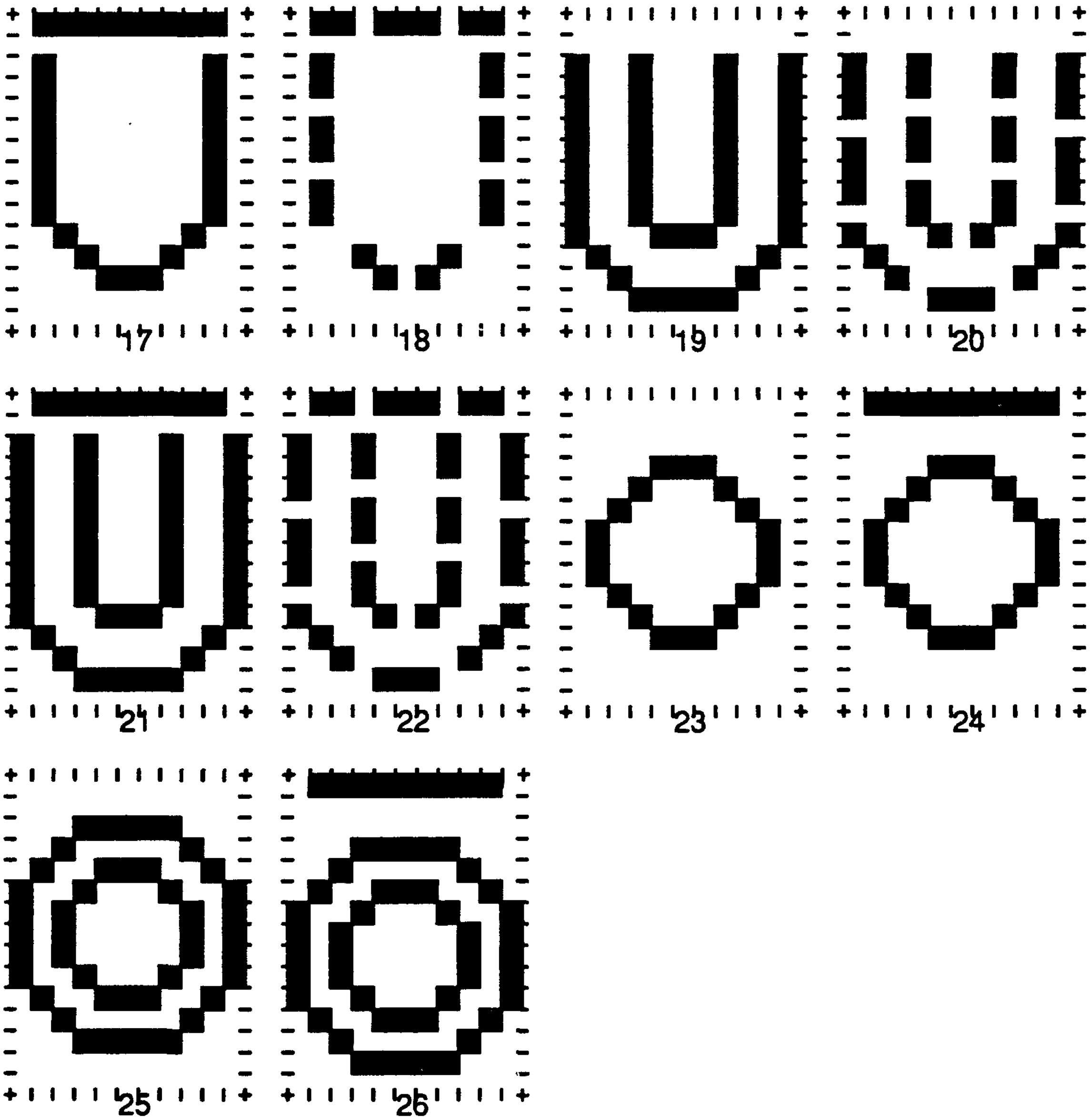

Figure 12 (continued).

On the first day of the experiment, the subjects read a written 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 (see Appendix) and were asked to read them silently as the experimenter read them aloud. Subjects were then given 5 minutes to become familiar with the 26 Army symbols, which were presented on the CRT and on a sheet of paper. Subjects were instructed to pay careful attention to the differences among the symbols.

Subjects then 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 was also displayed which designated the rotation angle for that trial. 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-hand button on the mouse input device which started the timer. The screen was filled with a random pattern of the symbols, including the target. Subjects searched the screen for the target. Upon location of the target, subjects pressed the left-hand button on the mouse input device, which stopped the timer and erased the screen. A blocking pattern was then displayed briefly, followed by a nine-cell grid resembling a tic-tac-toe pattern. Each of the nine cells was numbered and the subjects were asked to report the number of the cell in which the target appeared. The experimenter entered the subjects' verbal response into the computer after each trial. Search time was recorded automatically by the PC.

RESULTS

Search Time

For each subject, the mean response time of the nine trials per experimental condition was calculated and used in an analysis of variance (ANOVA). In this and the subsequent ANOVAs, significant ($p < .05$) within-subject sources of variance were checked against violation of the sphericity assumption using minimum (worst case) degrees of freedom (Winer, 1971). When the minimum degrees of freedom calculation resulted in a nonsignificant result, Greenhouse and Geisser (1959) ε calculations were performed and the degrees of freedom were adjusted accordingly.

The results of the ANOVA of the response time data are summarized in Table 1. Post hoc simple effect F tests were performed for significant interactions, and Newman-Keuls comparison tests were used for significant main effects.

Rotation angle

Figure 13 illustrates the rotation angle effect, which shows that search time is minimal at the vertical 0° angle and generally is greater at all other angles. The Newman-Keuls test (see Table 2) confirms that search times for all rotated positions do not vary significantly ($p > .05$). While the dip in search time at 95° is suggestive, it is not statistically significant.

Matrix size

As expected, larger matrix sizes produce shorter search times, as illustrated in Figure 14. All differences between means are significant (see Table 3).

Matrix size by rotation angle interaction

The rotation angle effect is somewhat different for each matrix size (see Figure 15), being less in magnitude as the matrix size increases. At 0° rotation, the search times for all three sizes are not significantly different (see Table 4). However, at all other rotation angles, size has a significant effect (see Table 4). Thus, the effects of distortions created by angular rotation can be reduced by increasing matrix size.

Table 1

Analysis of Variance Summary Table for Search Time

Source of variance	*df*	*MS*	*F*	*p*
Subjects (S)	9	169.53		
Angle (A)	7	113.85	10.01	0.0001*
S x A	63	11.37		
Size (SZ)	2	735.99	29.13	0.0001*
S x SZ	11	25.27		
Distance (D)	1	29.78	2.01	0.1904
S x D	9	1.51		
Direction (DIR)	1	5.26	1.21	0.3003
S x DIR	9	4.36		
A x SZ	14	24.57	2.65	<0.01 **
S x A x SZ	126	9.28		
A x D	7	5.75	0.82	0.5753
S x A x D	63	7.02		
A x DIR	7	5.46	0.78	0.6060
S x A x DIR	63	6.99		
SZ x D	2	2.85	0.52	0.6046
S x SZ x D	18	5.51		
SZ x DIR	2	17.89	2.53	0.1075
S x SZ x DIR	18	7.07		
D x DIR	1	4.16	0.49	0.5007
S x D x DIR	9	8.46		
A x SZ x D	14	7.58	1.29	0.2224
S x A x SZ x D	126	5.87		
A x SZ x DIR	14	6.34	0.84	0.6245
S x A x SZ x DIR	126	7.54		
SZ x D x DIR	2	11.54	3.57	<0.05 ***
S x SZ x D x DIR	18	3.23		
A x D x DIR	7	5.45	0.95	0.4724
S x A x D x DIR	63	5.71		
A x SZ x D x DIR	14	4.05	0.61	0.8531
S x A x SZ x D x DIR	126	6.64		
TOTAL	959			

* $p < .01$ with lower bound Greenhouse and Geisser (1959) correction
** Greenhouse and Geisser (1959) $\varepsilon = 0.7936$
***Greenhouse and Geisser (1959) $\varepsilon = 0.7647$

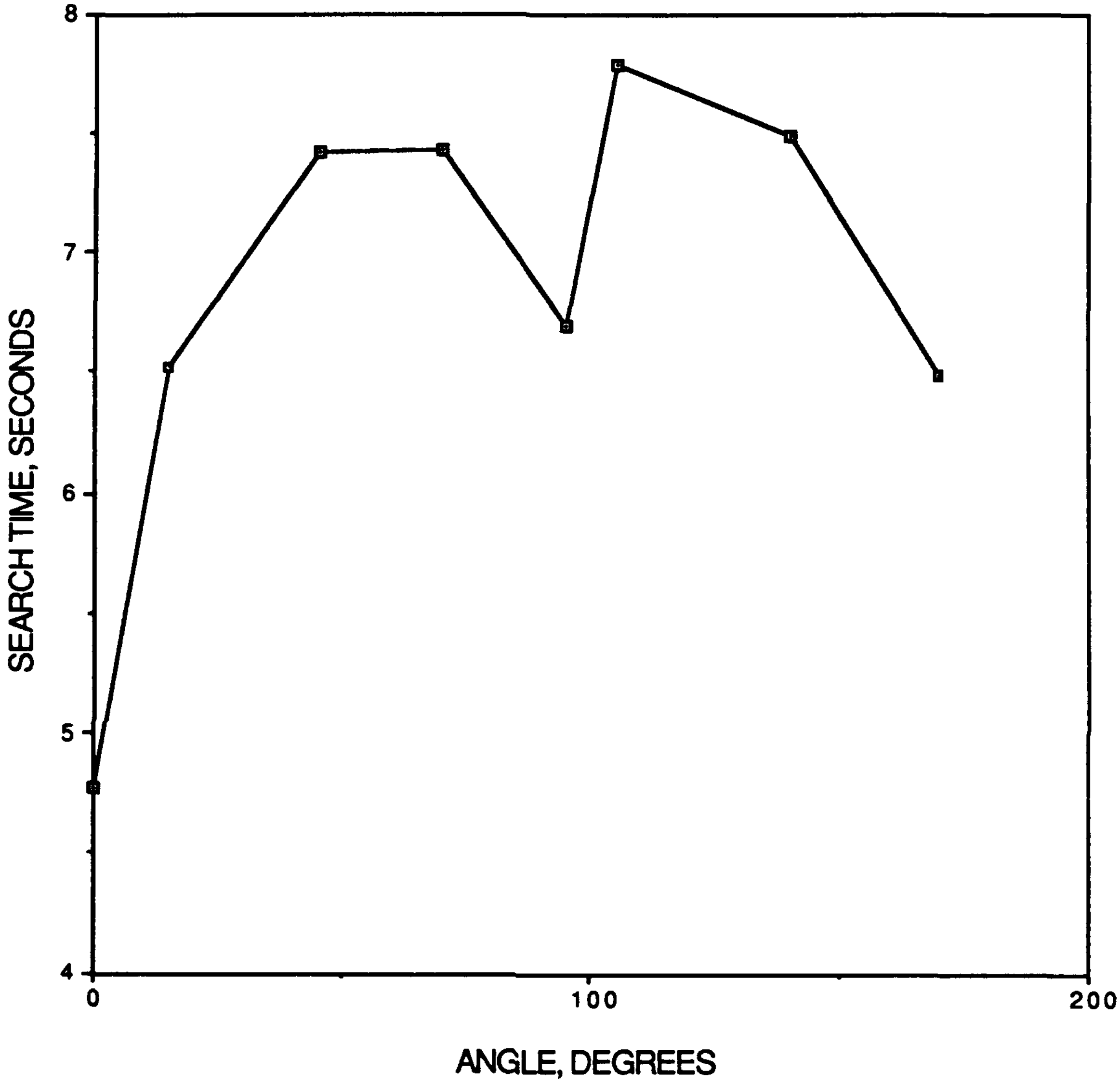

Figure 13. The effect of rotation angle on search time.

Table 2

Newman-Keuls Test for Angle Differences

Angle	Search time, seconds		
105	7.79	A	
45	7.49	A	
140	7.47	A	
70	7.40	A	
95	6.62	A	
170	6.50	A	
15	6.48	A	
0	4.76		B

Note. Means with the same letter are not significantly different, $p > 0.05$.

Table 3

Newman-Keuls Test for Matrix Size Differences

Size	Search time, seconds			
7 x 9	8.39	A		
9 x 11	6.68		B	
11 x 15	5.37			C

Note. Means with the same letter are not significantly different, $p > 0.05$.

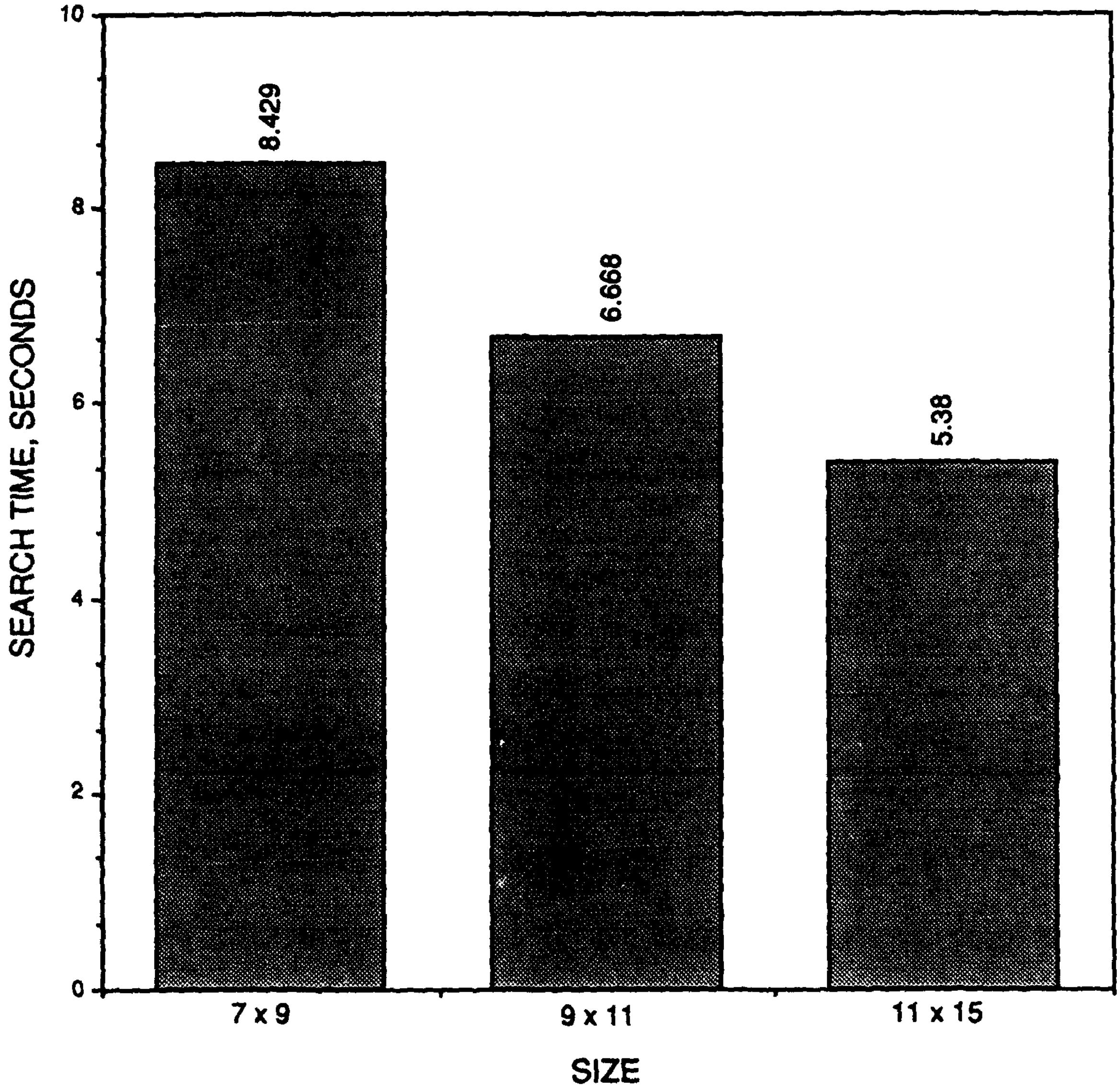

Figure 14. The effect of matrix size on search time.

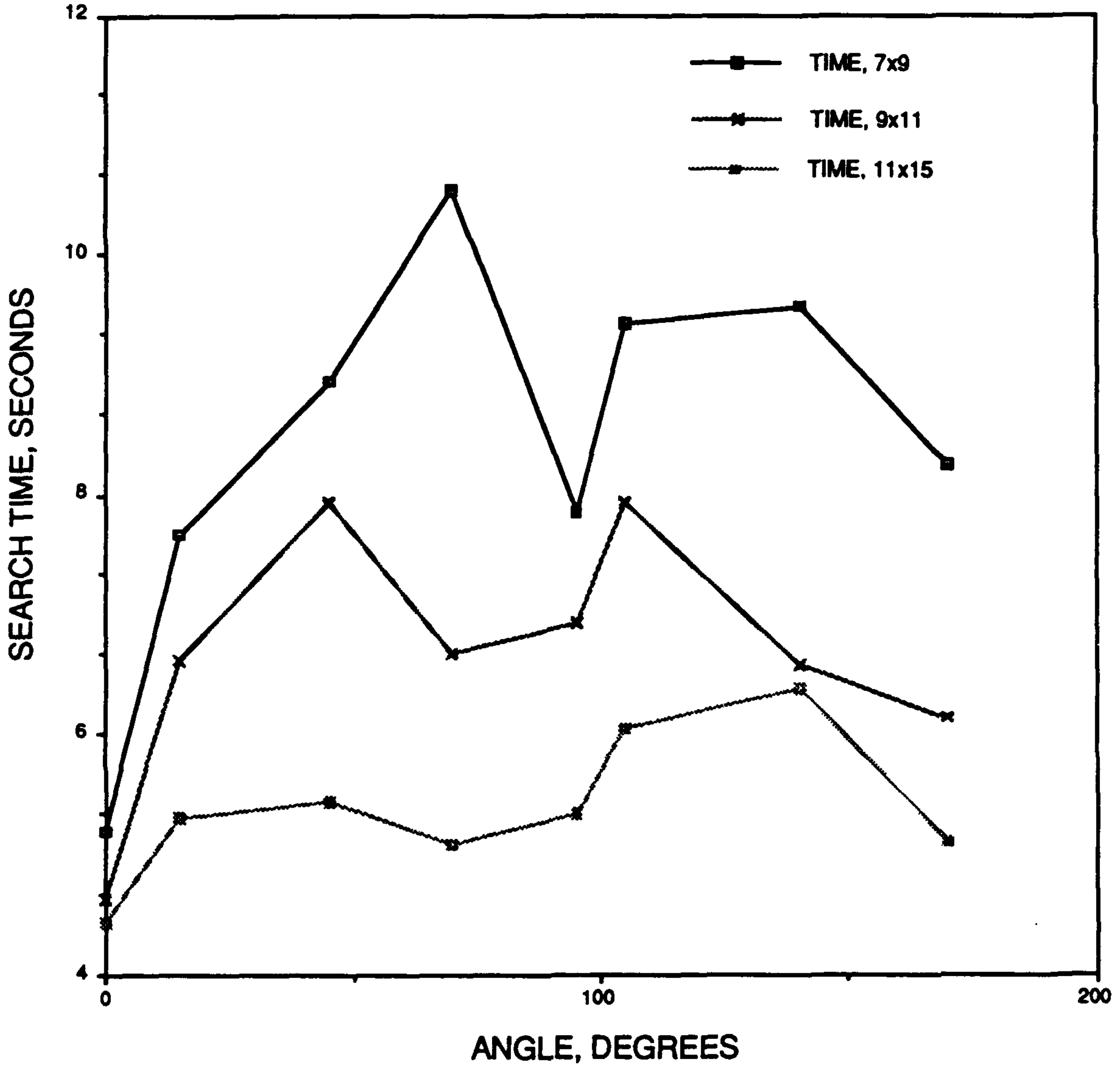

Figure 15. The effect of matrix size by rotation angle interaction on search time.

Table 4

Simple Effect F Test for Size at Each Angle

Source of variance	*df*	*MS*	*F*	*p*
Size at Angle 0	2	5.89	0.63	> .05
Size at Angle 15	2	56.81	6.12	< .01
Size at Angle 45	2	137.40	14.80	< .01
Size at Angle 70	2	299.76	32.29	< .01
Size at Angle 95	2	58.94	6.35	< .01
Size at Angle 105	2	124.05	13.37	< .01
Size at Angle 140	2	123.02	13.25	< .01
Size at Angle 170	2	102.10	11.00	< .01
Size x Angle x Subjects	126	9.28		

Search Accuracy

Table 5 summarizes the ANOVA results on the percentage of correct responses, the percentages that were correct of all nine responses per subject under each experimental condition. As seen in this table, only three main effects and no interactions were statistically significant ($p < .05$).

Rotation angle

The effect of angle on accuracy, essentially a mirror image of the search time effect, is illustrated in Figure 16. The greatest accuracy occurs with vertical (0° rotation) images; moreover, all rotated positions produce significantly fewer correct responses (see Table 6). The 95° position is significantly better than the 45°, 105°, and 140° rotations. This result suggests that the 95° dip in response time (see Figure 13), while not statistically significant, is perhaps indicative of a real effect, that the 95° position is close enough to 90° that minimal distortion occurs.

Matrix size

Increases in matrix size provide accuracy improvements (see Figure 17), with all increases being statistically significant (see Table 7). This effect is also very consistent with the improvements in search time found with increasing matrix size.

Direction of rotation

Symbols rotated clockwise produced significantly higher accuracy rates, as illustrated in Figure 18. That is, when the top of the symbols were rotated to the right (rather than to the left) from the vertical position, accuracy increased very slightly (less than 2%). No supportable reason for this difference is known, although it seems likely that practice from a population stereotype (e.g., book titles on a bookshelf) may be at work.

Table 5

Analysis of Variance Summary Table for Response Accuracy

Source of variance	*df*	*MS*	*F*	*p*
Subjects (S)	9	0.4742		
Angle (A)	7	0.2687	15.12	0.0001*
S x A	63	0.0178		
Size (SZ)	2	0.6290	20.89	0.0001*
S x SZ	11	0.0301		
Distance (D)	1	0.3779	1.12	0.3169
S x D	9	0.3366		
Direction (DIR)	1	0.1045	8.23	0.0185
S x DIR	9	0.0127		
A x SZ	14	0.0152	0.91	0.5516
S x A x SZ	126	0.0167		
A x D	7	0.0196	1.35	0.2406
S x A x D	63	0.0144		
A x DIR	7	0.0083	0.45	0.8644
S x A x DIR	63	0.0184		
SZ x D	2	0.0161	1.14	0.3424
SX SZ x D	18	0.0141		
SZ x DIR	2	0.0280	1.79	0.1962
SX SZ x DIR	18	0.0157		
D x DIR	1	0.0081	1.62	0.2349
S x D x DIR	9	0.0050		
A x SZ x D	14	0.0170	1.12	0.3506
S x A x SZ x D	126	0.0152		
A x SZ x DIR	14	0.0189	1.10	0.3658
S x A x SZ x DIR	126	0.0172		
SZ x D x DIR	2	0.0059	0.55	0.5860
S x SZ x D x DIR	18	0.0108		
A x D x DIR	7	0.0154	1.24	0.2952
S x A x D x DIR	63	0.0125		
A x SZ x D x DIR	14	0.0169	1.11	0.3585
S x A x SZ x D x DIR	126	0.0153		
TOTAL	959			

*$p < .01$ with lower bound Greenhouse and Geisser (1959) correction

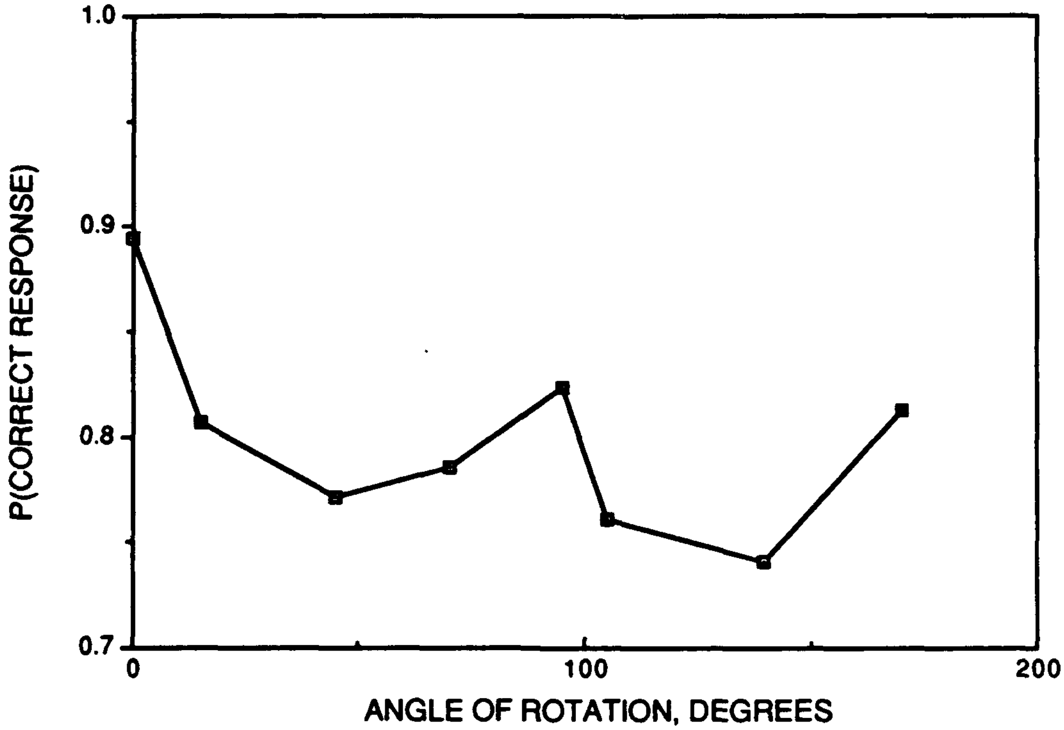

Figure 16. The effect of rotation angle on correct responses.

Table 6

Newman-Keuls Test Results for Angle

Angle	Probability of a correct response				
0	0.8944	A			
95	0.8225		B		
170	0.8119		B	C	
15	0.8066		B	C	
70	0.7857		B	C	D
45	0.7717			C	D
105	0.7604				D
140	0.7407				D

Note. Means with the same letter are not significantly different, $p > 0.05$.

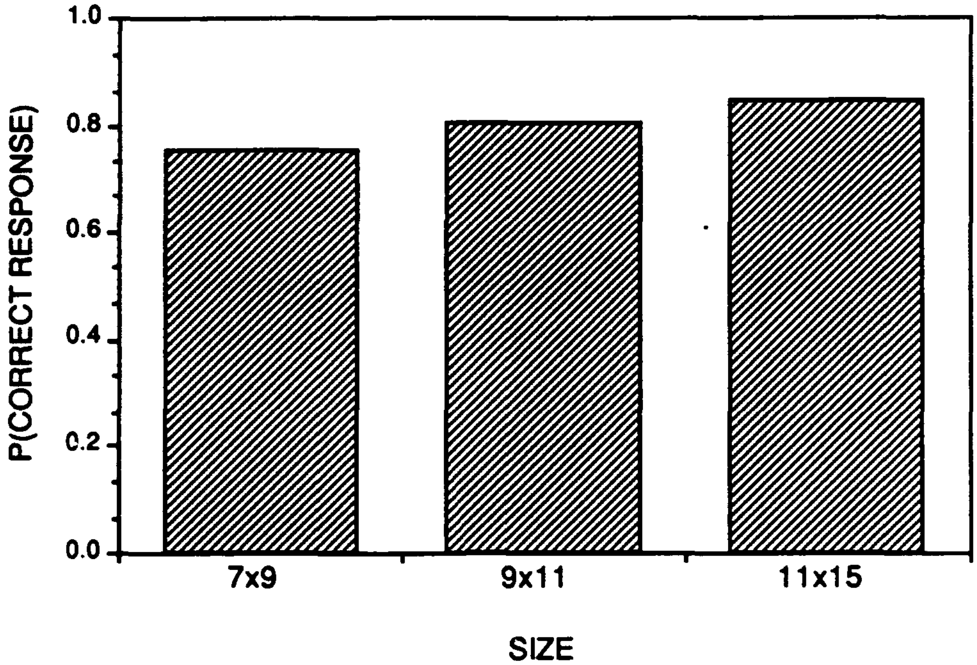

Figure 17. The effect of matrix size on response accuracy.

Table 7

Newman-Keuls Test Results for Matrix Size

Size	Percent correct responses			
11 x 15	0.8419	A		
9 x 11	0.8025		B	
7 x 9	0.7534			C

Note. Means with the same letter are not significantly different, $p > 0.05$.

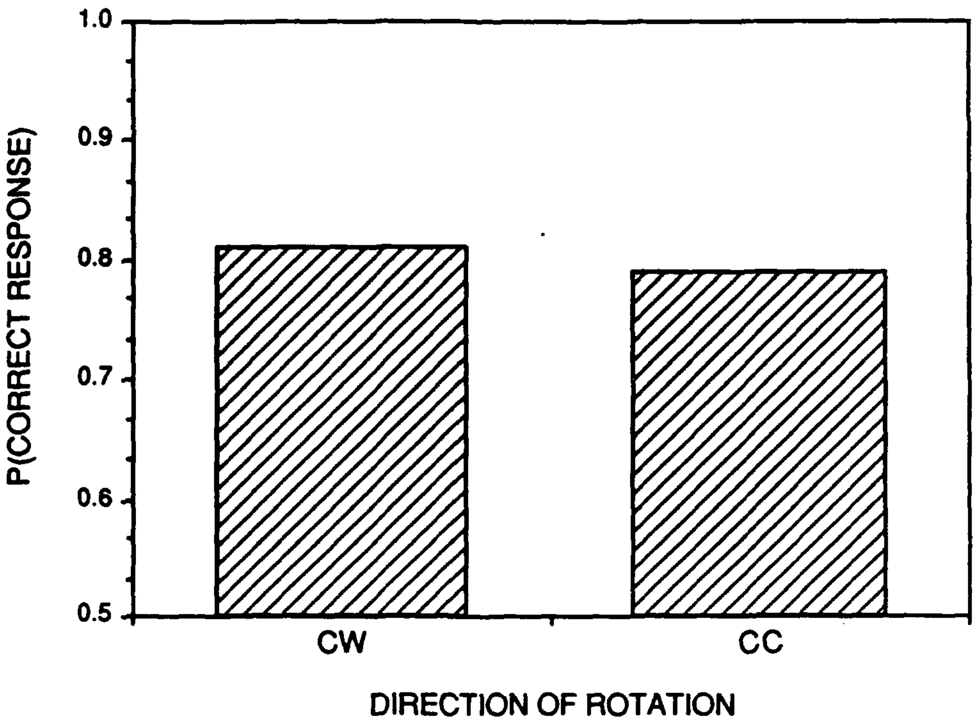

Figure 18. The effect of direction of rotation on response accuracy.

Character and Symbol Effects

While the 36 characters and symbols were not factorially combined with the other independent variables in this experiment, they were assigned with the constraint of at least two and no more than three replications of each character or symbol per factorial combination of the four independent variables. Assuming this random assignment of targets per condition to produce equal difficulty per condition, it is possible to analyze the effects of character-symbol differences on performance using an ANOVA with a pooled error term. Figure 19 illustrates the overall character-symbol effect on search time ($F_{35,\ 5330} = 48.89$, $p < .0001$). As indicated, there are very large differences in search times across the 36 targets, with the very familiar alphanumerics producing the shortest search times and the less familiar Army symbols yielding the longer search times. Symbols 17 and 18 have the longest search times, probably because of their similarities to one another and the need for subjects to be careful in identifying them, particularly in the rotated positions. Similarly, symbols 3 and 24 are nearly alike and thus produced longer search times.

While there is no statistically significant rotation angle-by-character interaction, several interactions with the character variable are significant. The most meaningful one of these significant interactions is the character-by-size interaction ($F_{70,\ 5330} = 3.18$, $p < .0001$), illustrated in Figures 20 through 22. As these figures show, longer search times are consistently associated with the smaller matrix sizes. As matrix size increases, the same generally short search times are found for the familiar alphanumerics, and longer search times with the Army symbols. The most difficult symbols (3, 17, 18, and 24) for the 7 x 9 matrix are generally the most difficult for the larger matrices, although the difficulty with symbol 3 is clearly reduced with the 9 x 11 size and virtually eliminated with the 11 x 15 matrix size. Thus, evidence clearly exists that increased matrix size can ameliorate the effects of symbols under the more difficult search conditions. Moreover, these results suggest that the geometric constraints of smaller matrix sizes can alter symbol uniqueness to the point of creating greater similarity to other symbols and therefore reduce visual task performance.

In general, the results of analyses of character-symbol accuracy data are consistent with those of search time and are not repeated here.

DISCUSSION AND CONCLUSIONS

Rotation Effects

In general, the obtained effects of display or character rotation agree with those of previous studies (e.g., Kurokawa et al., 1991; Vanderkolk, 1976). The best visual search performance was obtained for nonrotated (0°) characters, and the minimal degradation in accuracy but not search time was found at 95° of rotation. Presumably, this latter result relates both to the relative ease of a 90° mental rotation and to the lesser distortion of characters near the 90° axis.

Character and Matrix Size

As expected and consistent with prior studies, increases in matrix-character size led to decreases in search time and increases in search accuracy, each size difference being statistically significant for both dependent variables. Increases from the 7 x 9 size to the 9 x 11 and 11 x 15 sizes led to reductions in search time of 21% and 36%, respectively, while the same size increases led to 6.5% and 11.7% increases in accuracy.

Clearly, these improvements in performance, practically as well as statistically, strongly argue for the use of larger character and matrix sizes when display rotation is expected. The largest characters (11 x 15 dots) subtended 18 by 25 arcminutes, an angular size found nearly optimal for visual search under nonrotated conditions (Snyder & Maddox, 1978).

While the present study does not permit the separation of the effects of matrix size from those of character size, such a distinction is not always meaningful. First, it is clear that larger characters produce improved search and recognition performance, even if matrix size is held constant (Snyder & Maddox, 1978). Secondly, from a design perspective, pixel spacing is dictated by hardware constraints for a given flat panel display or technology; therefore, the only way to obtain larger characters is to use a larger matrix of dots and vice versa. Hence, in the real world of flat panel displays, these variables are nearly always totally confounded, and the present results apply directly to the design issue.

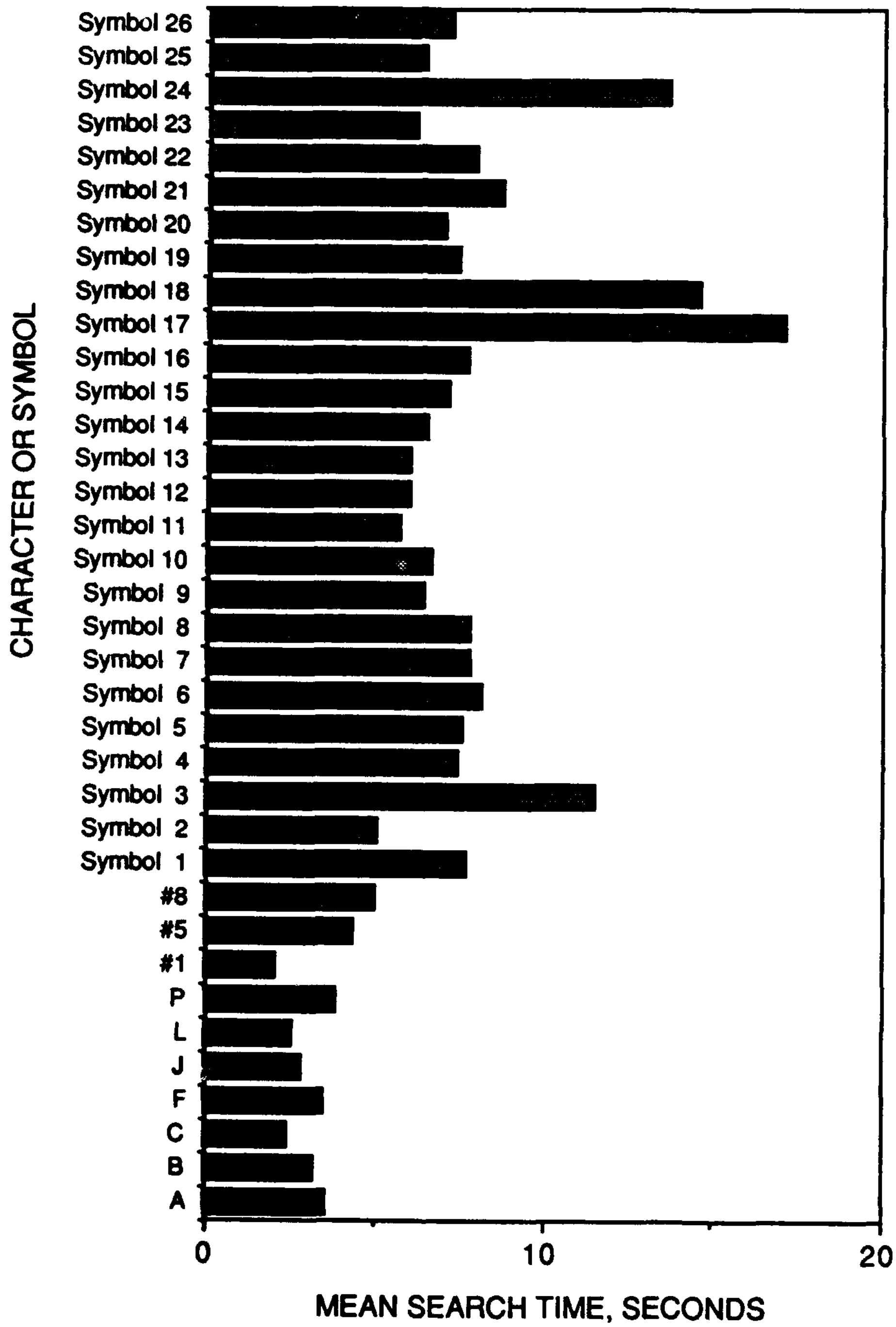

Figure 19. The effect of character or symbol on mean search time.

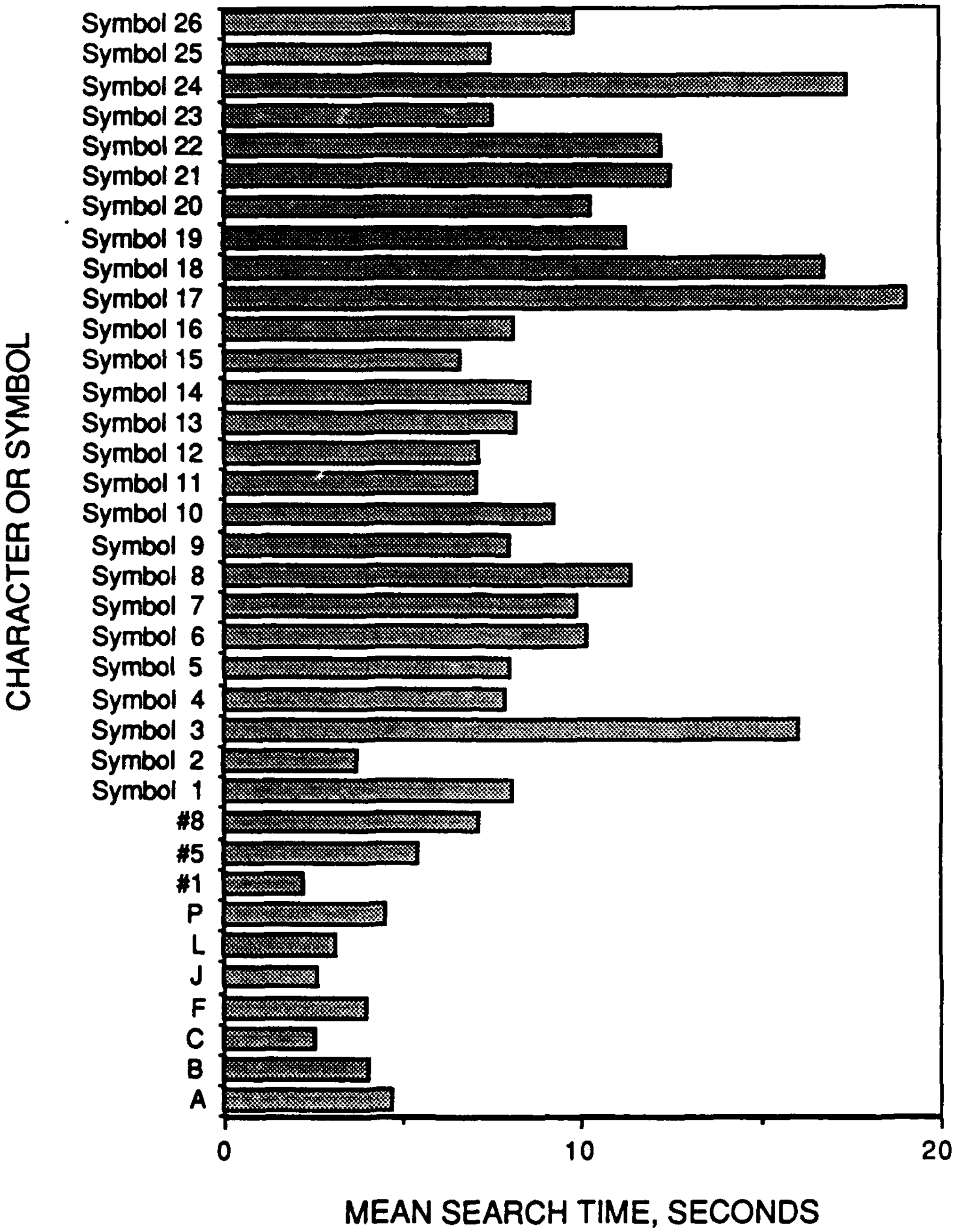

Figure 20. The effect of character or symbol on search time, 7 x 9 matrix size.

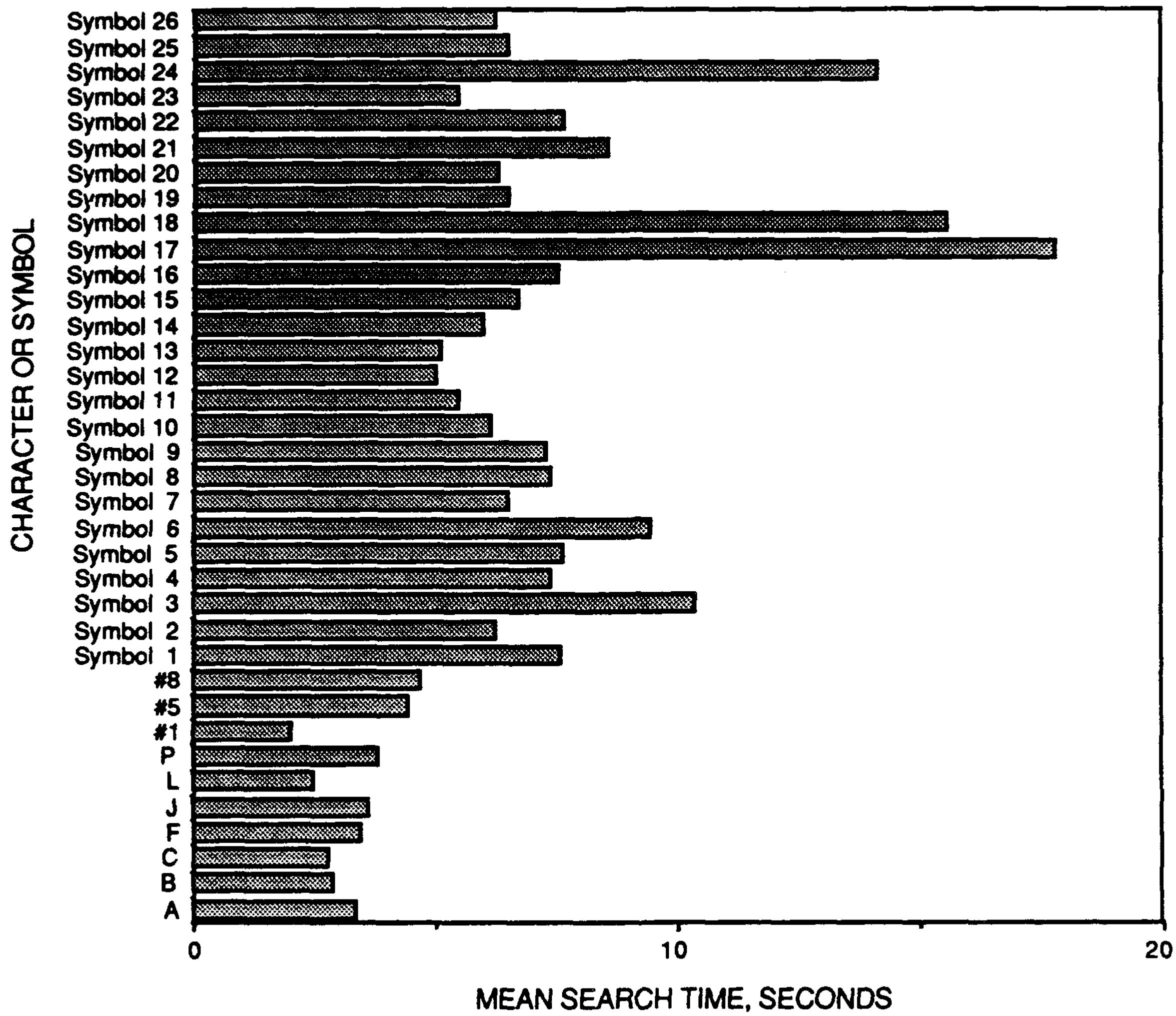

Figure 21. The effect of character or symbol on search time, 9 x 11 matrix size.

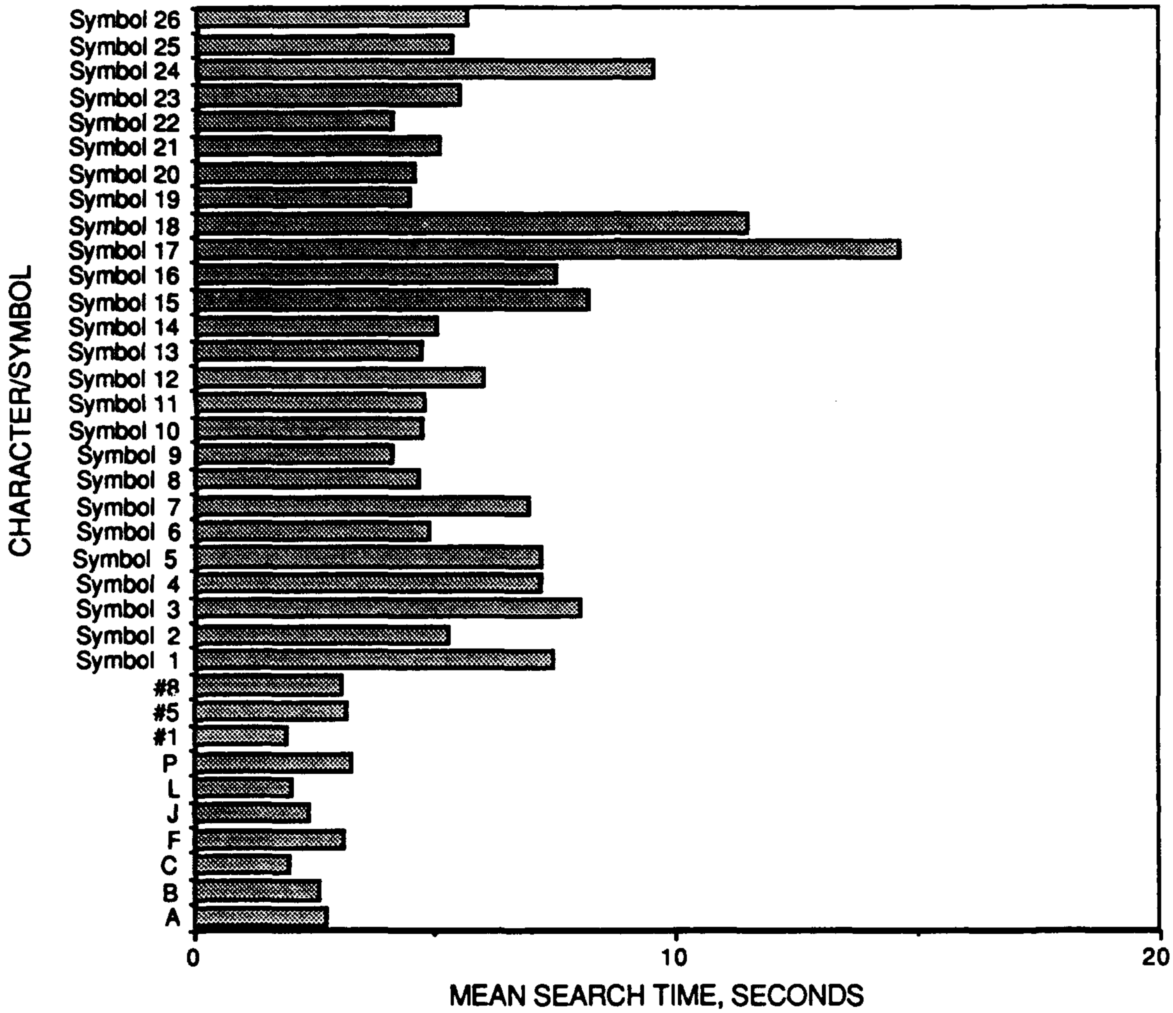

Figure 22. The effect of character or symbol on search time, 11 x 15 matrix size.

The character-matrix size effects in this experiment are, for all practical purposes, independent of rotation angle. At every rotated angle investigated, performance is best for the 11 x 15 size and worst for the 7 x 9 size. No inversions of this ordering were found. In a related fashion, the 11 x 15 size was consistently best at both distances from the center of rotation, regardless of the direction of rotation.

Character and Symbol Effects

This experiment was not designed specifically to investigate design issues related to the specific characters and symbols used as targets. Nonetheless, several useful pieces of information come from an inspection of the character-symbol effects.

First, it is clear that there are very large differences in search difficulty among the 36 targets used in this study. The very familiar alphanumerics were most easy to find, even under rotated conditions with the smallest matrix sizes. The more difficult symbols required, on the average, a search time greater by a factor of six to eight over the alphanumerics. This is probably because the subjects were unfamiliar with the Army symbols, which were not meaningful to the subjects (although prior pilot studies showed that the 5 minutes allotted to study the symbols produced both familiarity and 100% discrimination). It is believed that only a long-term working experience with the symbols would have appreciably increased this familiarity and changed performance differences.

The difficulty in Army symbol search also probably occurred because many of the symbols were similar, which can be easily seen by comparing the search times for those symbols that look most alike. Since the symbols were not combined factorially with the other variables for all subjects, a more detailed analysis and confusion analyses were not feasible. Further study of the perceived similarities and differences among the Army symbols is required to obtain a dot-matrix set of Army symbols that is most recognizable and offers the least number of confusions. Dot-matrix display optimization of symbols is obviously as critical as that of common alphanumerics to maximize visual task performance.

Second, and perhaps most important, is the indication that some symbols are considerably reduced in difficulty (e.g., symbol number 3) by using a larger matrix. Thus, one solution for the symbol legibility and confusion problem is the use of more symbol definition and differentiation through more dots to form the symbol, a differentiation present in the stroke symbol that is lost in the smaller matrix size symbol. Further research of this subject is clearly warranted.

Recommendations

Based on these data, there is little question that larger character-matrix sizes significantly reduce the deleterious effects of character rotation. Use of an 11 x 15 matrix for alphanumerics as well as dot-matrix formatted U.S. Army symbols provides search performance at all rotated angles essentially equivalent to that obtained with 7 x 9 symbols in an upright, nonrotated display. Accordingly, the use of 11 x 15 matrix sizes (assuming an angular subtense of about 18 x 25 arcminutes) is recommended for rotated dot-matrix displays in which recognition of isolated symbols is important.

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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 numeral) or 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.

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 in 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 Figures 10 to 12 on the 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 No. 0) and one is missing some dots (e.g., diamond symbol No. 1). These should be considered as separate symbols.

The U in the alphabet is very similar to the U symbol No. 14. Examine these differences.

Diamond symbols (No. 4, 5, 6, and 7) are similar to circular symbols (No. 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.