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THE EFFECTS OF LINE AND CELL FAILURES ON READING AND SEARCH PERFORMANCE USING MATRIX-ADDRESSABLE DISPLAYS

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Reading and visual search speed and accuracy were used to evaluate the effects of simulated line and cell failures on a visual display. Five experimental variables (failure type [cell, vertical line, and horizontal line], percent failure [0% , 4%, 8%, or 12% cells failed], display polarity [light characters on dark background or dark characters on light background], mode of failure [failures match the symbols or failures match the background], and matrix size [7 x 9, 9 x 11, or 11 x 15 dots]) significantly affected performance of both the reading and search tasks. Additionally, many of the interactions among these variables were significant.

The experimental results indicate that as the percentage of failures increased, performance systematically decreased. For failure levels of less than 4%, little effect on performance was found. Performance increased as the size of characters increased. A 30% improvement in search time and a 7% improvement in reading time was obtained by using dot-matrix sizes larger than 7 x 9 pixels. In general, dark symbols presented on a light background (negative contrast) were read and searched for more quickly than light symbols presented on a dark background (positive contrast).

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Cell failures were more degrading than the same percentage of horizontal or vertical line failures. Cell failures interfered with performance to a much greater degree when failed cells matched the symbol luminance rather than the background luminance. The random search task was more strongly affected by display failures than was the reading task.

These findings suggest a number of recommendations for failure-tolerant design of matrix-addressable display systems.

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THE EFFECTS OF LINE AND CELL FAILURES ON READING AND SEARCH PERFORMANCE USING MATRIX-ADDRESSABLE DISPLAYS

INTRODUCTION

An important difference between the cathode-ray tube (CRT) and many of the matrix-addressable display technologies lies in the types of failure modes characteristic of each. Matrix-addressable displays frequently use long, thin, transparent electrodes deposited on a glass substrate to transmit signals to individual pixels. If an electrode or a column or row driver fails, a whole column or row of pixels may remain permanently on or off. Technologies such as certain varieties of liquid crystal and electroluminescent displays incorporate thin film transistors for each pixel which are deposited on the glass substrate in the vicinity of each pixel. Since transistors can fail either actively or inactively, individual pixels may remain permanently on or off.

Line and cell (pixel) failures have been shown to have a significant impact on user performance (Decker, Pigion, & Snyder, 1987). Pastor and Uphaus (1982) examined the effects of cell losses on the accuracy of identification of 7 x 9 numerals. The authors found a significant linear relationship between the variables.

Riley and Barbato (1978) evaluated the effects of discrete element degradation on a number of 5 x 7 dot-matrix alphanumeric fonts. They presented stimuli tachistoscopically and measured identification accuracy. Results indicated that the quality and location of degraded spots strongly influenced accuracy.

Laycock (1985) developed a technique for storing and systematically adding line and cell failures to text images. Using subjective analysis, he noted a differential effect of "on" failures versus "off" failures. Laycock concluded that as much as 1% of off point failures might be tolerated when the text contains redundancies, whereas less than 0.01% of on failures can be tolerated. No performance data were collected to substantiate Laycock's preferences.

Abramson, Mason, and Snyder (1983) investigated the effects of line and cell failures on readability using a plasma display. The parameters investigated were failure type, failure mode, percentage of failures, case, and font. Very generally, the results indicated the following:

1. Cell failures degraded performance more than line failures did;

2. On failures degraded performance more than off failures did, although the effect was much stronger for cell failures than for line failures;

3. As the percentage of failures increased, performance decreased; if the failure rate was kept below 2%, the impact was minimal.

The two current experiments were conducted to gather additional quantitative performance data about the effects of line and cell failures. As in the Abramson et al. (1983) experiment, the effects of percent failure, failure type, and failure mode on reading performance were investigated. The authors also examined the variables (polarity and matrix size) to see how they behaved in the presence of failures.

The second experiment extends the scope of the Abramson et al. (1983) experiment into the realm of cartographic applications by employing a special set of cartographic symbols. Since cartographic applications frequently require visual search for symbols other than alphanumerics, the second experiment used a random search task.

OBJECTIVES

The objectives of this experiment were to provide quantitative data about the effects of line and cell failures on the readability and legibility of matrix-addressable displays. Five experimental variables were manipulated in this experiment. These variables and their levels were (a) failure type (cell, vertical line, and horizontal line); (b) percent failure (0, 4, 8, or 12% cells failed); (c) display polarity (light characters on dark background [positive contrast] or dark characters on light background [negative contrast]); (d) mode of failure (failures match the symbols or failures match the background); and (e) matrix size (7 x 9, 9 x 11, or 11 x 15 dots).

This study is one in a series of studies designed to examine the effects of a large number of matrix-addressable display design variables on human performance. Decker, Pigion, and Snyder (1987) provided an overview of this series of studies. An overall objective for the series of studies is to provide a human performance data base from which metrics can be derived for predicting image quality and human performance. The data collected in this study will contribute to this human performance data base.

METHOD

Subjects

Ten subjects (four males, six females) participated in this study. Subjects were screened for corrected near and far point 20/22 acuity and normal lateral and vertical phoria using a Bausch and Lomb Orthorater. Subjects were then screened for normal near and far point contrast sensitivity using a Vistech Consultants' contrast sensitivity evaluation system. Finally, subjects were required to speak English as their native language.

Apparatus

Stimuli were presented on a Tektronix GMA201 high resolution monochrome CRT. This monitor had an addressability of 1024 x 1024 pixels within a display active area of 27 x 27 centimeters (cm) for an overall pixel density of 37.9 pixels/cm. The GMA201 has an advertised spot size of 0.19 mm. To more completely characterize line widths for this monitor, horizontal and vertical microphotometric line spread measurements were made for both light lines on a dark background and dark lines on a light background. These measurements are described below.

The Tektronix monitor was driven by a Vectrix Corporation PEPE graphics controller installed in an IBM personal computer (PC-AT). This PC also controlled stimulus presentation and the acquisition and timing of subject responses. Subjects made responses using a three-button mouse input device produced by Mouse Systems.

Subjects sat in a dentist's hydraulic chair positioned in front of the monitor. This chair had an adjustable headrest, seatpan, and backrest, as well as adjustable height and distance from the display. Subjects were positioned so that the distance from their eyes to the center of the screen was 50.8 cm. The angle of the subjects' line of sight was set to 15° below horizontal. The CRT was tilted back 15° with respect to vertical so that the subjects' line of sight was normal to the CRT surface at the center of the display.

Photometric Measurements

Resolution of the Tektronix monitor was characterized using a Gamma Scientific GS-2110 scanning microphotometer equipped with a D-46 photomultiplier tube, an SC-1 scanning controller, and a DR-2 digital radiometer. Line spread scans were measured using a 1X objective lens and a scanning aperture of 0.010 x 3.0 mm with the long dimension of the aperture oriented perpendicular to the direction of scan. The line spread measurements were made at nine positions across the display. The mean line widths (full width, half maximum) were 0.294 mm for vertical lines and 0.126 mm for horizontal lines.

Contrast ratios were calculated using the peak (positive or negative) luminance of the line and the space-averaged luminance of the background. The contrast ratio was held constant at 9:1 for all conditions of this experiment.

Stimuli

Reading Task

Stimuli for the reading task consisted of a series of short reading passages which are equated in difficulty (Carver & Tinker, 1970). Each passage was comprised of one or two sentences containing approximately 30 words. One of the words near the end of the passage did not make sense with respect to the context of the rest of the passage. The subject's task was to read the passage, determine the out-of-context word, and inform the experimenter of that word as quickly as possible. Two examples of these passages are provided below.

Uncle Time gave Micky a new pair of roller-skates, and as she went down the street she called to the mailman, "See how fast I go on my new sled."

Jean made some delicious muffins for her father's breakfast, and he was so pleased he said he would give her a dollar every time she made such good pictures.

Both upper and lower case letters were used to construct these passages. The same Lincoln/MITRE font used in the search task was used in the reading task.

Search Task

Stimuli for the search task consisted of single alphanumeric and cartographic symbols randomly positioned on the display. The set of characters included the 26 upper case letters of the alphabet plus the digits 0 to 9. Additionally, 26 cartographic symbols were used. These symbols were extracted from a set of symbols used by the U.S. Army for displaying the position of objects on maps. The symbols, which are usually drawn with strokes, were represented by using patterns of pixels within the appropriately sized dot matrix. The complete set of characters and symbols used in this experiment is presented in Figures 1 through 9.

For both the reading and search tasks, three sizes of symbols were used corresponding to matrix sizes of 7 x 9, 9 x 11, and 11 x 15 dots. The height, width, and aspect ratios for these matrices are provided in Table 1.

Table 1

Dimensions and Aspect Ratios of Dot Matrices for 50.8-cm Viewing Distance

Size	Number of pixels	Dimensions[a] (mm)	Visual angle[a] (arcminutes)	Aspect ratio
Large	11 x 15	2.64 by 3.69	17.9 by 25.0	1.39
Medium	9 x 11	2.11 by 2.64	14.3 by 17.9	1.25
Small	7 x 9	1.58 by 2.11	10.7 by 14.3	1.33

[a]Dimensions and visual angles are to centers of pixels.

Procedure

Before each experimental session, the monitor was turned on and allowed to warm up for 30 minutes, a process which, based on previous experience, stabilized the display. The luminance of a full-on field was then calibrated using a Minolta CS-100 spot photometer. The display was adjusted using the "brightness" control on the monitor until the luminance at the center of the display matched a calibration value determined by using the scanning microphotometer. The ambient lighting level was then adjusted so that the wall luminance directly behind the CRT (facing the subject) measured 15 candelas per square meter (cd/m^2). The reflected ambient light from the surface of the display had no measurable effect on symbol or background luminance.

Experiment 1--Speed of Reading

A modified Tinker Speed of Reading Test (Carver & Tinker, 1970) was employed to assess the readability of displayed text. Five variables were manipulated in this experiment in a full factorial, within-subjects design. These variables and their levels include failure type (cell, vertical line, and horizontal line), percent failure (0, 4, 8, or 12% of the cells failed; locations were randomly selected on each trial), display polarity (positive contrast or negative contrast), mode of failure (failures match the symbols or failures match the background), and matrix size (7 x 9, 9 x 11, or 11 x 15 dots).

Figure 1. Upper case letters, 7 x 9 matrix size.

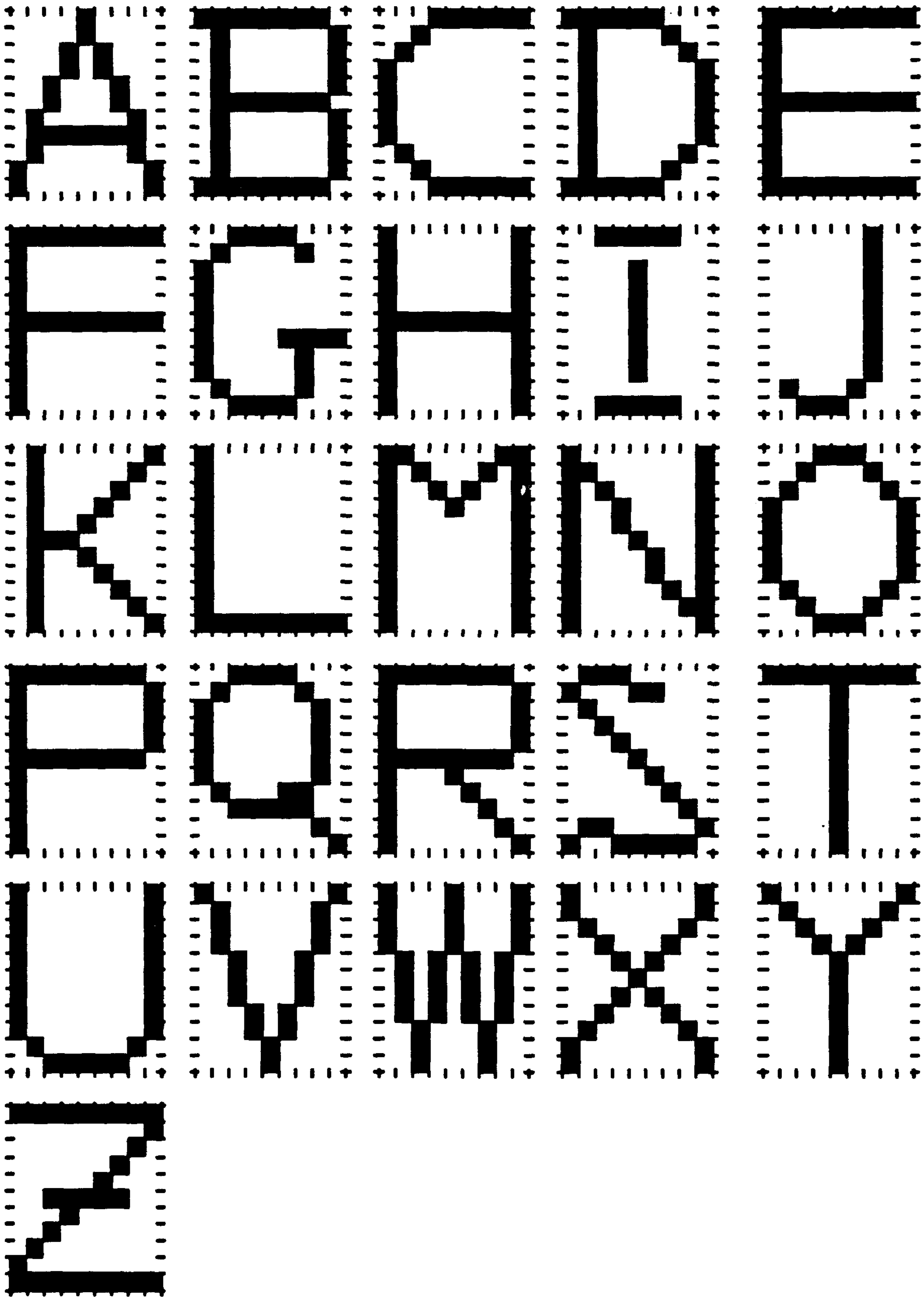

Figure 2. Upper case letters, 9 x 11 matrix size.

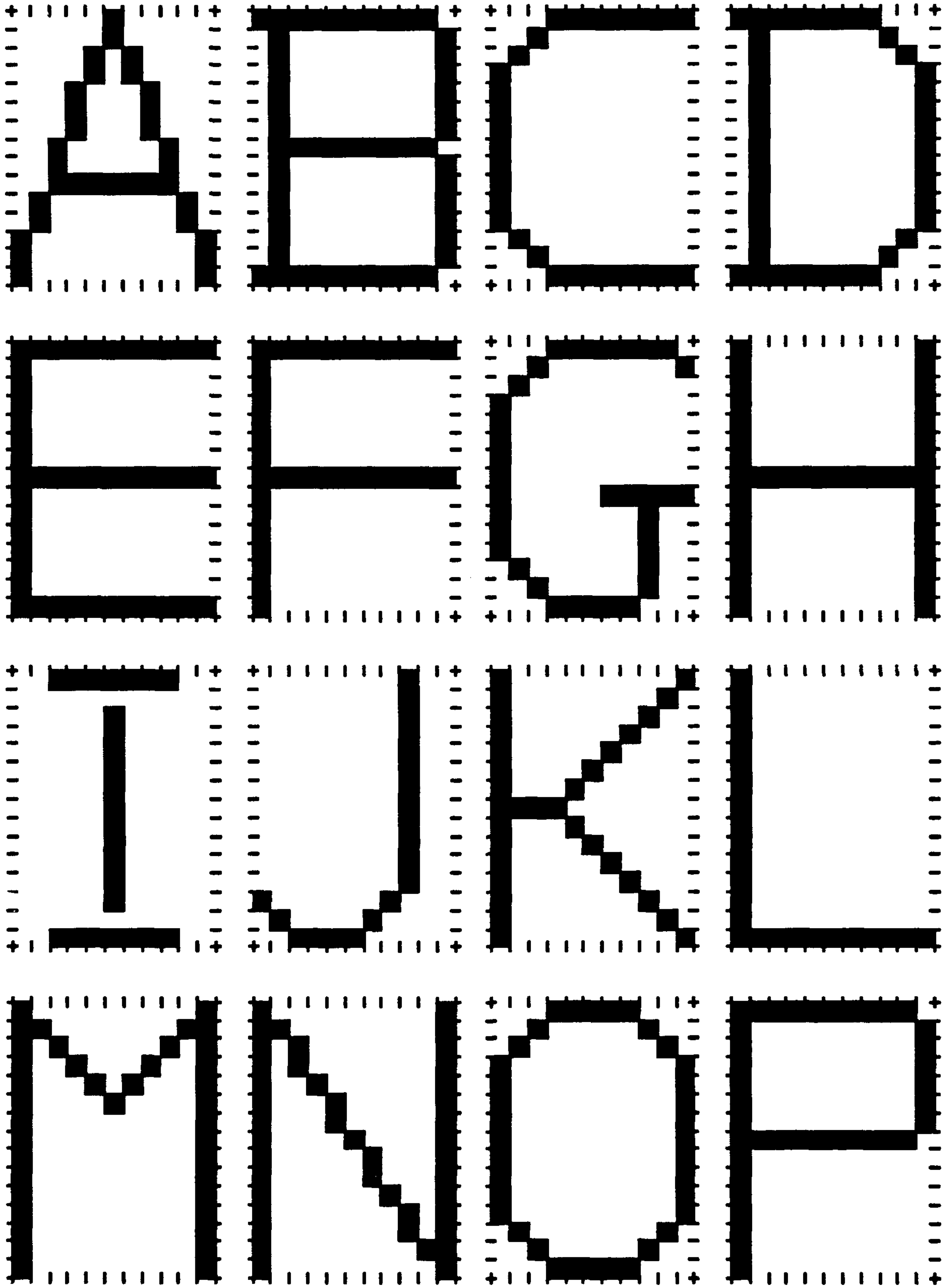

Figure 3. Upper case letters, 11 x 15 matrix size.

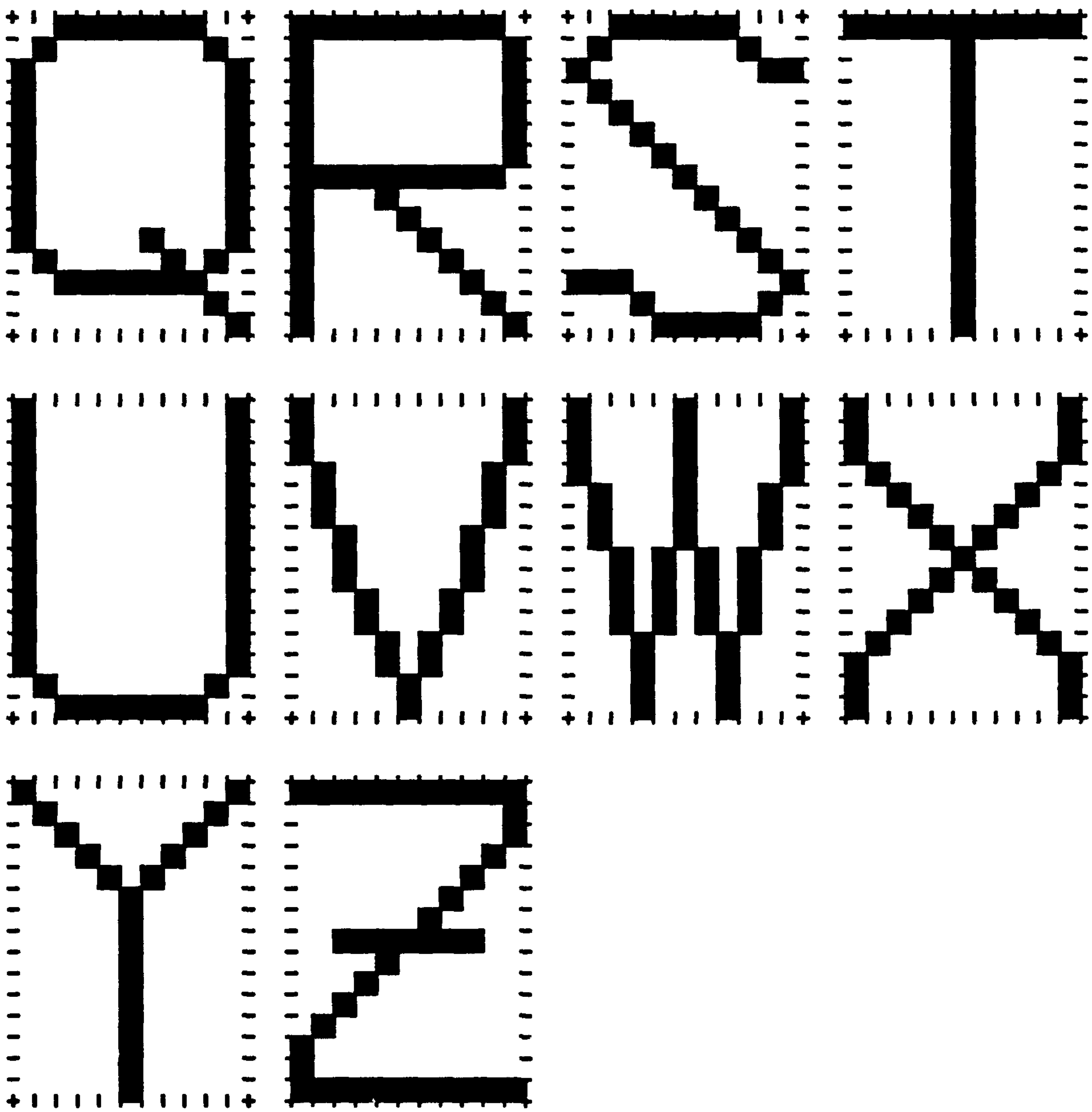

Figure 3 (continued).

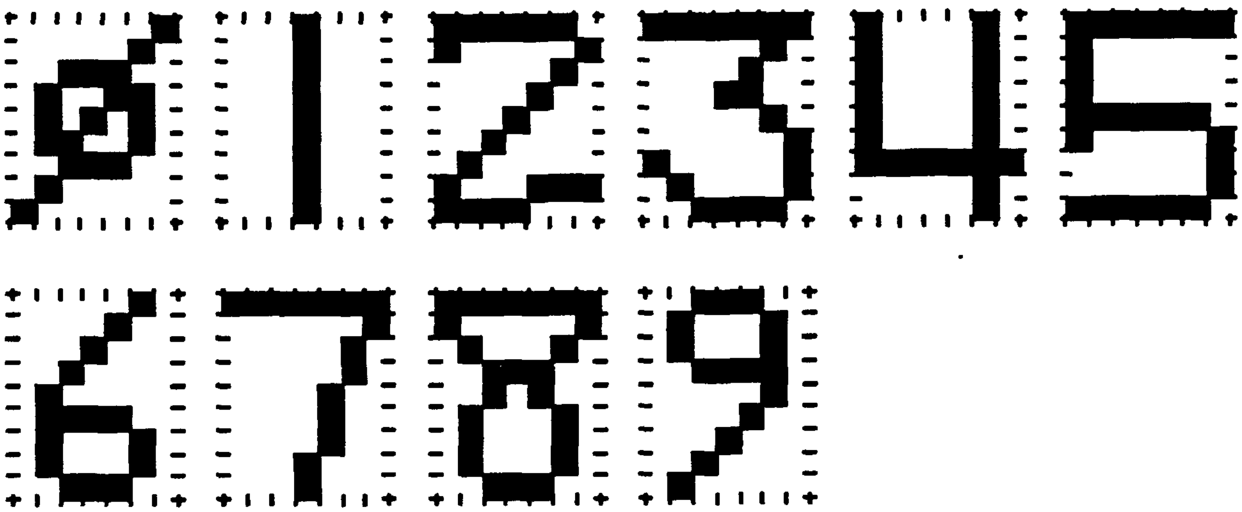

Figure 4. Numerals, 7 x 9 matrix size.

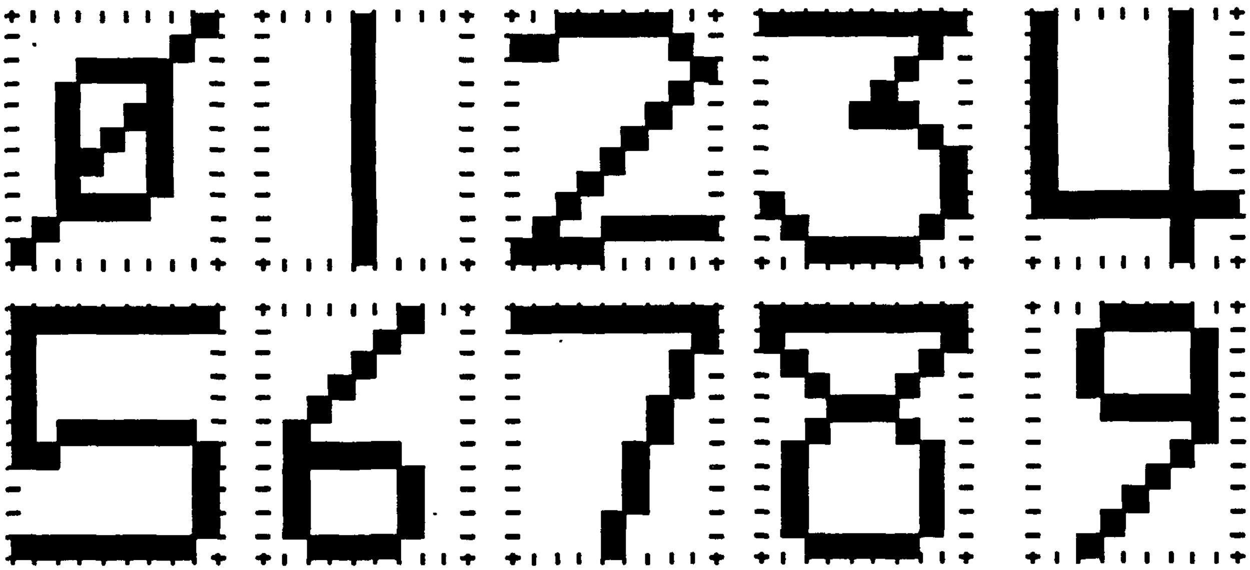

Figure 5. Numerals, 9 x 11 matrix size.

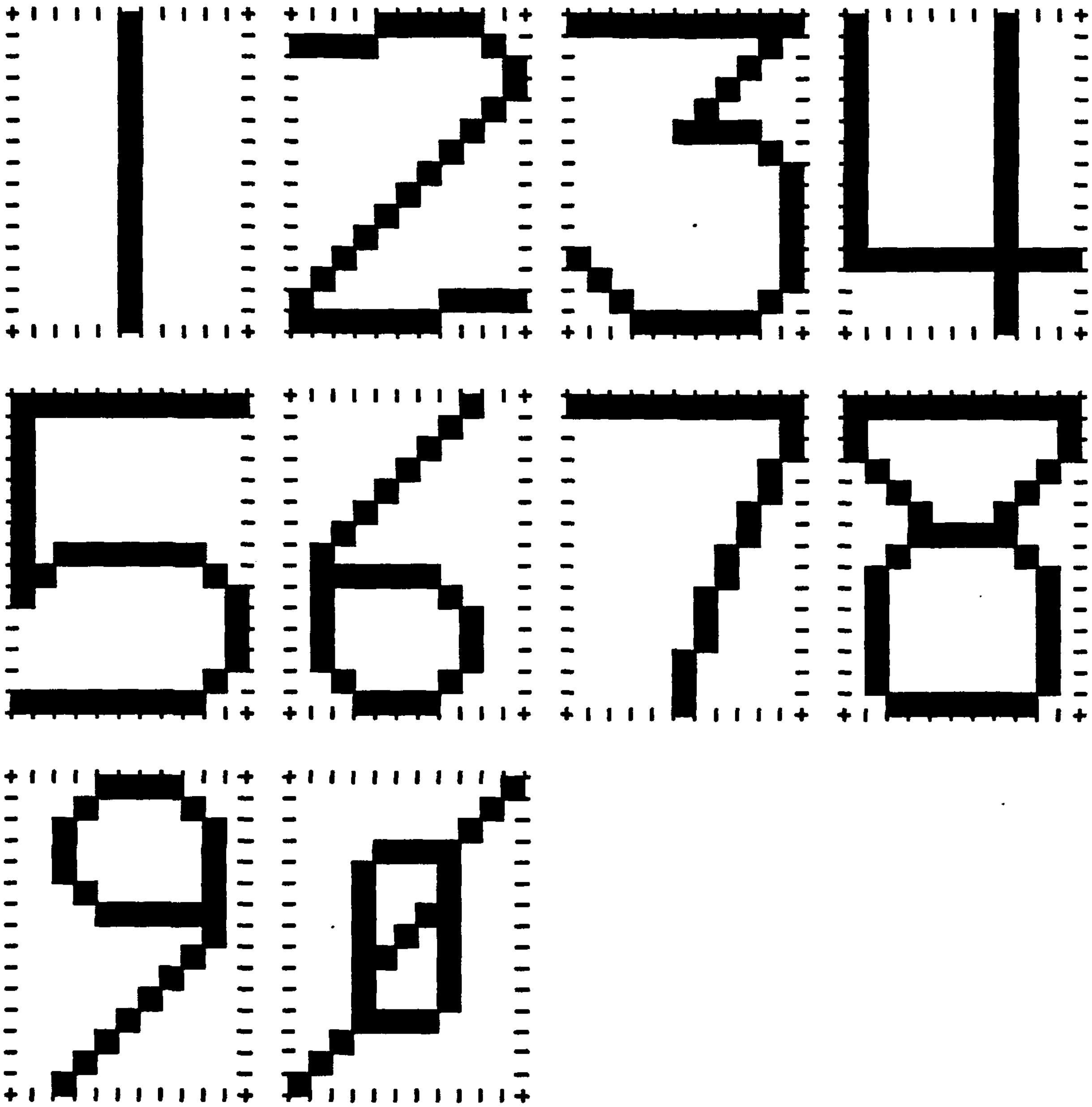

Figure 6. Numerals, 11 x 15 matrix size.

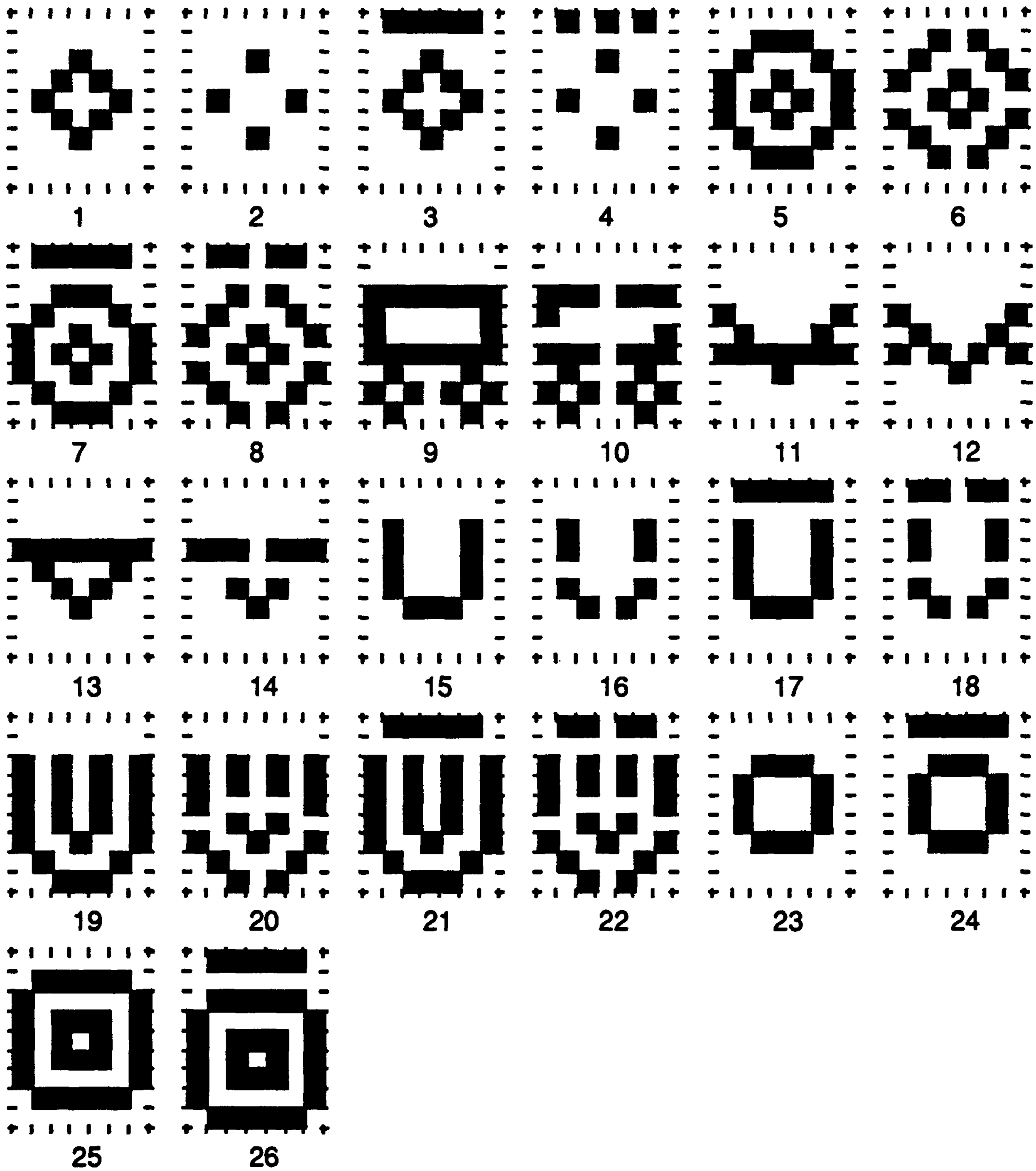

Figure 7. U.S. Army symbols, 7 x 9 matrix size.

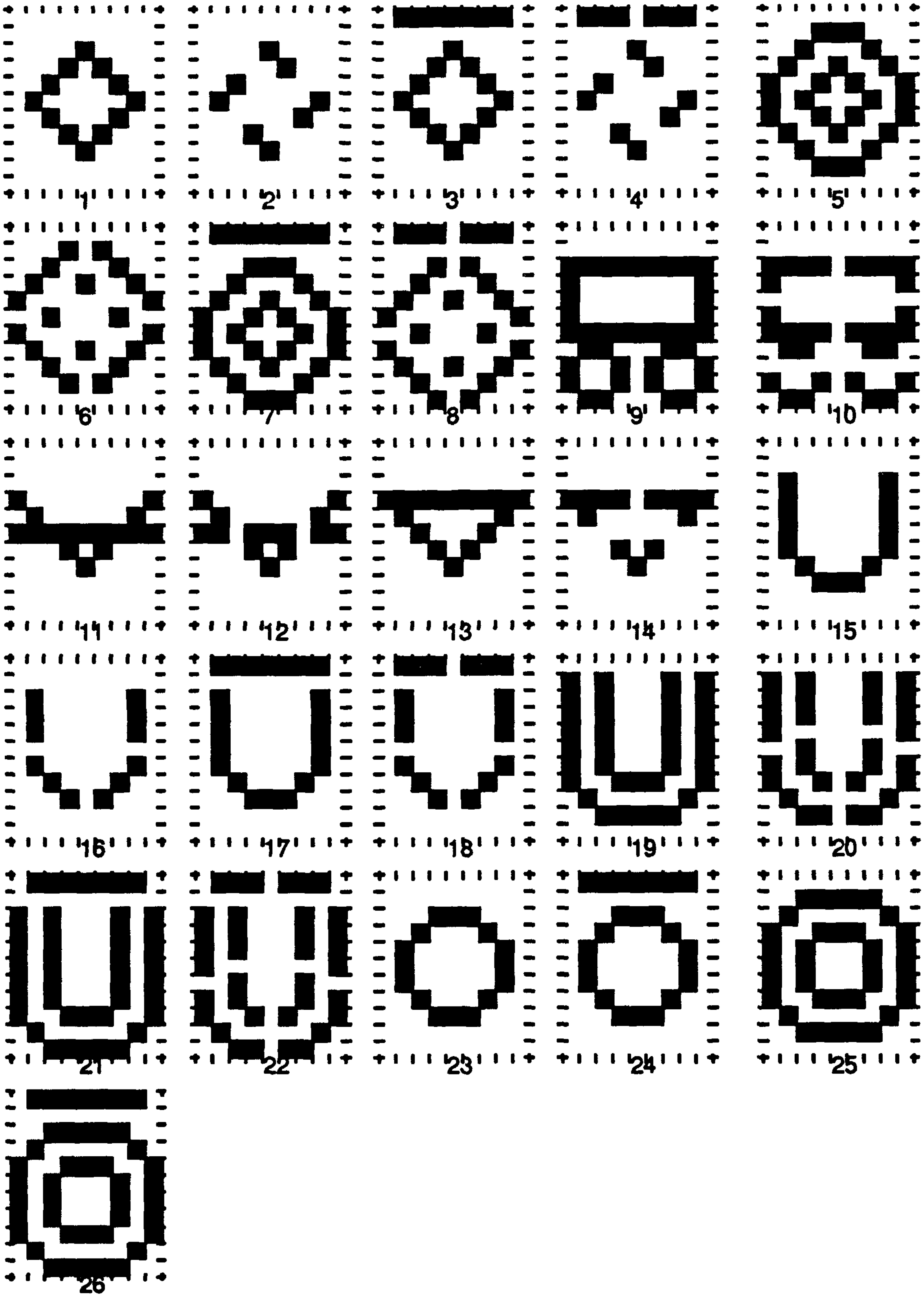

Figure 8. U.S. Army symbols, 9 x 11 matrix size.

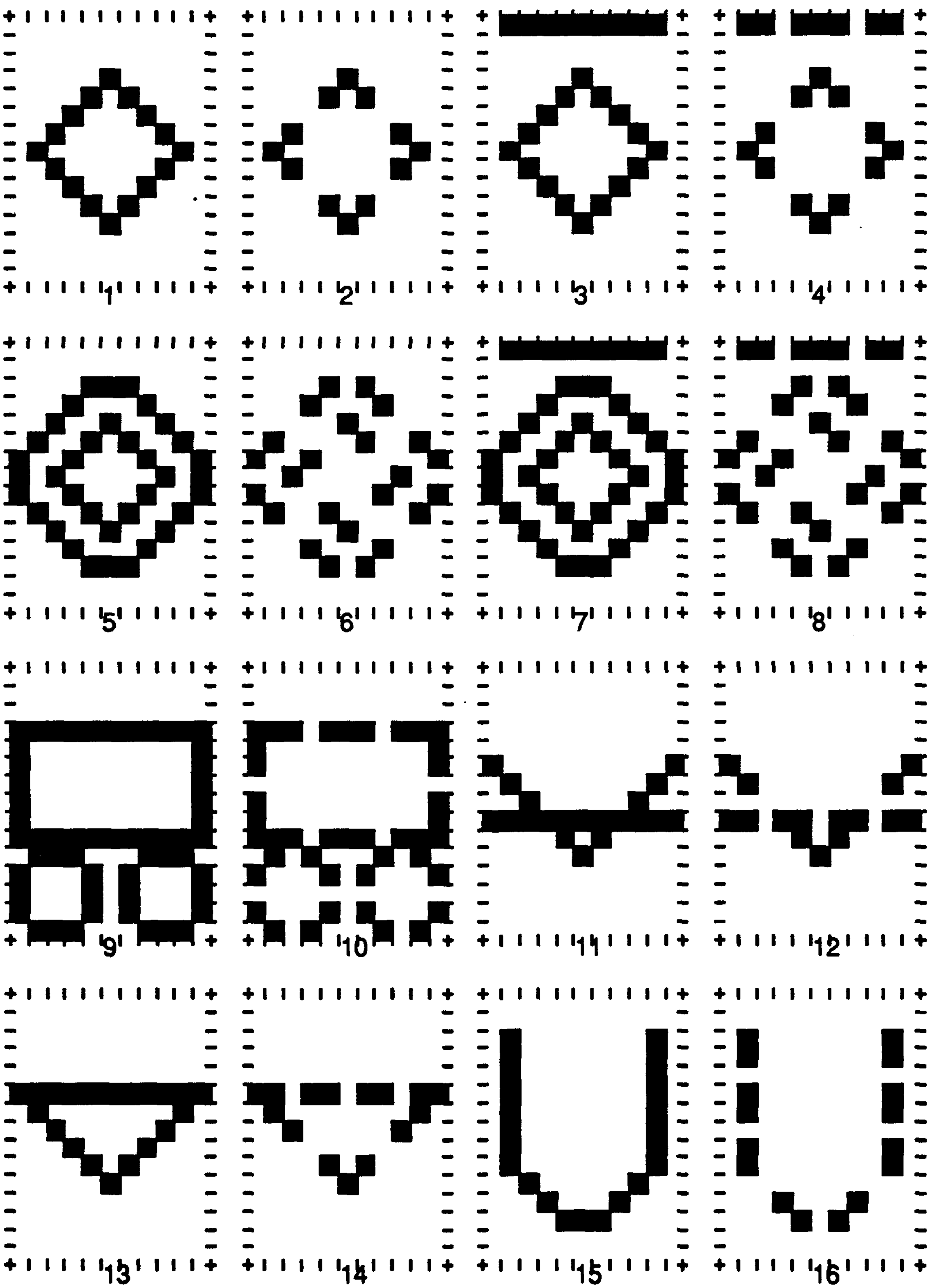

Figure 9. U.S. Army symbols, 11 x 15 matrix size.

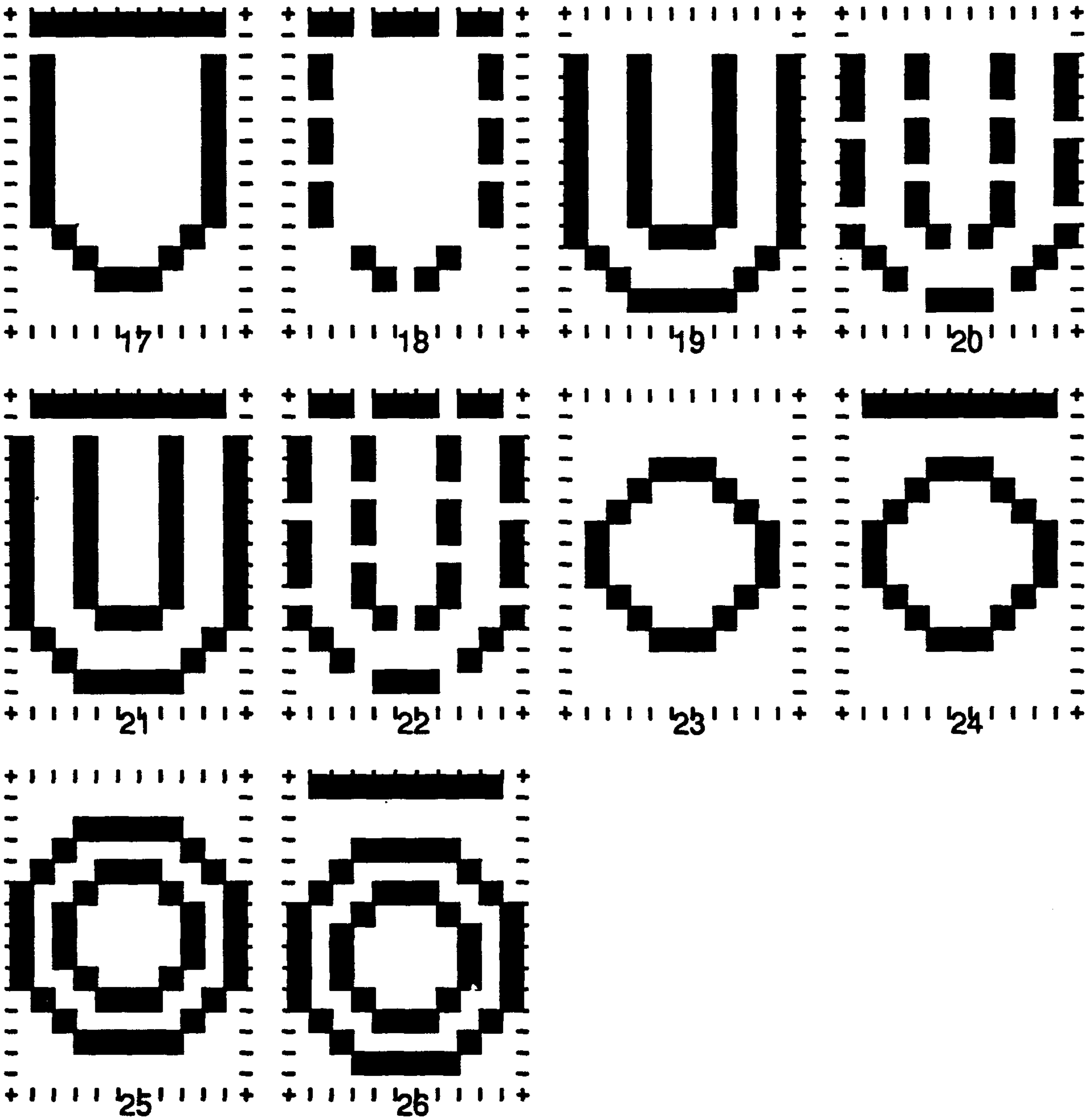

Figure 9 (continued).

Ten subjects participated in the experiment for approximately 9 hours each. Each subject received a different randomly selected reading passage for each of the 144 experimental conditions, with three trials per conditions. That is, each subject participated in a total of 144 times 3, or 432 reading trials. Reading time and accuracy of selecting the inappropriate word were recorded for each trial. The response data were analyzed with analysis of variance (ANOVA) techniques using the statistical analysis system (SAS) running on an IBM mainframe.

Appendix A contains the instructions given to subjects for the reading task. Subjects were given 5 minutes to learn the symbols, a time shown to be adequate in prior research.

Experiment 2--Random Search

A random search task was employed in which subjects searched for a single alphanumeric or cartographic symbol that was randomly positioned among approximately 50 other randomly selected symbols on the display. Search time and identification accuracy were recorded for each trial. (Appendix B contains the instructions given to subjects for the random search task.) The hardware, experimental design, and method of analysis were identical to those used in Experiment 1.

Three days were required to collect data for both experiments for each subject.

RESULTS

Reading Time

Table 2 contains the ANOVA summary for reading times. In this and subsequent analyses, significant ($p < .05$) 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.

As might be expected for this task, all five independent variables plus a number of the interactions significantly influenced reading times. The effects are described below.

Matrix size

Small but statistically significant decreases in reading time occurred with increases in matrix size from 14 to 18 to 25 arcminutes (vertical angle), as illustrated in Figure 10. While the total decrease in reading time is only 9%, the result is in keeping with other experimental results and recommendations that at least 16 arcminutes, and preferably 18 arcminutes, of vertical visual angle be used for best readability (e.g., Human Factors Society, 1988). Further, the results agree with the recommendations of Snyder and Maddox (1978) that larger matrix sizes be used for better legibility.

Table 2

Analysis of Variance Summary for Reading Times

Source of variance	*df*	*MS*	*F*	*p*
Size (S)	2	82.87	18.96	0.0001
Polarity (P)	1	106.07	22.94	0.0010
Mode (M)	1	98.49	35.08	0.0002
Type (T)	2	35.46	6.71	0.0067
Percent (L)	3	339.13	25.75	0.0001
S x P	2	0.68	0.15	0.8641
S x M	2	0.25	0.08	0.9238
S x T	4	6.31	0.68	0.6100
S x L	6	30.32	2.22	0.0550
P x M	1	23.24	15.09	0.0037
P x T	2	2.20	0.27	0.7641
P x L	3	16.07	2.42	0.0879
M x T	2	181.70	75.23	0.0001
M x L	3	117.16	16.81	0.0001
T x L	6	36.78	2.75	0.0309*
S x P x M	2	7.47	1.07	0.3631
S x P x T	4	21.27	1.90	0.1321
S x P x L	6	6.29	0.36	0.8987
S x M x T	4	7.87	1.62	0.1916
S x M x L	6	12.74	0.83	0.5520
S x T x L	12	48.94	0.99	0.4636
P x M x T	2	11.53	4.66	0.0344**
P x M x L	3	11.05	3.12	0.0548***
P x T x L	6	12.31	1.26	0.2899
M x T x L	6	108.81	8.41	0.0001
S x P x M x T	4	6.51	0.78	0.5426
S x P x M x L	6	18.95	1.21	0.3138
S x P x T x L	12	22.19	0.93	0.5172
S x M x T x L	12	36.13	1.85	0.0661****
P x M x T x L	6	28.41	1.69	0.1402
S x P x M x T x L	12	19.52	0.81	0.6398

* Greenhouse and Geisser (1959) $\varepsilon = 0.8172$
** Greenhouse and Geisser (1959) $\varepsilon = 0.7913$
*** Greenhouse and Geisser (1959) $\varepsilon = 0.8214$
****Greenhouse and Geisser (1959) $\varepsilon = 0.8021$

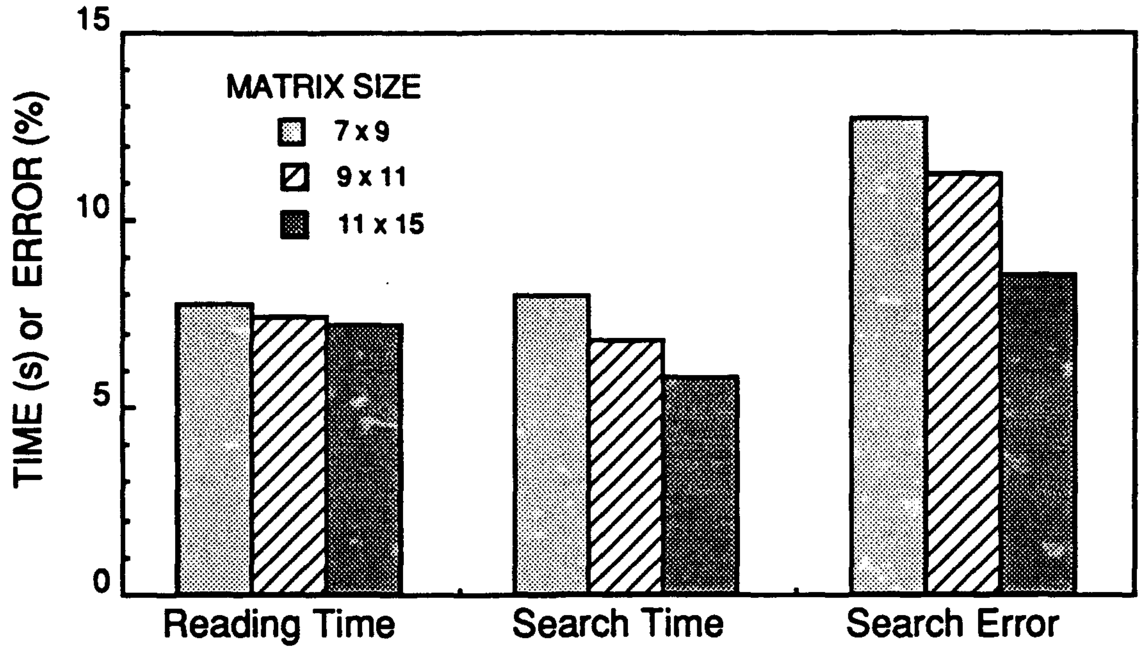

Figure 10. The effect of matrix size on performance.

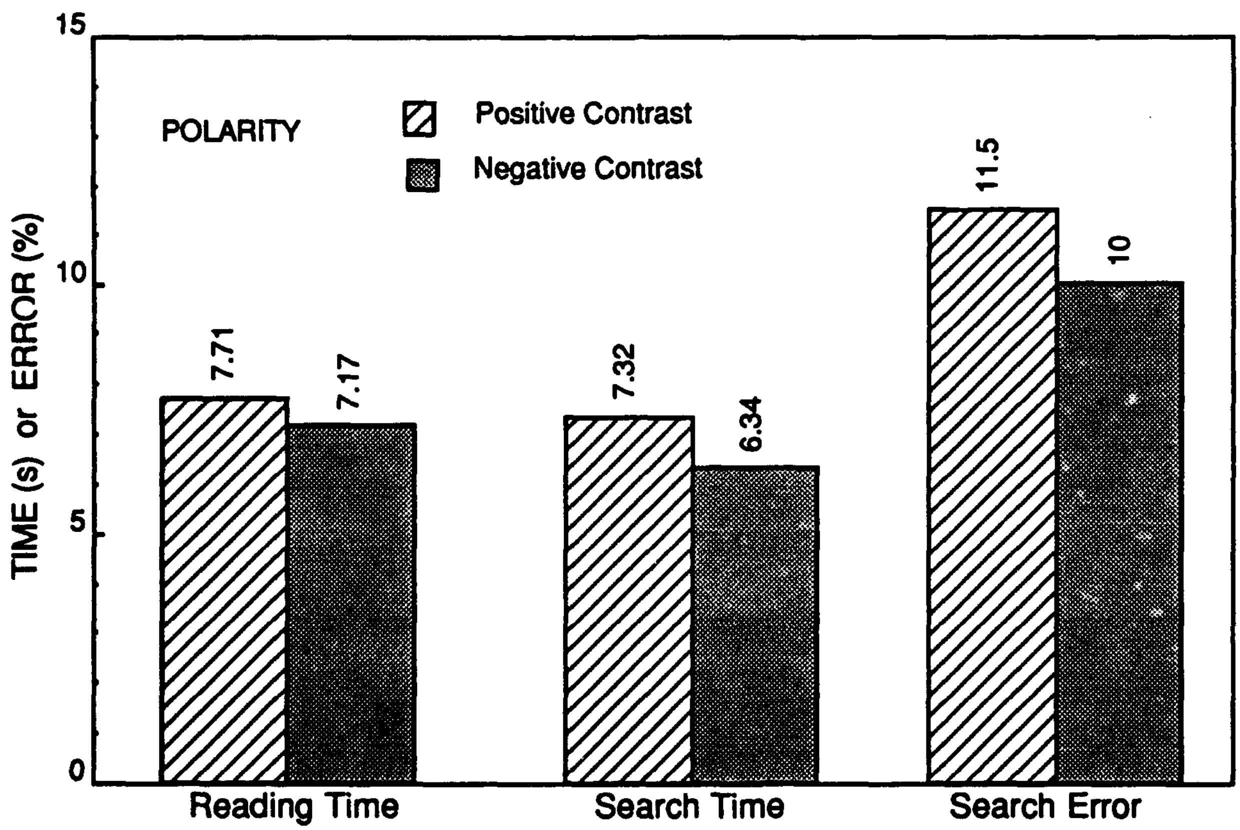

Figure 11. The effect of polarity on performance.

Polarity

Reading is faster by approximately 10% with a negative contrast display than with a positive contrast display (see Figure 11). This result is important in that it adds to the small, but growing body of data that suggest benefits of negative contrast when the display resolution and contrast ratio are held constant.

Failure Mode

As shown in Figure 12, display failures that match the symbol luminance cause longer reading times than failures that match the background luminance. As would be anticipated, many failures that match the background go undetected because of the greater proportion of background pixels than symbol pixels. Only when a background-matching failure intersects a symbol is it detectable, whereas a symbol-matching failure is only detectable when it occurs in a background (non-symbol) location. Thus, symbol-matching failures are more frequently detectable and thereby more likely to intrude on reading task performance. These results agree with those of Abramson et al. (1983).

Failure Type

In general, horizontal line failures are not as detrimental to reading task performance as are cell failures or vertical line failures (see Figure 13). However, this overall effect is somewhat oversimplified, as is illustrated by the Mode x Type interaction in Figure 14. For either type of line failure, there is no significant difference between failure modes, but for cell failures, those matching the symbol are much more detrimental than those matching the background.

Percent Failure

Increases in the percentage of cells that failed consistently yield increased reading times, as illustrated in Figure 15. As reported by Abramson et al. (1983) and Laycock (1985), failure rates of 4% yield significantly poorer performance than that obtained with failure-free displays. Increases from 8% to 12% produced the largest decrement in performance.

One means of reducing the impact of display failures is to use larger character matrices. As matrix size increases, the number of pixels that comprise features of the symbols (e.g., lines, curves, corners) increases. Symbols with more pixels per feature should be more robust to noise since a failure would be less likely to completely eliminate a critical feature. Thus, as matrix size increases, the impact of greater numbers of failures decreases (see Figure 16), although reading time continues to increase with percentage of failures even for the largest matrix size.

Other Interactions

The lesser interference of failures that match the background is consistent for both polarities, although the effect is slightly greater for the light character on a dark background (see Figure 17). In addition, as the percentage of cells that failed increases, the impact is greater when the failed cells match the symbols as opposed to the background (see Figure 18).

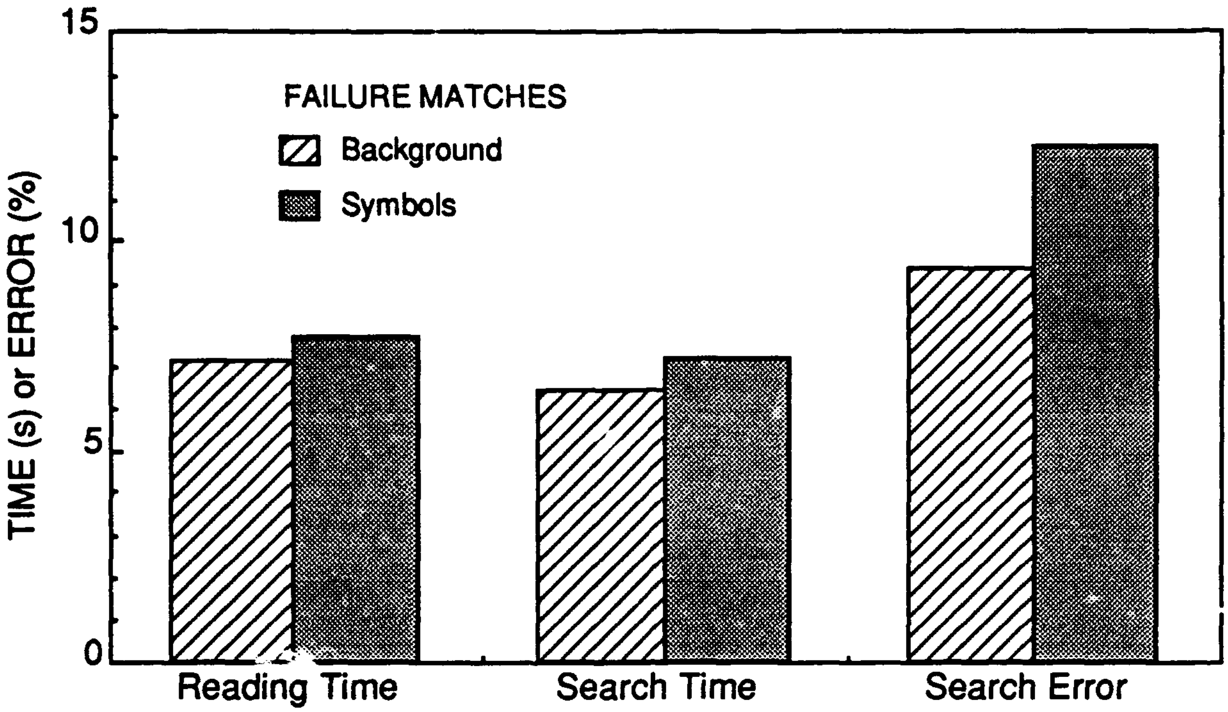

Figure 12. The effect of failure mode on performance.

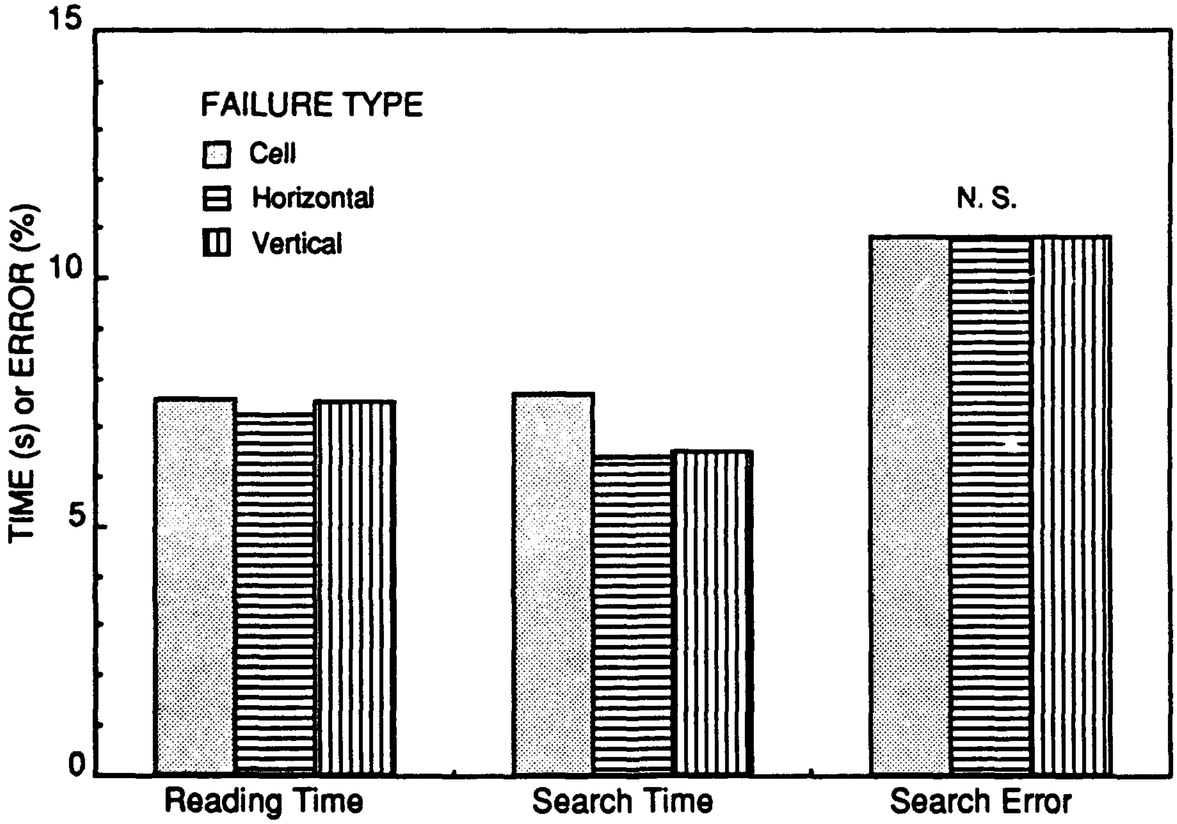

Figure 13. The effect of failure type on performance.

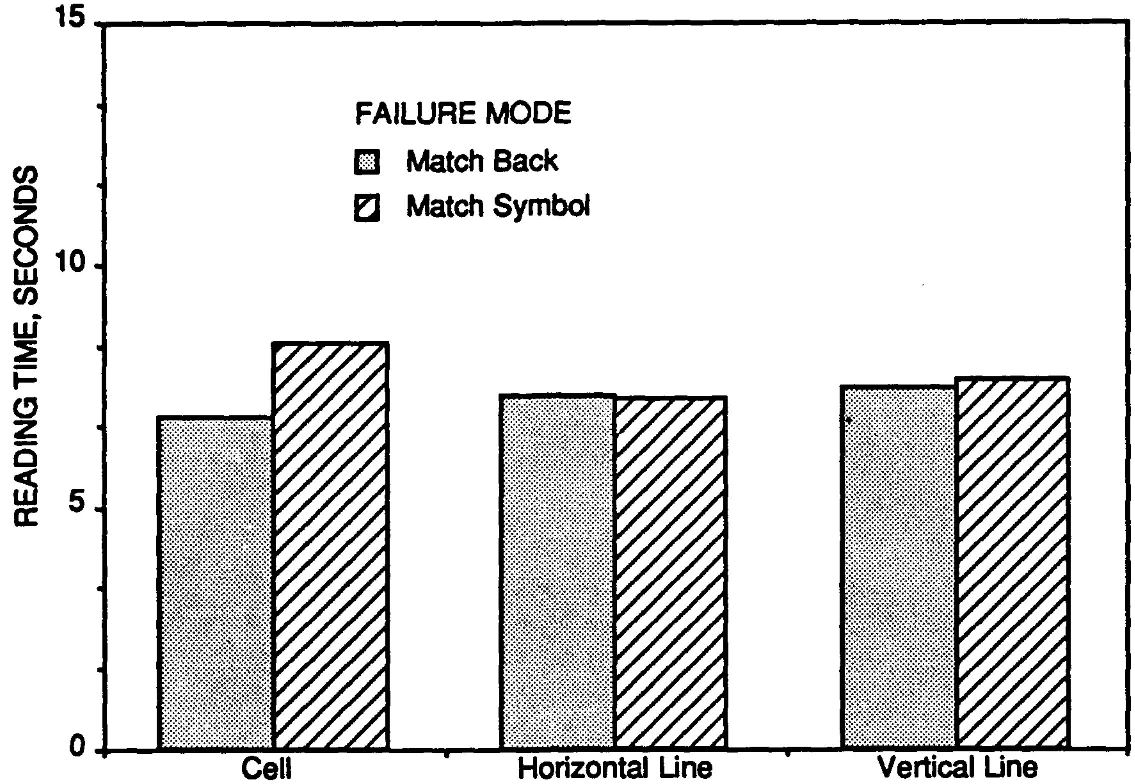

Figure 14. The effect of failure type x failure mode interaction on reading time.

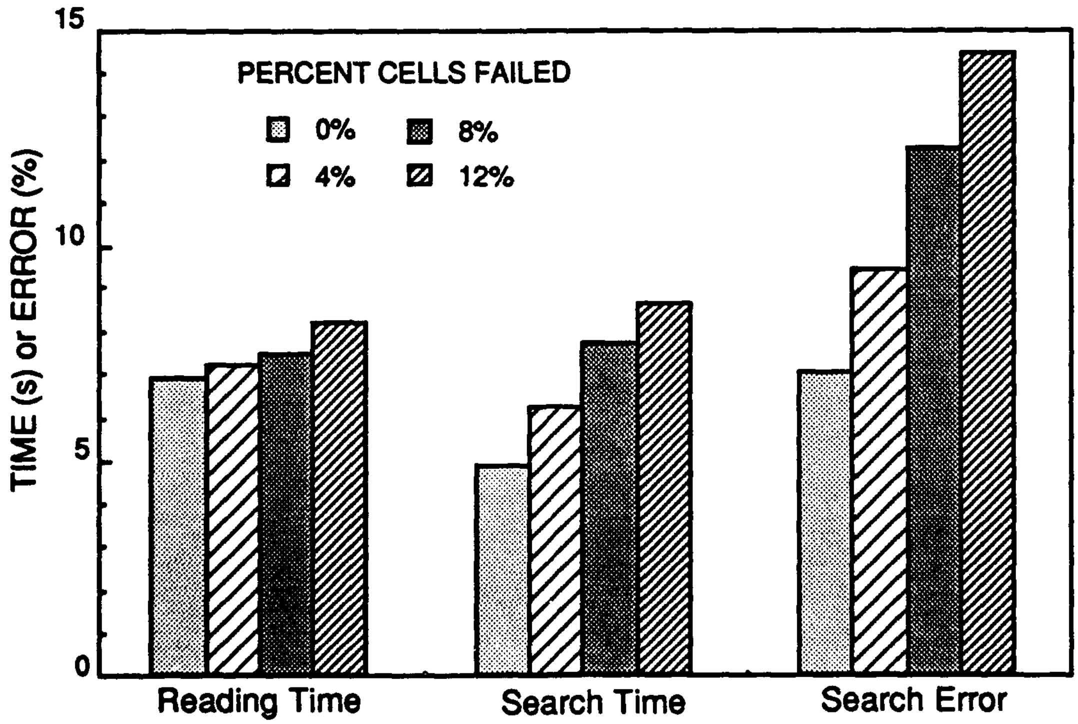

Figure 15. The effect of percent failures on performance.

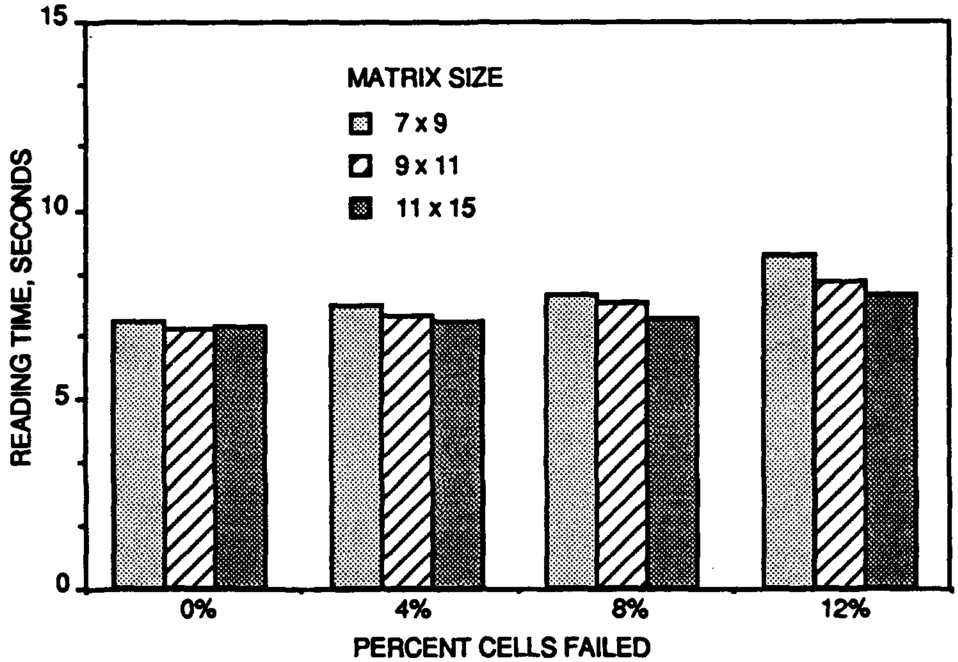

Figure 16. The effect of percent failure x size interaction on reading time.

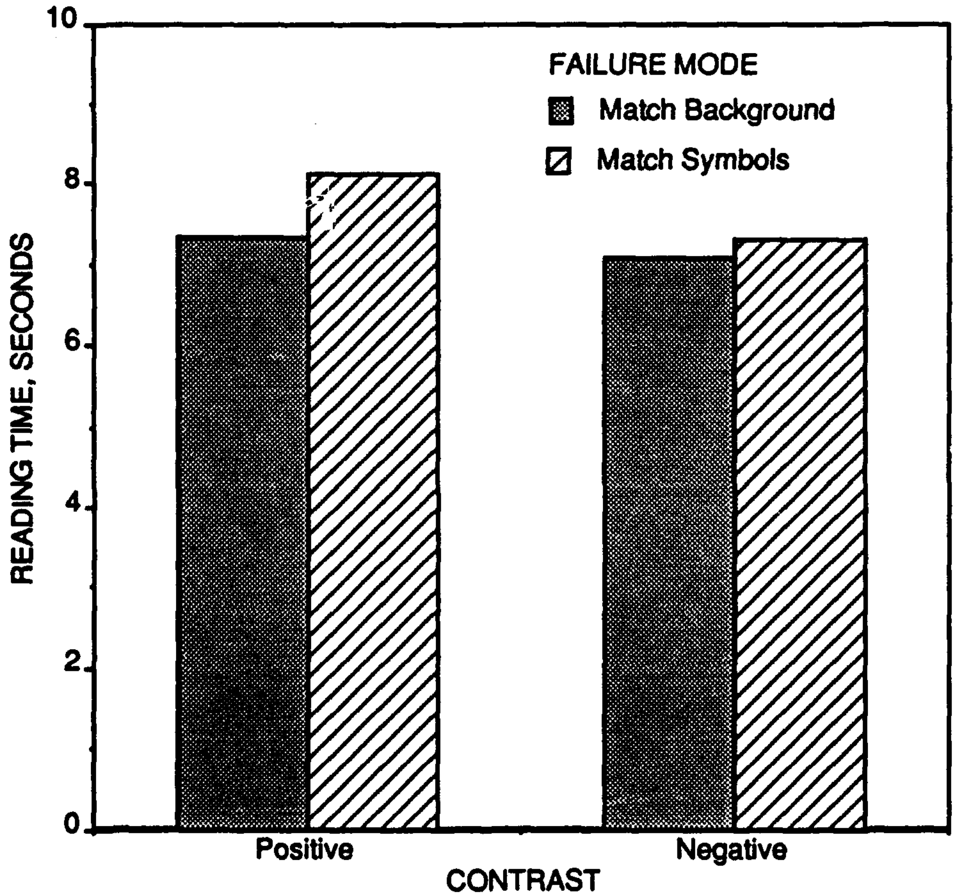

Figure 17. The effect of failure mode x polarity interaction on reading time.

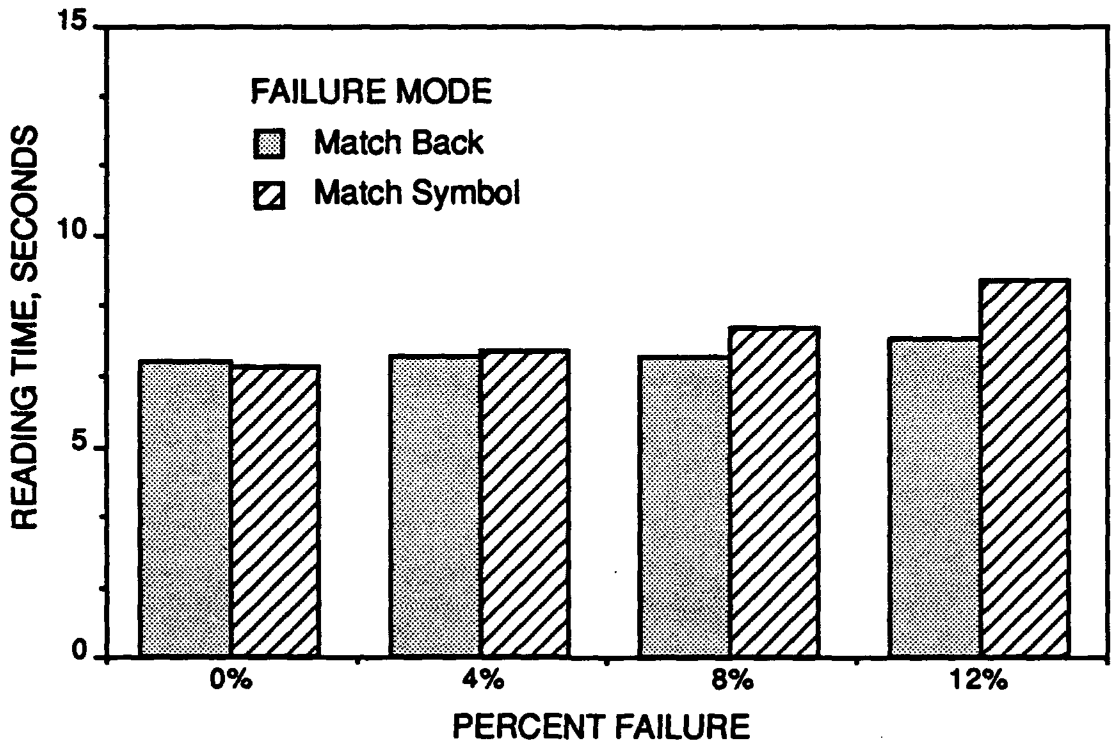

Figure 18. The effect of percent failure x failure mode interaction on reading time.

As might be expected, horizontal line failures are less sensitive to increases in the percentage of failed cells than are either cell failures or vertical line failures (see Figure 19). The "salt and pepper" appearance of cell failures provides a random overall distraction, whereas the characters contain more vertical line segments than horizontal line segments and are thus more susceptible to either line segment obliteration or confusion from vertical line failures.

Finally, stronger effect of cell failures is particularly important for positive contrast (light on dark) displays when failures match the symbols, as shown in Figure 20. The combination of positive contrast and cell failures that match the symbols produces the greatest increase in reading time. Further, as the percentage of failed cells increases, cell failures that match the character or symbol have disproportionately greater effects (see Figure 21).

Reading Errors

Table 3 summarizes the ANOVA for reading errors. As is expected in research using this task, the error rate is quite low (less than 1%) and is largely unaffected by the independent variables of interest. Only one effect (a triple interaction) is marginally significant ($p < .05$) following the correction for sphericity, and an evaluation of it leads to no meaningful conclusions. Clearly, subjects performed largely as instructed, maintaining high accuracy in reading the passages.

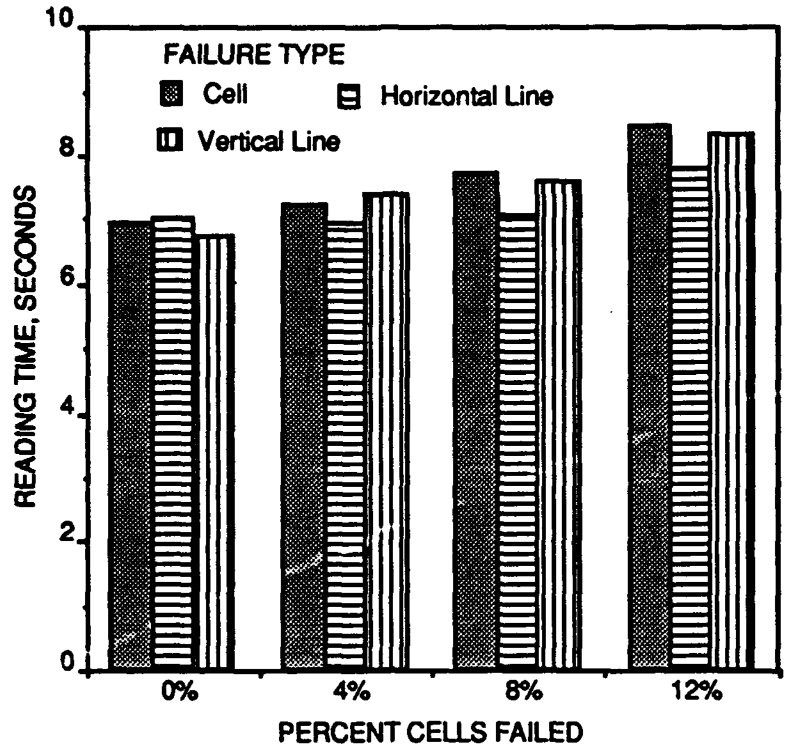

Figure 19. The effect of percent failures x failure type interaction on reading time.

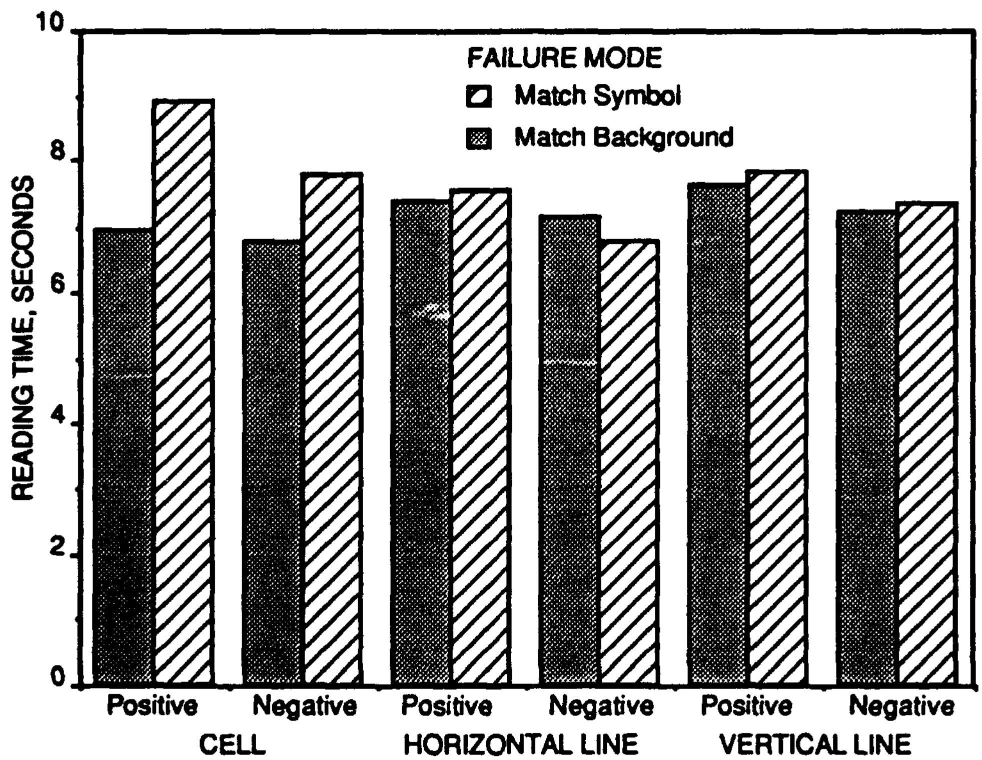

Figure 20. The effect of failure type x failure mode x polarity interaction on reading time.

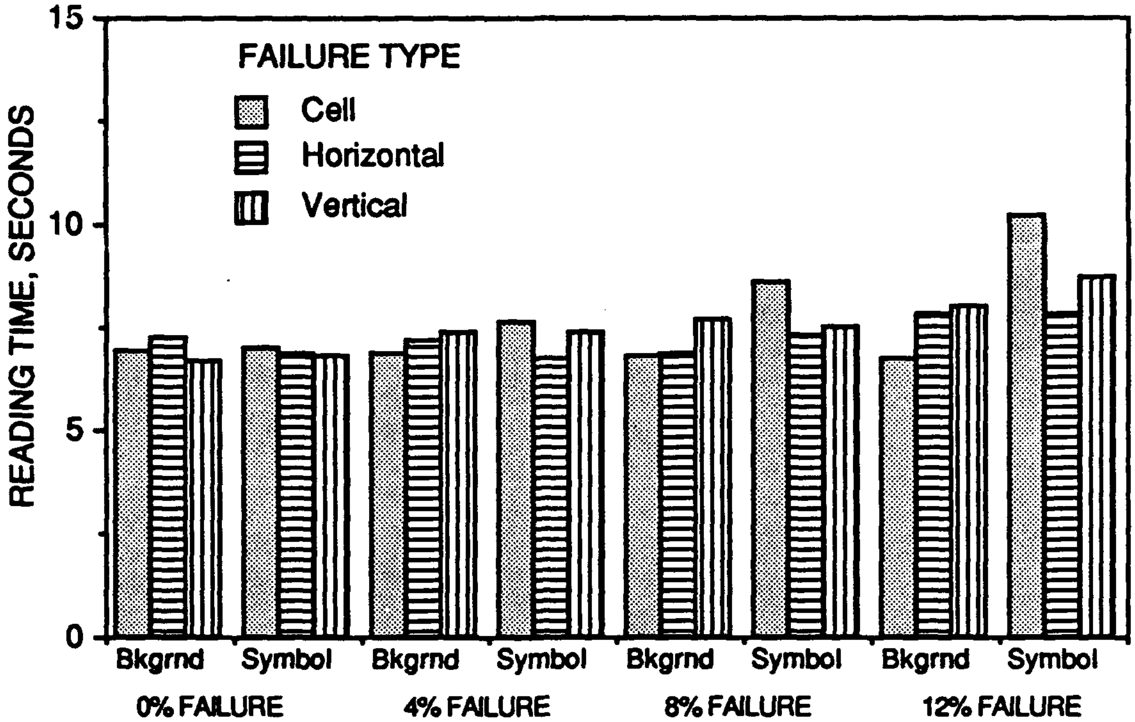

Figure 21. The effect of failure type x failure mode x percent failure interaction on reading time.

Search Time

The search experiment produced data that are sensitive to all the independent variables and many of the interactions, as indicated by Table 4. In evaluating these effects to the extent possible, the mean search times (and search error means) are plotted with the reading time means, all in an effort to show the consistency of the independent variable effects.

Matrix Size

As illustrated in Figure 10, larger matrix sizes yield shorter search times, as was expected (Snyder & Maddox, 1978).

Display Polarity

Consistent with the reading experiment results, a negative contrast (dark symbols) display produced shorter search times (see Figure 11).

Failure mode

Again, consistent with the reading time results, failures that matched the symbols caused longer search times than did failures that matched the background (see Figure 12). In addition, the polarity and mode interact in such a way that the combination of failures that match light symbols produces the longest search times (see Figure 22).

Table 3

Analysis of Variance Summary for Reading Errors

Source of variance	*df*	*MS*	*F*	*p*
Size (S)	2	0.00293	0.94	0.4072
Polarity (P)	1	0.00278	0.94	0.3572
Mode (M)	1	0.00123	0.88	0.3732
Type (T)	2	0.01034	3.12	0.0684
Percent (L)	3	0.00062	0.12	0.9490
S x P	2	0.00139	0.62	0.5499
S x M	2	0.00108	0.56	0.5822
S x T	4	0.00031	0.06	0.9920
S x L	6	0.00818	0.76	0.6039
P x M	1	0.00031	0.26	0.6193
P x T	2	0.00046	0.11	0.9008
P x L	3	0.00278	0.46	0.7123
M x T	2	0.00664	2.82	0.0857
M x L	3	0.00432	1.25	0.3120
T x L	6	0.00447	0.44	0.8477
S x P x M	2	0.00571	3.23	0.0632
S x P x T	4	0.00648	1.06	0.3924
S x P x L	6	0.02454	2.46	0.0527*
S x M x T	4	0.00494	0.74	0.5695
S x M x L	6	0.00262	0.30	0.9321
S x T x L	12	0.00895	0.55	0.8739
P x M x T	2	0.00478	2.56	0.1051
P x M x L	3	0.00648	1.82	0.1678
P x T x L	6	0.01435	1.59	0.1684
M x T x L	6	0.01188	1.11	0.3674
S x P x M x T	4	0.00864	1.25	0.3085
S x P x M x L	6	0.00787	1.02	0.4209
S x P x T x L	12	0.01389	1.03	0.4313
S x M x T x L	12	0.02284	1.12	0.3537
P x M x T x L	6	0.00880	0.75	0.6112
S x P x M x T x L	12	0.01296	0.62	0.8198

*Greenhouse and Geisser (1959) $\varepsilon = 0.7682$

Table 4

Analysis of Variance Summary for Search Times

Source of variance	*df*	*MS*	*F*	*p*
Size (S)	2	1121.75	32.08	0.0001
Polarity (P)	1	349.00	28.19	0.0005
Mode (M)	1	233.43	9.76	0.0122
Type (T)	2	496.37	19.01	0.0001
Percent (L)	3	2957.52	54.93	0.0001
S x P	2	24.08	0.68	0.5209
S x M	2	118.13	2.14	0.1472
S x T	4	122.89	1.45	0.2383
S x L	6	191.97	2.02	0.0784
P x M	1	118.02	20.46	0.0014
P x T	2	177.00	6.57	0.0072
P x L	3	6.93	0.22	0.8784
M x T	2	1540.50	46.71	0.0001
M x L	3	222.72	5.45	0.0043
T x L	6	340.55	6.67	0.0001
S x P x M	2	8.36	0.36	0.7012
S x P x T	4	55.49	2.10	0.1007
S x P x L	6	147.94	2.20	0.0565
S x M x T	4	171.23	2.89	0.0483*
S x M x L	6	141.65	1.50	0.1955
S x T x L	12	232.40	1.68	0.0814
P x M x T	2	44.84	0.98	0.3943
P x M x L	3	64.36	1.08	0.3747
P x T x L	6	87.44	1.04	0.4128
M x T x L	6	1425.09	23.59	0.0001
S x P x M x T	4	48.17	0.94	0.4497
S x P x M x L	6	122.28	1.69	0.1404
S x P x T x L	12	239.87	2.12	0.0343**
S x M x T x L	12	259.86	1.95	0.0584***
P x M x T x L	6	113.71	1.48	0.2039
S x P x M x T x L	12	155.33	0.99	0.4661

* Greenhouse and Geisser (1959) $\varepsilon = 0.8146$

** Greenhouse and Geisser (1959) $\varepsilon = 0.7823$

***Greenhouse and Geisser (1959) $\varepsilon = 0.7287$

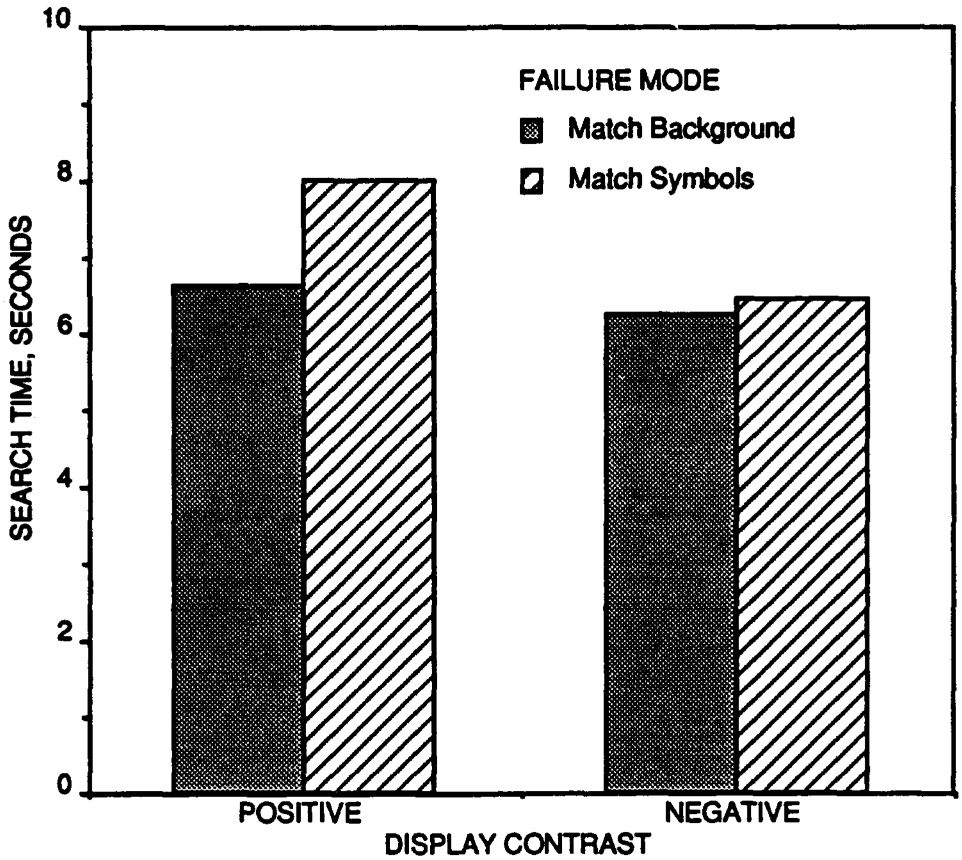

Figure 22. The effect of failure mode x polarity interaction on search time.

Failure Type

As is the case with reading performance, cell failures cause longer search times than do line failures (see Figure 13). This effect appears to be greater for the search task than for the reading task. Much of this strong cell effect occurs when the cell failures match the symbol (see Figure 23) or when the cell failures occur on a positive contrast display (see Figure 24).

Percent failures

Search times increase consistently with increases in the number of cells that failed (see Figure 15), with the effect being fairly linear. As seen in Figure 25, increases in the percentage of cells that failed have a greater impact for cell failures than for line failures. Also, the effect of the percentage of cells that failed is greater when they match the symbols (see Figure 26).

Other Interactions

As might be generalized from the above results, certain combinations of variables are most harmful. Particularly, high percentages of cell failures that match the characters (see Figure 27) and cell failures that match symbols written with small character matrices (see Figure 28) are most damaging.

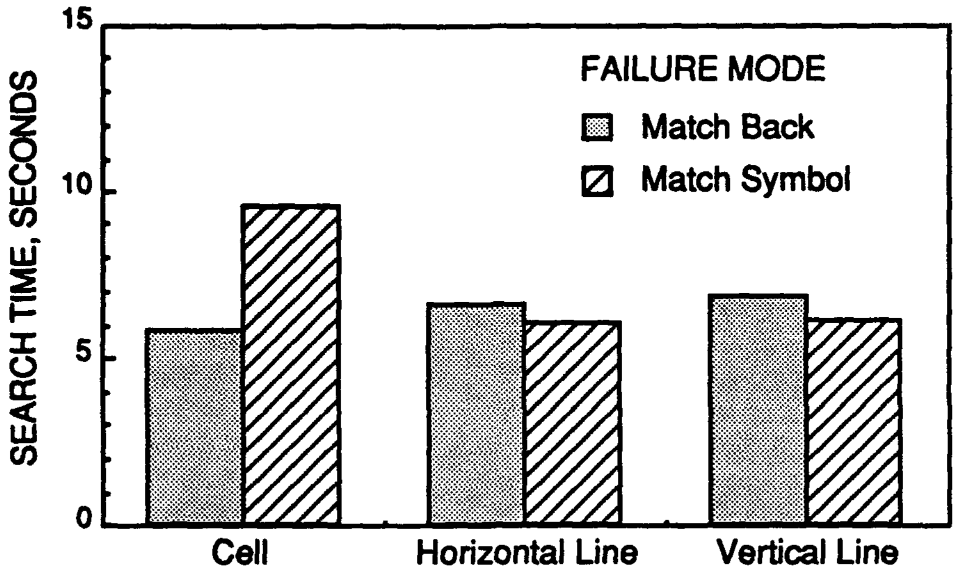

Figure 23. The effect of the failure mode x failure type interaction on search time.

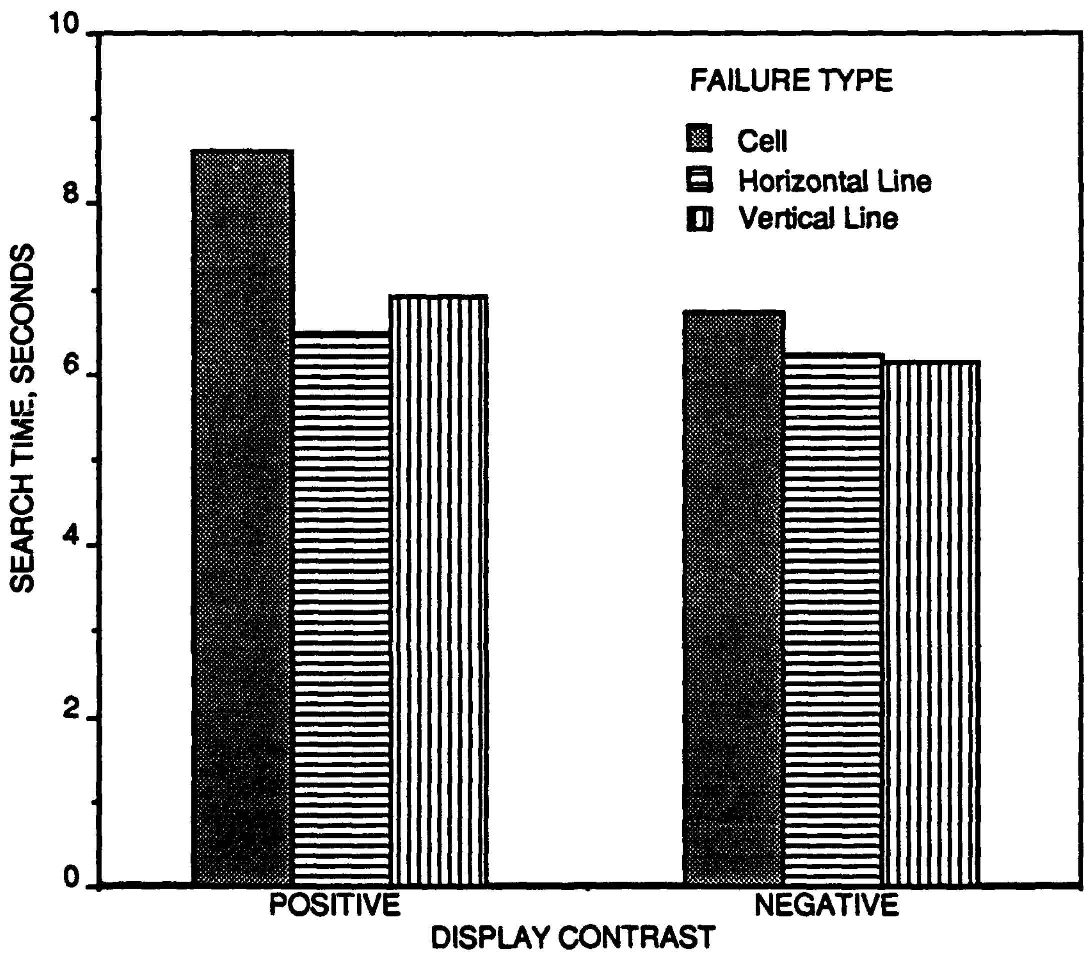

Figure 24. The effect of polarity x failure type interaction on search time.

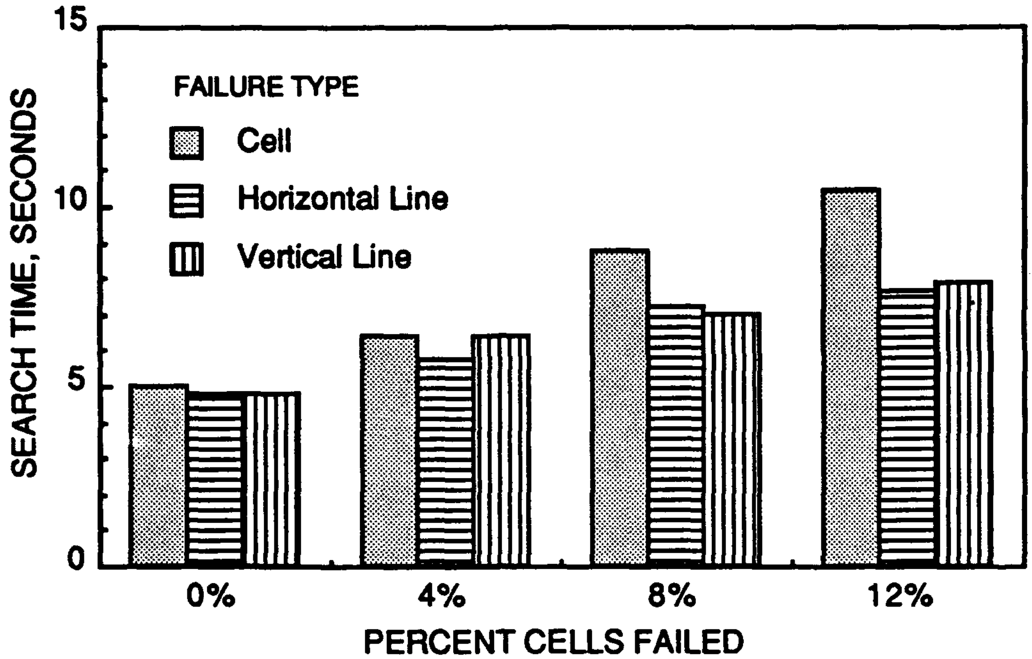

Figure 25. The effect of percent failure x failure type interaction on search time.

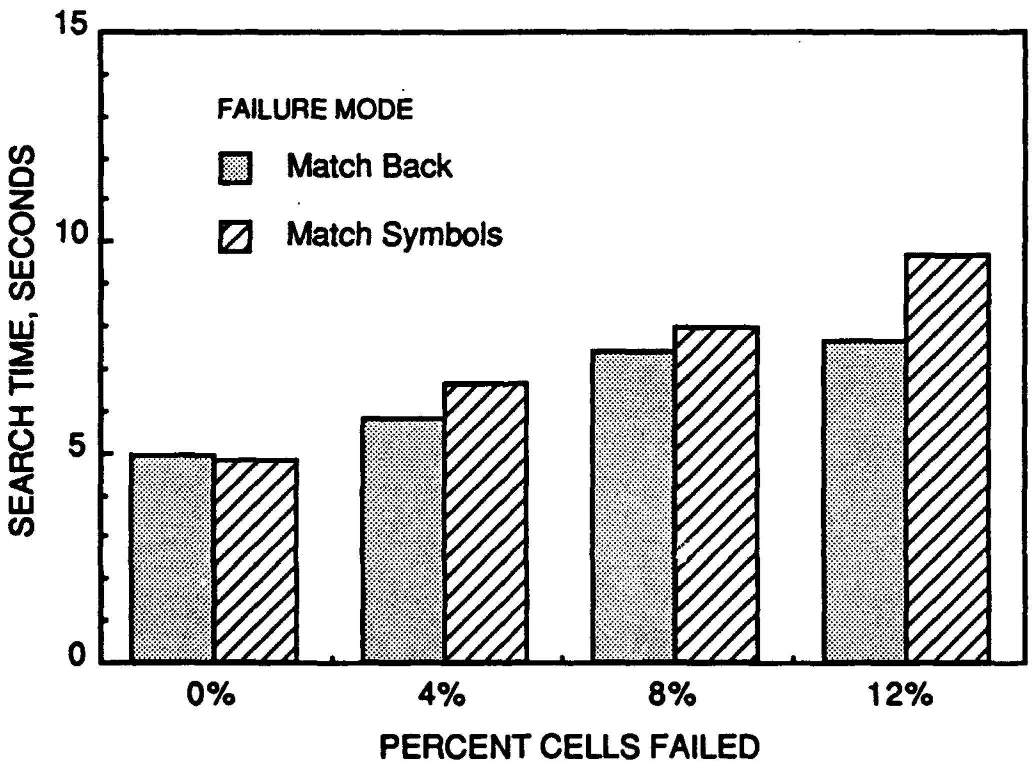

Figure 26. The effect of percent failure x failure mode interaction on search time.

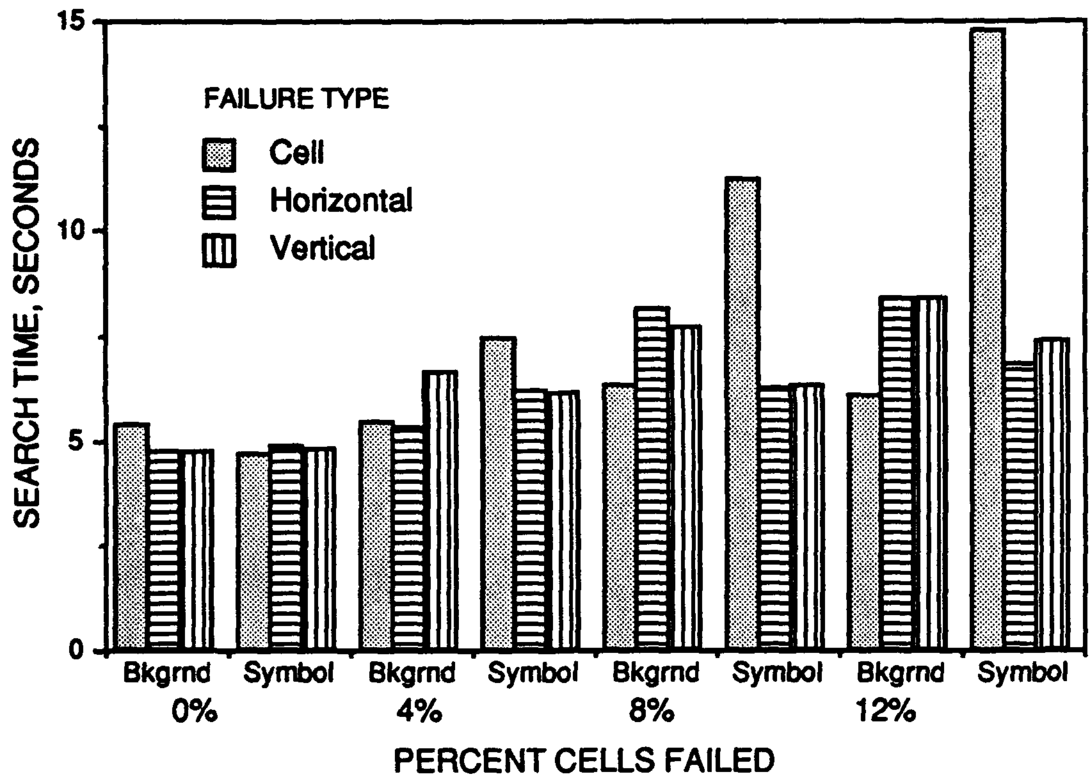

Figure 27. The effect of failure type x failure mode x percent failure on search time.

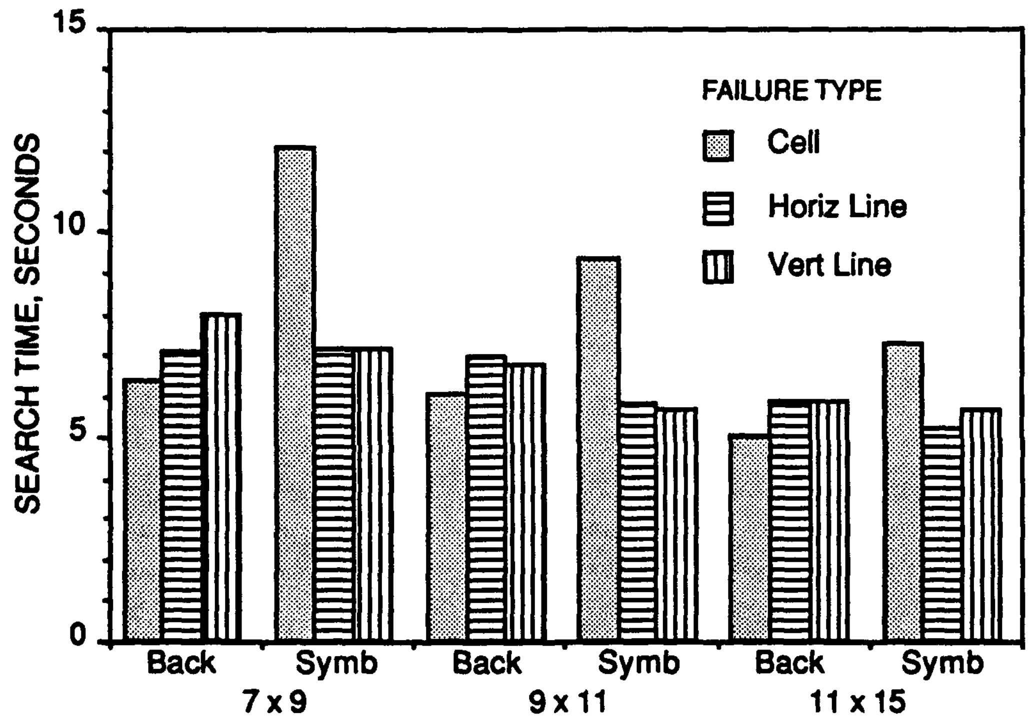

Figure 28. The effect of failure type x size x failure mode interaction on search time.

Search Errors

The errors made during the search task were more numerous (about 11%) than those made during the reading task, probably because of the lack of any contextual advantage (Snyder & Maddox, 1978). Thus, unlike the analysis of reading errors, the analysis of search errors (see Table 5) shows sensitivity to the independent variables nearly as great as that shown by reading time and search time. These effects are described below.

Matrix Size

Increases in matrix size decrease search errors (see Figure 10), an effect totally consistent with the results for reading and search times.

Display Polarity

As is the case for the time measures, better performance as evidenced by fewer search errors occurs with negative contrast than with positive contrast displays (see Figure 11).

Failure Mode

More search errors occur when the failures match the symbols than when they match the background (see Figure 12). This mode effect is large for the 7 x 9 matrix size, less for the 9 x 11 size, and nonexistent for the 11 x 15 matrix (see Figure 29).

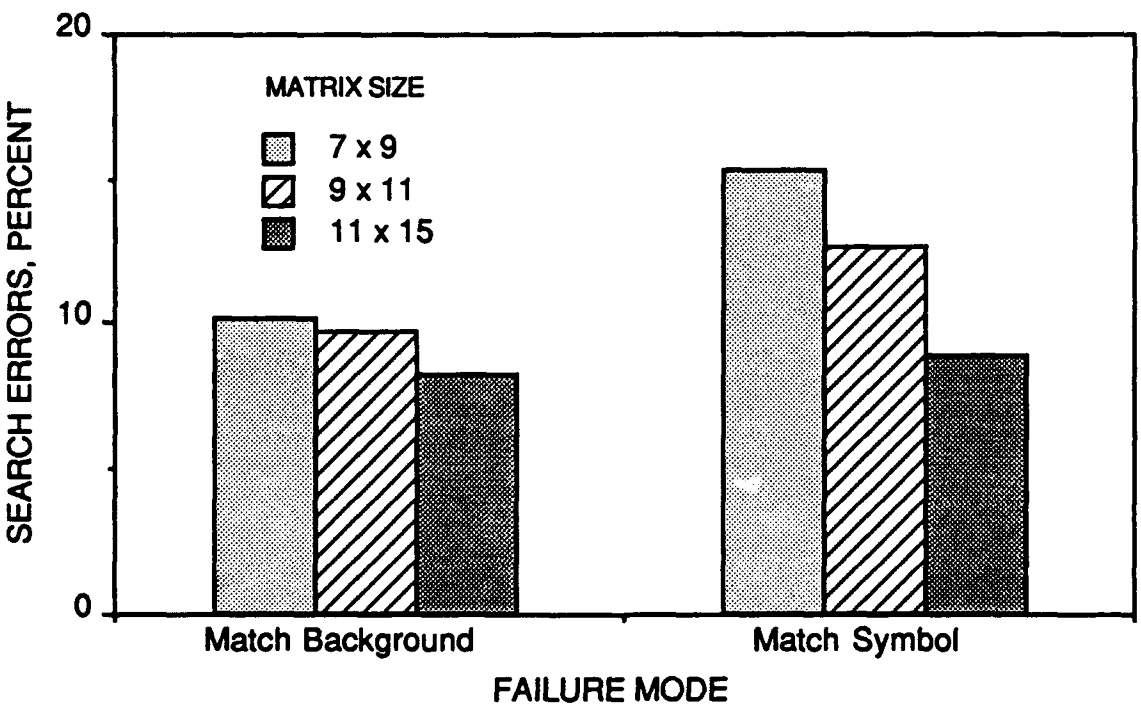

Figure 29. The effect of failure mode x size interaction on search errors.

Table 5

Analysis of Variance Summary for Search Errors

Source of variance	*df*	*MS*	*F*	*p*
Size (S)	2	0.4265	18.94	0.0001
Polarity (P)	1	0.0766	6.79	0.0285
Mode (M)	1	0.2918	17.41	0.0024
Type (T)	2	0.0488	1.76	0.2005
Percent (L)	3	1.1147	14.36	0.0001
S x P	2	0.0681	1.63	0.2237
S x M	2	0.1185	5.53	0.0134
S x T	4	0.0341	0.63	0.6462
S x L	6	0.0840	0.58	0.7460
P x M	1	0.0002	0.02	0.8874
P x T	2	0.0264	1.24	0.3117
P x L	3	0.0266	0.43	0.7341
M x T	2	0.3477	9.92	0.0012
M x L	3	0.1990	3.91	0.0286*
T x L	6	0.2659	4.60	0.0016**
S x P x M	2	0.0681	1.11	0.3512
S x P x T	4	0.1160	2.80	0.0562***
S x P x L	6	0.1063	1.09	0.3774
S x M x T	4	0.0796	1.96	0.1219
S x M x L	6	0.0293	0.51	0.7969
S x T x L	12	0.2637	1.20	0.2932
P x M x T	2	0.0074	0.17	0.8484
P x M x L	3	0.0561	0.67	0.5764
P x T x L	6	0.1364	1.20	0.3213
M x T x L	6	0.5525	4.79	0.0019****
S x P x M x T	4	0.0641	0.88	0.4841
S x P x M x L	6	0.1005	1.39	0.2363
S x P x T x L	12	0.2541	1.59	0.1039
S x M x T x L	12	0.1336	0.62	0.8172
P x M x T x L	6	0.1181	1.59	0.1682
S x P x M x T x L	12	0.2072	0.88	0.5696

* Greenhouse and Geisser (1959) ε = 0.8123
** Greenhouse and Geisser (1959) ε = 0.8092
*** Greenhouse and Geisser (1959) ε = 0.7819
****Greenhouse and Geisser (1959) ε = 0.7681

Failure Type

Interestingly enough, the error rate is totally unaffected on average by failure type (see Table 5 and Figure 13), although the combination of cell failures that matches the symbols (see Figure 30) is especially prone to error generation.

Percent Failures

As the number of failed cells increased, the search errors also increased, in linear fashion (see Figure 15). The percent failure effect was greater for cell failures (see Figure 31) and for failures that matched the characters (see Figure 32). Following this logic a step further, greater rates of cell failures that matched characters (see Figure 33) are particularly likely to produce higher search error rates.

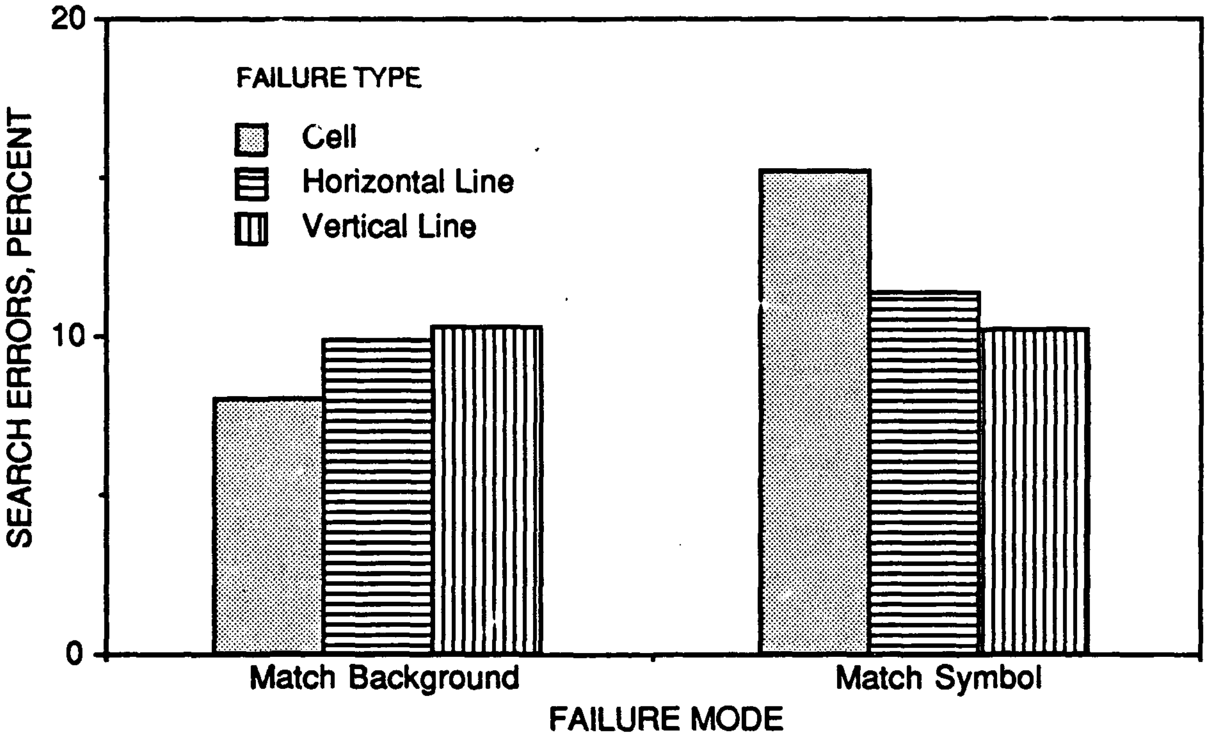

Figure 30. The effect of failure mode x failure type interaction on search time.

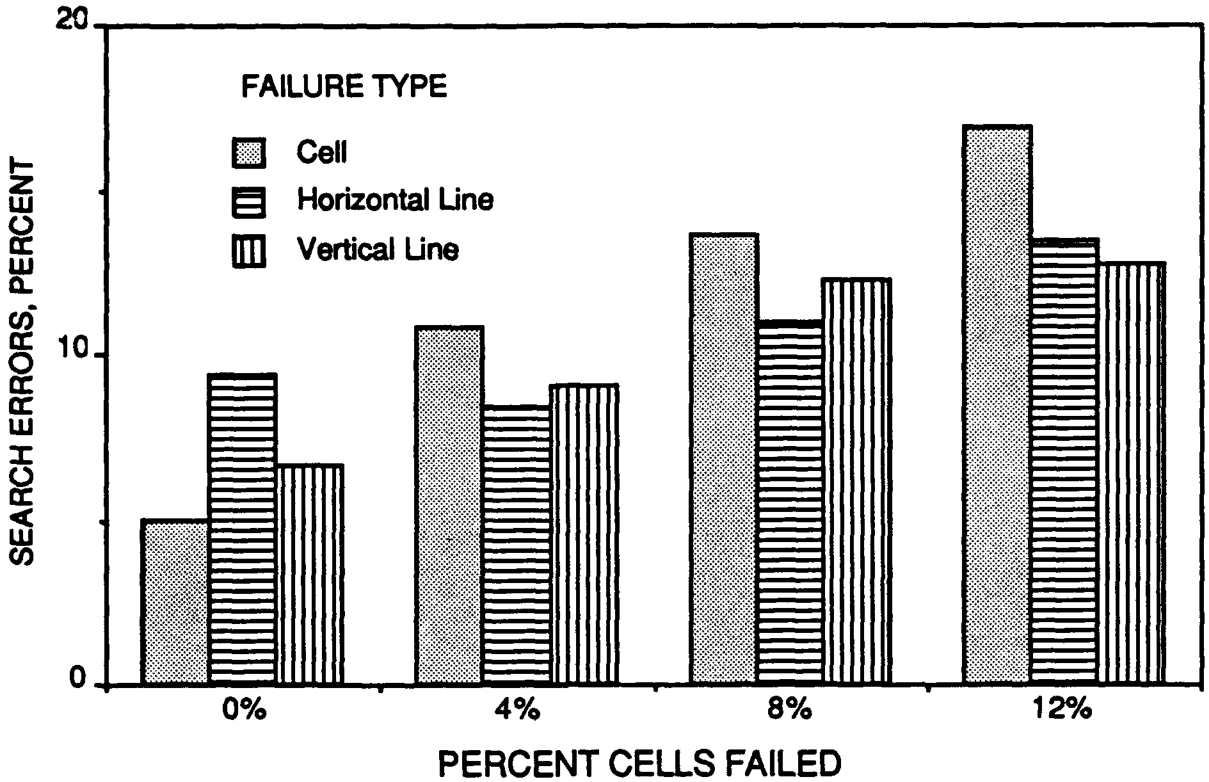

Figure 31. The effect of percent failure x failure type interaction on search errors.

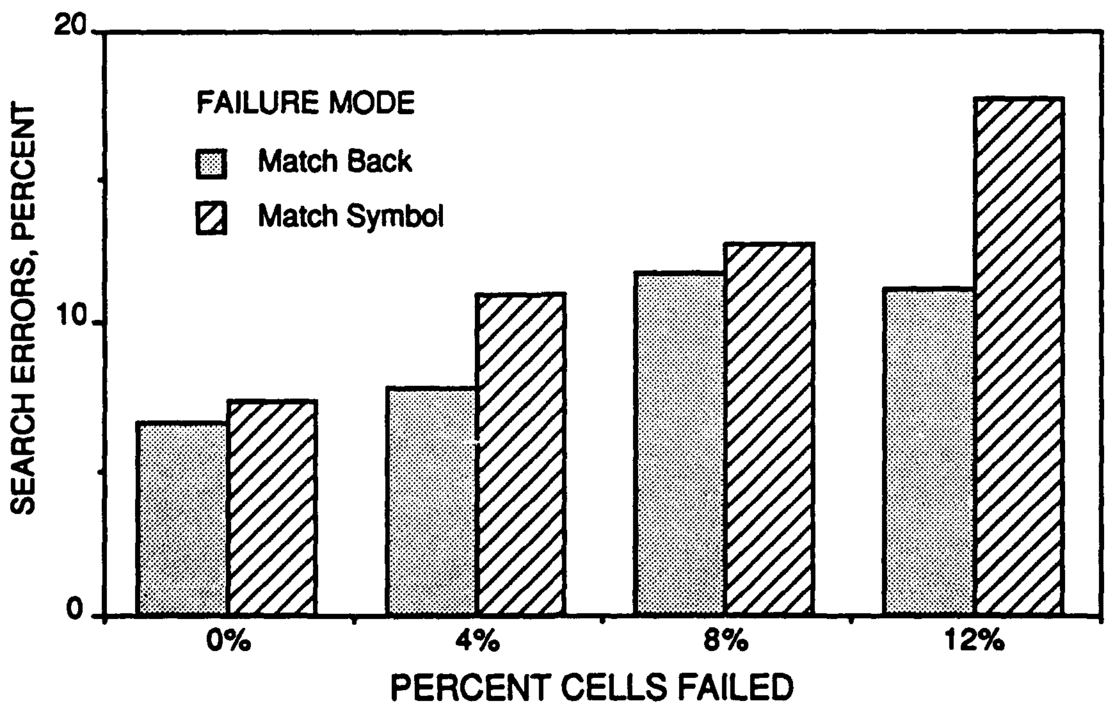

Figure 32. The effect of failure mode x percent failure interaction on search errors.

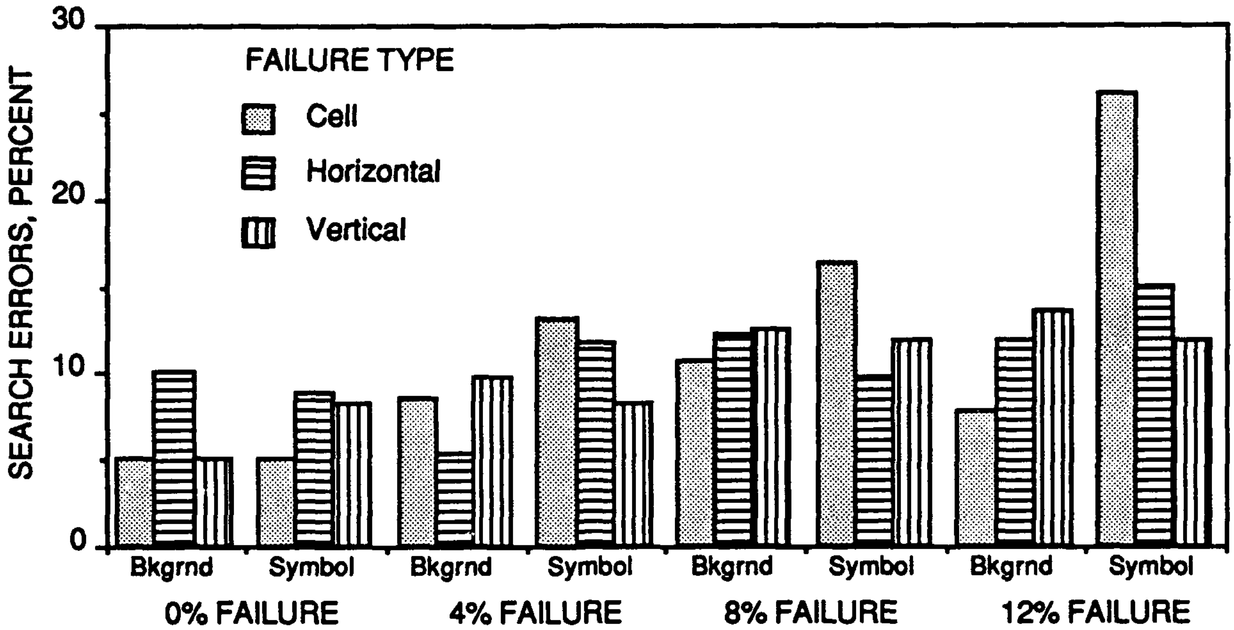

Figure 33. The effect of percent failure x failure type x failure mode interaction on search errors.

DISCUSSION

Much consistency is apparent between experimental tasks and among dependent measures. In every case of a significant main effect, reading time, search time, and search errors vary in the same fashion. Thus, there is little evidence of speed-accuracy tradeoffs being made across experimental conditions by the subjects.

By comparison, none of the main effects for the dependent variable reading errors was significant. This result is explainable by the fact that very few errors were made; the overall error rate for the reading task was only 0.5%.

Some care should be exercised in interpreting the results of the main effects of failure mode and failure type. These variables are biased toward the conservative side since the 0% failure level condition has been averaged with the non-0% level conditions. The variables failure mode and failure type are not meaningful if no failures are present.

With respect to the variables of failure type, failure mode, and percent failure, the results of both of the present experiments closely correspond to the results obtained by Abramson et al. (1983). In all three experiments, cell failures impact performance more strongly than do line failures, especially if the cells fail on (match the symbol luminance). Off failures (those matching the background luminance) were generally found to be less degrading than on failures.

Both experiments indicate that performance is better when using dark symbols on a light background than for the reverse condition. This result is particularly important, not only for flat panel display design purposes, but also for visual display terminal (VDT) applications. Current U.S. standards (Human Factors Society, 1988) make no recommendation between the two polarities, asserting that no reliable performance differences have been demonstrated. Heretofore, studies comparing the two polarities have not addressed the constancy of other variables such as line width, contrast, resolution, and the display's modulation transfer function (MTF). In this experiment, these other variables were kept essentially constant. Thus, it appears that a negative contrast display has inherent performance differences beyond those related to glare reduction by the light background.

Comparisons across these experiments show the random search task to be much more sensitive to failures than the reading task. With 4% failures, search performance is degraded 28%, whereas reading performance is degraded only 4% from the no-failure condition. This result is to be expected, since the reading task provides contextual benefit by partial redundancy among characters within words.

In the present two experiments, many of the interactions between variables were significant. In all cases, the interactions indicate that the deleterious effects of the independent variables are multiplicative. Eliminating one negative influence therefore significantly reduces its combined effect with other variables.

CONCLUSIONS

A number of display design and use recommendations are supported by the results of these experiments.

Polarity

The experiments indicate that roughly a 14% improvement in search time, a 12% improvement in search error rate, and a 7% improvement in reading time can be expected by using dark symbols on a light background as compared with light symbols on a dark background. These values are generally consistent with other research in which relevant display variables were held constant.

Size

For failures of any type or level, improvements of about 27% for search time, 33% for search error rate, and 7% for reading time were obtained by using dot matrices larger than 7 x 9 pixels. These values are also in general agreement with existing literature.

Failure Mode

If cell failures are expected, it is important that they match the background. At the 12% failure rate, failures matching the background luminance degraded search time by 20% whereas failures matching the symbol luminance degraded performance by 300% when compared with the 0% failure condition. Similarly, failures matching the background degraded search error rate by 10% whereas failures matching the symbols degraded performance by 370%. These results support the notion put forth by Laycock (1985) regarding manufacturing yields, "If point failures of the 'on' type could be detected in the early stages of manufacture and converted into 'off' failures, then the yield of viable displays could be considerably increased."

On a similar note, if many more on than off failures are detected, the display might be used with the polarity opposite that which was originally planned. The on failures would thus be interchanged with the off failures.

Task

Finally, these experiments show that the random search task is affected more than is the reading task by display failures. Consequently, display design parameters for search type tasks in particular need to be selected in such a manner as to limit the effects of partial display failures.

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APPENDIX A

INSTRUCTIONS FOR READING TASK

INSTRUCTIONS FOR READING TASK

In this experiment, you will be shown short (one or two sentences) passages on the display. One word in each of the passages does not fit into the context of the rest of the passage. Your task is to identify this word **as quickly and as accurately as you can**, and to report it aloud to the experimenter.

At the beginning of each trial, the word "READY" will appear on the screen. When you feel you are ready to read a passage, press the far right button on the mouse input device. As soon as the passage is written on the screen, begin reading the passage to yourself. When you have found the incorrect word, press the far left button on the mouse input device. Pressing the left button erases the screen and stops the timer for that trial. **After** you have pressed the left button, report the incorrect word aloud to the experimenter. During the trials, noise may be introduced onto the screen, and you will be required to read the passage which is embedded in the noise.

During the experiment, please respond **as quickly and accurately as possible**--both are important. Also, please keep your head in a straight and upright position throughout the experiment. Moving your head will move your eyes from the intended position.

You will first participate in several practice trials to familiarize you with the passages and the input device. After the practice session if you have any questions, please ask. The experimental trials will begin immediately following the practice session. The experiment will take approximately 2-1/2 hours. You will be given several short rest periods throughout.

Do you have any questions?

APPENDIX B

INSTRUCTIONS FOR SEARCH TASK

INSTRUCTIONS FOR SEARCH TASK

In this experiment, you will be asked to search for an alphanumeric character (letter or numeral) 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-hand 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-hand 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 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 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.