Technical Memorandum 6-91

THE EFFECTS OF CHARACTER SIZE, MODULATION, POLARITY, AND FONT ON READING AND SEARCH PERFORMANCE IN MATRIX-ADDRESSABLE DISPLAYS

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This research is the second in a series of experiments undertaken to develop optimum design criteria for matrix-addressable displays. This study examined the effects of character size, luminance modulation, font, and polarity on both contextual task (reading) performance and performance in a random search task.

The random search task consisted of locating a target letter or numeral within one of nine sectors on the display. Only upper case alphabetic characters and the numerals 0 through 9 were used. Using a font (3) by modulation (3) by polarity (2) by character size (3) within-subjects factorial design, only the main effects of character size, font, and polarity were found to be significant. There were no significant interactions. Post hoc analyses indicated that response speed increased as character size increased from a

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7 x 9 matrix, to a 9 x 11 matrix, to an 11 x 15 matrix. Post hoc analyses revealed that response times were longest with the maximum dot font, but did not significantly differ between the Huddleston and Lincoln/MITRE fonts. Additional post hoc comparisons indicated that negative contrast (dark characters on a light background) produced significantly faster response times than did positive contrast (light characters on a dark background).

The contextual task consisted of a modified version of the Tinker speed of reading task. Using a font (3) by modulation (3) by polarity (2) by character size (3) by case (2) within-subjects factorial design, significant case, font, and polarity main effects and a case-by-font interaction were found. The maximum dot font required longer reading times than the Huddleston font, which was in turn inferior to the Lincoln/MITRE font. Reading times were shorter for negative contrast (dark characters on a light background) than for positive contrast. Mixed case text was read more quickly than all upper case text.

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INTRODUCTION

Although a wealth of experimental data exists about various factors affecting the visual perception of information on the printed page, the systematic investigation of these same factors about the perception of visual information on cathode ray tube (CRT) and flat panel display devices is lacking in the literature. Many designers have applied the results of studies based on printed reading tasks, but the generalization from the printed page to the electronic display is questionable at best. The constraints that this medium imposes upon the placement and composition of characters and symbols are different in nature and perhaps greater than those imposed by printing. For example, most designers of printed pages can choose from a variety of discrete widths to use for a character's "stroke width," whereas the designer of the electronic display must build characters from a series of discrete dots or lines fixed in width and height. In addition, there is a fundamental difference between printed and electronic displays, specifically the occasional tendency for electronic (matrix-addressed) displays to fail locally (Decker, Pigion, & Snyder, 1987). That is, some electronic displays will fail by having certain portions or elements of the display remain in the "on" or "off" state, regardless of the intended state of that display location. As the display failures increase in number, the display becomes logically less legible and therefore less usable. Unfortunately, data to support acceptability decisions and product quality assurance are generally unavailable, so the user or purchaser must decide whether to accept or reject a partially failed display with no supporting quantitative basis or data.

The absence of design criteria and quality metrics regarding display failure rates is characteristic, however, of a general lack of quality measures for most aspects of electronic display performance. Most of the existing research was developed around spatially continuous displays. The data that exist for matrix-addressed displays typically address one or two variables (e.g., matrix size, font, case) in isolation (often confounding the variables of interest with other significant factors) and fail to describe the possible interactions among these variables.

The present research was undertaken to examine the effects of four such variables in combination on visual task performance using a matrix-addressed display: character size, font, modulation, and polarity. Two tasks were used, namely, a modified Tinker reading task and a random search task. In the reading task, an additional variable, case, was added because of its known effect on reading speeds (Tinker, 1955; Vartebedian, 1970b). Both speed of response and accuracy data were collected during both tasks. Each of these independent variables is discussed.

Character Size

In general, performance has been found to improve with increases in character size until the size of the character exceeds the amount of important information that can be obtained within one fixation. Using stroke-generated alphanumerics, Howell and Kraft (1959) investigated the effects of character size, blur, and contrast on legibility of single alphanumeric characters and found that characters of 26.8 minutes of arc (arcmin) vertical subtense were necessary to maintain high accuracy during degraded viewing conditions. An increase to 36.8 arcmin did not improve performance. During nondegraded conditions, performance at 16.4 arcmin was approximately equal to performance for the larger sizes of 26.4 and 36.8 arcmin.

Giddings (1972) compared five alphanumeric character heights subtending 28, 21, 18, 14, and 7 arcmin and found increases in reading speed for both the smallest and largest character sizes. Giddings therefore recommended an optimum character height between 18 and 21 arcmin for stroke-generated characters.

In his 1978 review of the literature, Smith found recommendations ranging from 10.31 to 24.06 arcmin, with 5.16 arcmin the lower limit based on normal visual acuity. Using these recommendations, he experimentally determined that a mean letter height of 6.53 minutes was the limit of legibility for stroke characters, while 10.31 minutes resulted in 90% legibility and 24.06 minutes resulted in 100% legibility.

Snyder and Taylor (1979) manipulated character size, display luminance, and viewing distance. For accuracy data, there was a significant improvement in performance as character size increased. However, character size interacted with display luminance (and therefore contrast) so that the greatest improvement in accuracy with larger characters occurred at 80 candelas per square meter (cd/m^2), followed by 27 cd/m^2, and finally, 8 cd/m^2. Their response time data also showed significant effects of character size, luminance, and viewing distance. As character size or luminance increased, response time decreased.

Character size is a critical design parameter in legibility. Although most research has examined this parameter regarding stroke-generated characters, it is questionable whether the results from these studies can be generalized to dot-matrix characters. The primary distinction between stroke-generated and dot-matrix fonts lies in the fact that the dot-matrix font is comprised of discrete elements in geometrically constrained locations. Thus, the legibility of these fonts rests heavily on element size, interelement spacing, and the number of elements used to form each character.

In the dot-matrix display, element size, interelement spacing, and character size are necessarily confounded. If element size is increased, interelement spacing must decrease to keep the character size the same. Conversely, if interelement spacing is increased, the elements must be decreased in size. When researchers try to compare 5 x 7 matrices with other matrix sizes, they are usually confounding interelement spacing, leaving character size, element size, and shape constant. Matrix size is often investigated so that character size is allowed to increase with matrix size. The importance of matrix size is largely attributable to the belief that the larger the matrix, the more elements used to generate the character, with the more dots per unit area more closely approximating the shape of a stroke font.

Only one study to date examined the effects of character size, matrix size, and interelement spacing without confounding these variables. Snyder and Maddox (1978) investigated the effects of matrix size on the legibility of four different fonts. Three matrix sizes were investigated: 5 x 7, 7 x 9, and 9 x 11. Character size was allowed to increase as dots were added; however, these investigators also designed 7 x 9 and 9 x 11 matrix size characters to remain the same size as the 5 x 7 characters by reducing the dot size and using the same dot-to-space ratios for each matrix. This approach provided a condition during which the effects of character size were not confounded with matrix size. Using a single character recognition task, the main effect of matrix size was found to be significant. In general, the results of this study indicate that larger matrix sizes result in better single character recognition performance (fewer recognition errors). Results also indicate that performance with the larger matrix sizes combined with smaller character size was better than that obtained using larger matrix sizes and larger characters. The superior performance with larger matrix size agrees with results of studies in which character and matrix sizes are confounded. Vartebedian (1971a) investigated the difference between 5 x 7 and 7 x 9 matrix sizes and found the 7 x 9 matrix to be superior. This study is frequently cited as the basis for matrix size recommendations, although it should be noted that Vartebedian confounded matrix size and character size, as well as other factors.

The present study examined the effects of three matrix sizes (7 x 9, 9 x 11, and 11 x 15) and allowed character size to increase as dots were added to the matrix. Thus, the visual angle subtended by each character increased as matrix size increased, which is the most typical design condition, assuming that character and matrix size is a software-controlled parameter for a display that has fixed pixel size and spacing.

Font

Font refers to the geometrical characteristics or style of the symbols or alphanumerics. Character font or style can have a significant effect on both readability and legibility of characters and symbols. As noted by Cornog and Rose (1967), the visual attractiveness of a font does not necessarily correlate with its legibility, most readable fonts being those that seem the least interesting and vice versa.

According to Sherr (1979), electronic displays are limited in the types of fonts that can be displayed based on the generation technique used. The "stroke" technique for character generation offers the widest flexibility in font generation, but the "dot-matrix" technique is the most commonly used (Sherr, 1979). Of course, only matrix-generated characters are possible on matrix-addressed displays. Unlike stroke-generated characters, dot-matrix alphanumeric characters are limited by the available matrix size in the amount of detail or distinguishing characteristics for each character. As noted by Maddox, Burnette, and Gutmann (1977), "It has not been satisfactorily demonstrated that the conclusions from stroke font research are directly transferable to dot-matrix fonts," yet few studies exist that directly compare the two. Vartebedian (1970a, 1971a) compared stroke versus dot-matrix characters in which the dot-matrix characters were presented in both 5 x 7 and 7 x 9 matrices. The dot-matrix font was one designed by Vartebedian for maximum legibility, whereas the stroke characters were based on the Leroy font. Not surprisingly, he concluded that dot-matrix generation was superior to stroke generation. It should be noted, however, that this conclusion seems unwarranted since font was confounded with the character generation technique, thus precluding any direct, unbiased comparison of fonts.

In another study, Vartebedian (1971b) investigated font generation technique, letter size, and case (upper and lower). Once again, font generation technique was confounded with font. The only significant effect found in this study was that of case: upper case words were recognized significantly faster than lower case words. One possible explanation is the generally larger size of upper case characters compared to lower case characters.

Maddox et al. (1977) compared three fonts presented in a 5 x 7 matrix using a letter recognition task. Their fonts included a dot-matrix adapted Lincoln/MITRE font, a maximum angle font, and a maximum dot font, the latter two developed specifically for this study. The maximum dot font was created using as many dots in the matrix as possible to represent each character; thus, the characters had a "box-like" appearance. The maximum angle font used fewer dots to lend an angular appearance to the characters. Single letters were presented tachistoscopically to the subjects, and accuracy data were collected. Significantly fewer errors were recorded for the maximum dot font than for either the Lincoln/MITRE or the maximum angle fonts. It should be noted, however, that since the maximum dot font used more dots per character, it appeared brighter although individual dot luminance and size were kept constant across fonts.

Snyder and Maddox (1978) compared these same three fonts and an additional (Huddleston) font across three matrix sizes (5 x 7, 7 x 9, and 9 x 11). The character size was allowed to increase with increases in matrix size. These researchers also designed 7 x 9 and 9 x 11 fonts in which character size was kept constant to that of the 5 x 7 matrix by reducing dot size and spacing. They found a significant main effect of font as well as a font by matrix size interaction. Post hoc comparisons indicated that the Huddleston and Lincoln/MITRE fonts were significantly superior to the maximum dot font, but did not differ significantly from each other. For the 5 x 7 matrix, the Huddleston font was superior, while for the 7 x 9 and 9 x 11 matrices, the Lincoln/MITRE font was superior to the Huddleston.

In the present study, three fonts were investigated (Lincoln/MITRE, maximum dot, and Huddleston) to determine which of the three would yield the best performance during two types of tasks--a contextual (reading) task and a random search task. Mixed case fonts were included for the reading task.

Luminance Modulation

Luminance contrast or modulation is defined as the contrast between any "on" element and its "off" background. If the maximum or on luminance is symbolized as L_{max} and the background or off luminance is symbolized by L_{min}, the following relationship holds:

$$\text{Modulation, } M = (L_{max} - L_{min})/(L_{max} + L_{min}). \qquad (1)$$

Howell and Kraft (1959) manipulated character size, modulation (as defined by equation [1]), and blur. Simulated CRT characters and numerals in the Mackworth font were used as stimuli. All main effects and the modulation by size by blur interactions were significant. There was little difference in performance (as measured by correct identifications and response speed) when modulation was increased from 86% to 95% for characters larger than 16 arcmin. When characters were smaller than 16 arcmin or blurred, an increase in contrast was necessary. The authors recommended modulations of 94% with 88% being considered acceptable.

Based on several additional research studies, Snyder and Maddox (1978) recommend a minimum dot modulation (for matrix displays) of 90% for noncontextual displays and a minimum dot modulation of 75% for contextual displays. Shurtleff (1980) recommended a modulation of 89% for characters smaller than 20 arcmin and possibly higher yet for character sizes smaller than 10 arcmin.

The recently promulgated American National Standard (ANSI) for visual display terminal (VDT) work stations (Human Factors Society, 1988) requires a minimum modulation of 0.5 (contrast 3:1) with a modulation of 0.75 being preferred. For characters smaller than 18 arcmin, higher contrast is recommended based on the following equation:

$$M = 0.3 + 0.7(20 - S), \tag{2}$$

in which S is the height of the characters in minutes of arc and modulation is defined as in equation (1).

Modulation is a critical display variable that has been found to interact with character size and type of display (contextual versus noncontextual), among other factors. In general, when the display is degraded in some form, such as by small character sizes or high ambient illumination, a compensating larger contrast ratio or modulation is required to achieve a given legibility. The present study included three levels of modulation (82%, 72%, and 50%) for both contextual and noncontextual display conditions while manipulating character size, polarity, font, and case (in the reading task).

Display Polarity

Display polarity refers to whether images on a display are light on a dark background (positive contrast) or dark on a light background (negative contrast). According to Rupp (1981), Europe is concerned with this topic, and recommendations for "positive image" (negative contrast) displays are typical. One occasionally expressed concern is that when display users are successively fixating between a source document with dark characters on a light background and a display screen with light characters on a dark background, the pupillary response is taxed and may result in user visual fatigue. Rupp (1981) found that this was not a problem.

Bauer and Cavonius (1980) investigated the effect of polarity on the legibility of four-letter nonsense words. Polarity conditions were positive contrast with a background luminance of 4 cd/m^2, positive contrast with a background luminance of 80 cd/m^2, and negative contrast with a background luminance of 80 cd/m^2. Subjects were required to change their eye fixations from the screen to another display to simulate the situation in which users are looking back and forth between the display and a source document. Error rates were collected. The authors equated perceived stroke width by reducing the stroke width of letters for positive contrast displays by 20% to adjust for the effects of irradiation or spread of light characters on a dark background (D. Bauer, personal communication, 1981). Results indicated that the negative contrast condition (at 80 cd/m^2) resulted in a significantly lower error rate than the positive contrast (4 cd/m^2). The positive contrast (80 cd/m^2) conditions was significantly worse than the other two conditions, and observers complained that the letters were too bright.

In a review of the literature, Semple, Heapy, Conway, and Burnett (1971) found that display polarity did not affect character identification. Shurtleff (1980) discussed two studies by Seibert. One study found that negative contrast was superior to positive contrast, and the other study found the opposite results.

Cushman (1986) reported that reading speed and comprehension on CRT displays were unaffected by display polarity, although there was not a significant tendency for faster reading of dark characters. On the other hand, he reported that subjects complained of feeling more fatigued after reading dark characters on a CRT than after reading light characters. Gould et al. (1987a) and Gould, Alfaro, Finn, Haupt, and Minuto (1987b) found almost identical reading rates on high contrast photographs, printed in both polarities, of material shown on IBM 3277 displays and no differences when comparing the same subjects during a proofreading task designed to directly compare paper versus VDT reading. In the second study (1987b), 10 of 15 subjects preferred light characters on a dark background instead of reverse polarity. Five subjects thought that the light background was too bright, and four others thought the light background had more flicker and that the characters were less sharp. Those who preferred the negative contrast condition reported that it was close to the traditional way of reading.

The ANSI VDT standard (Human Factors Society, 1988) states that either image polarity is acceptable as long as requirements for luminance, contrast, and resolution are met. It also states that dark characters on a light background may reduce distracting reflections from the display surface.

Isensee and Bennett (1983) found that flicker was perceived at smaller angles for negative contrast images. Therefore, a higher refresh rate may be required for displays with negative contrast (light background).

Although the current status of the literature would suggest that there is no legibility difference between positive and negative contrast displays, there has been no assessment of the possible interaction between polarity and several other design variables. Consequently, both positive and negative contrast conditions were used in the current study to determine if the polarity variable interacts with character size, font, modulation, and case (in the reading task).

METHOD

Experiment 1: Random Search Task

Subjects

Twenty subjects (seven females) participated in this experiment. Subjects had a mean age of 21.4 years with a standard deviation of 1.7 years and were paid $5.00 per hour for participation. Subjects were tested for corrected 20/22 near and far point visual acuity, lateral phoria, and vertical phobia using a Bausch and Lomb orthorater. Subjects were then tested for normal near and far contrast sensitivity using a Vistech system.

Subjects estimated the number of hours per week they spent using a computer display. The mean use was 5.3 hours. The distribution of the estimates is markedly skewed with a median of 2 hours and a mode of 0 hour per week.

Apparatus

Stimuli were presented on a Tektronix GMA201 high resolution monochrome CRT with a 48-centimeter (cm) diagonal screen. The CRT had a bandwidth and spot size capability for displaying 2048 x 2048 pixels; however, the graphics controller constrained the active area to 1024 x 1024 pixels with dimensions of 27 x 27 cm. Horizontal and vertical pixel densities were both 38 pixels/cm.

An eight-bit plane PEPE graphics controller (Vectrix Corporation) was used to store and display images. The graphics controller was installed in an IBM personal computer (PC-AT) that controlled stimulus generation, stimulus presentation, and data collection. Subjects responded using a three-button mouse input device (Mouse Systems). The time-of-day clock built into the PC was used for timing the subject's responses. The resolution of this clock is 55 milliseconds (ms).

Subjects sat in an hydraulic dental chair that could easily be adjusted in height and distance from the CRT. Subjects rested their foreheads against a pad while a headrest attached to the chair was positioned against the backs of their heads. Subjects were positioned so that the distance from their eyes to the center of the screen was 50.8 cm, and their line of sight to the center of the CRT was 15° below horizontal. The display was tilted 15° so that the line of sight was normal to the center of the CRT.

Stimuli

Stimuli consisted of the 26 upper case letters of the alphabet and the numerals 0 through 9. Three characters sizes were used with characters drawn within 7 x 9, 9 x 11, and 11 x 15 dot matrices. Table 1 lists visual angles for these matrices.

Table 1

Dimensions of Dot Matrices

Number of pixels	Dimensions (mm)	Visual angle (arcmin)	Aspect ratio
11 x 15	2.86 x 3.91	19 x 25	1.36
9 x 11	2.34 x 2.86	15 x 19	1.22
7 x 9	1.82 x 2.34	12 x 15	1.29

Three fonts were investigated: Huddleston, Lincoln/MITRE, and maximum dot. These fonts are illustrated in Figures 1 through 27. The alphanumerics were displayed with modulations of 0.82, 0.72, and 0.50. Additionally, the alphanumerics were displayed as either positive contrast (light characters on a dark background) or negative contrast (dark characters on a light background). A 3 (fonts) x 3 (matrix sizes) x 3 (modulations) x 2 (polarities) within-subjects factorial design was used for the experiment.

Photometric Measurements

Luminance and modulation levels were set using a photometric system that consists of a scanning telemicroscope (Gamma Scientific, Model GS-2110) with a 10- x 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 system is controlled by an IBM PC-XT.

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

For each modulation and polarity condition, photometric scans were made of a vertical line displayed in the center of the screen. For the positive contrast conditions, the luminance of the line was set as closely as possible to 35 cd/m^2. The background luminance level was then varied to obtain modulation values as close as possible to 0.82, 0.72, and 0.50. These values are listed in Table 2.

Table 2

Measured Modulations for Each Contrast Condition

Nominal modulation	Negative contrast modulation	Positive contrast modulation
0.82	0.829	0.882
0.72	0.718	0.816
0.50	0.497	0.640

For the negative contrast conditions, the background luminance was set as closely as possible to 35 cd/m^2 by making scans across several columns of pixels. The line luminance was then varied to obtain the three modulation levels. Actual modulation values are shown in Table 2. The bit values for these luminance levels were programmed into the experimental software.

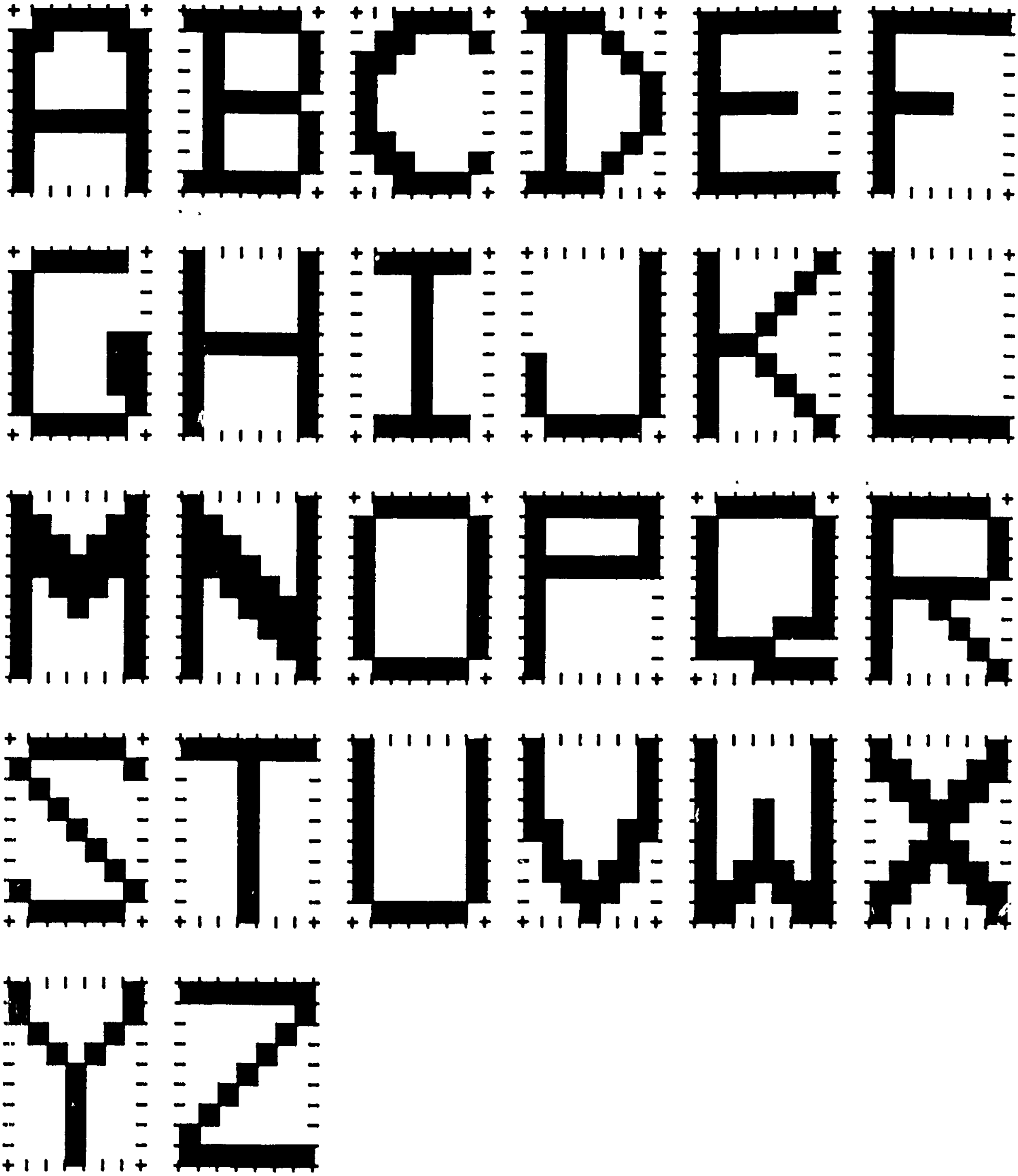

Figure 1. Huddleston font upper case letters in 7 x 9 matrix size.

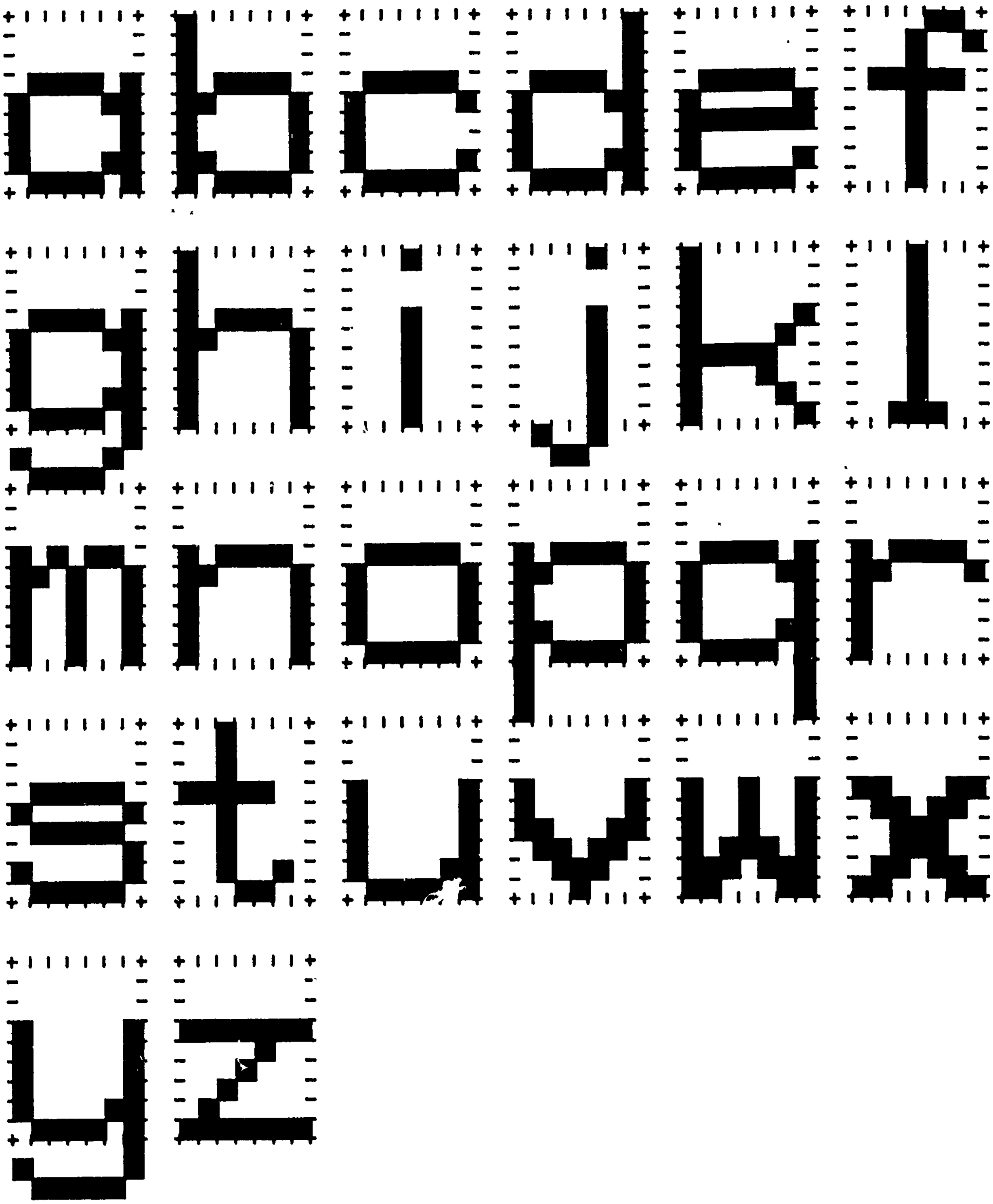

Figure 2. Huddleston font lower case letters in 7 x 9 matrix size.

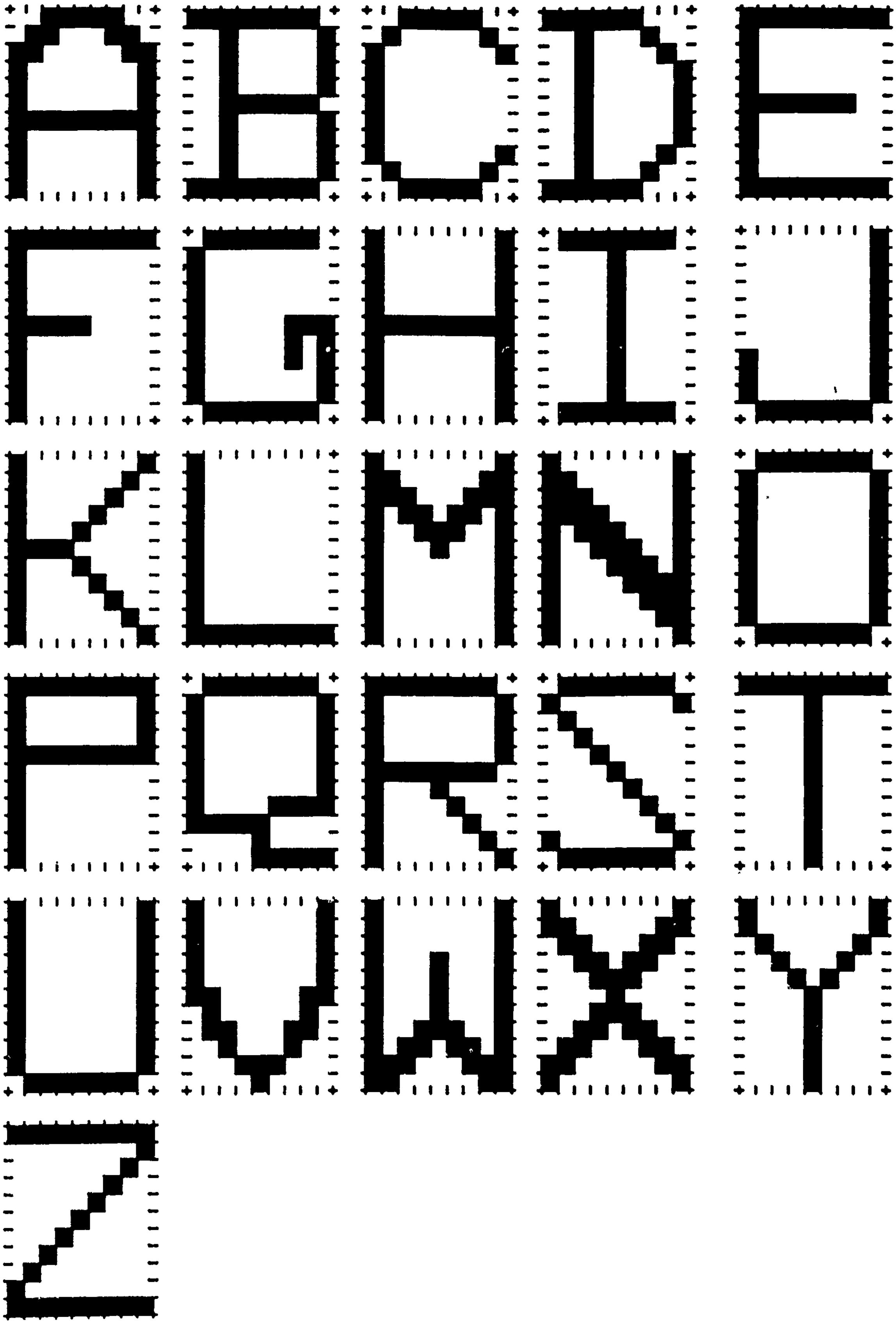

Figure 3. Huddleston font upper case letters in 9 x 11 matrix size.

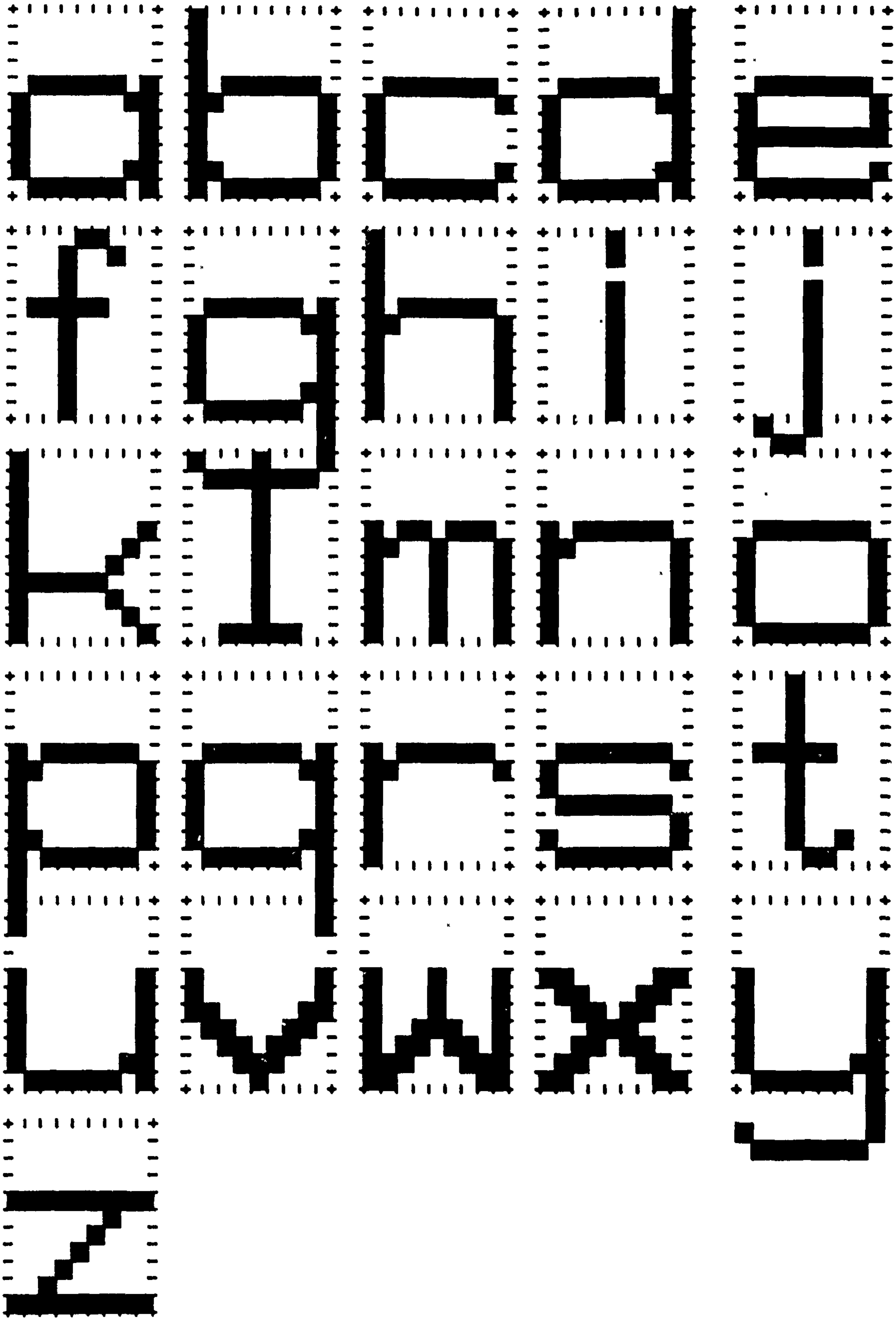

Figure 4. Huddleston font lower case letters in 9 x 11 matrix size.

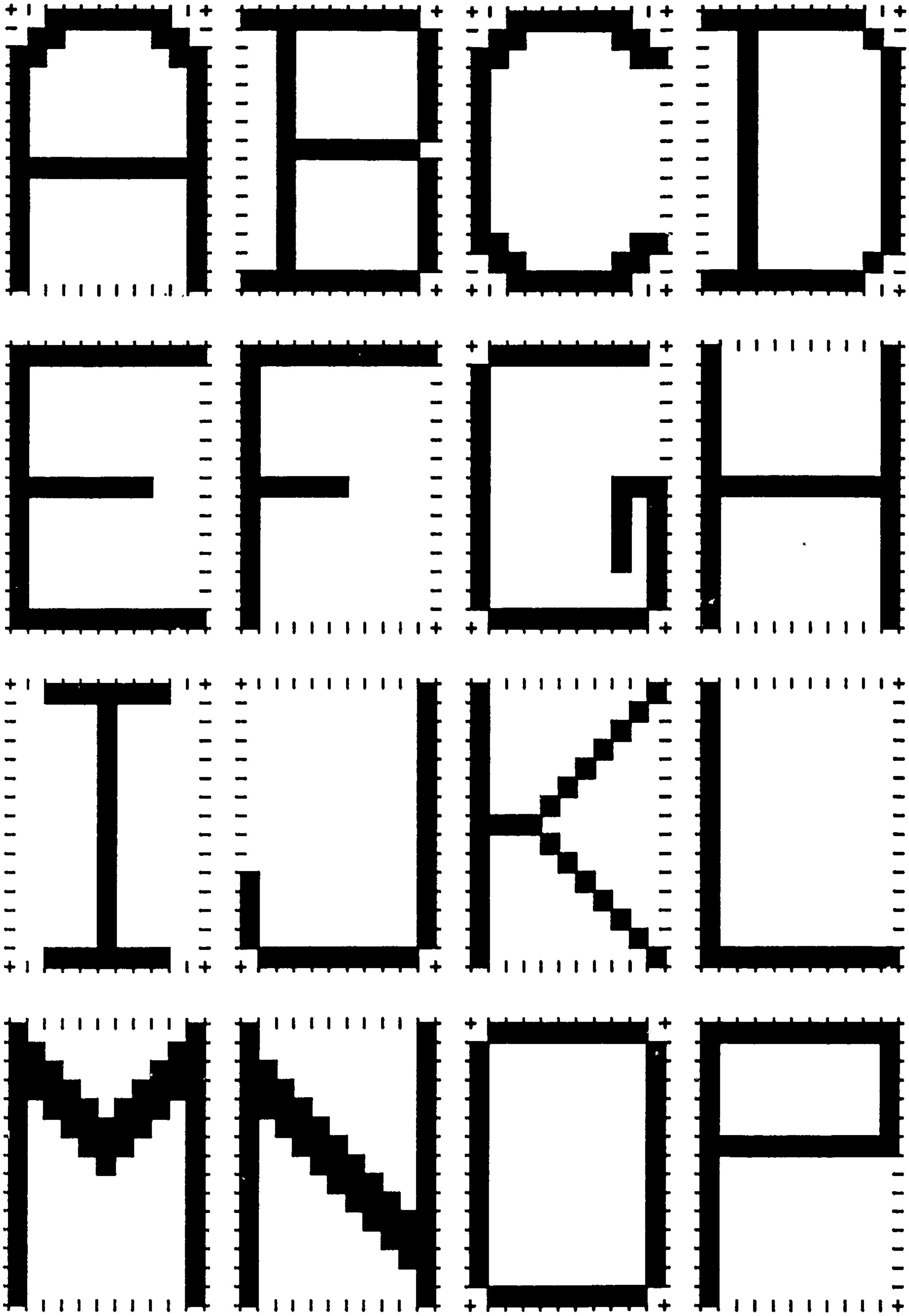

Figure 5. Huddleston font upper case letters in 11 x 15 matrix size.

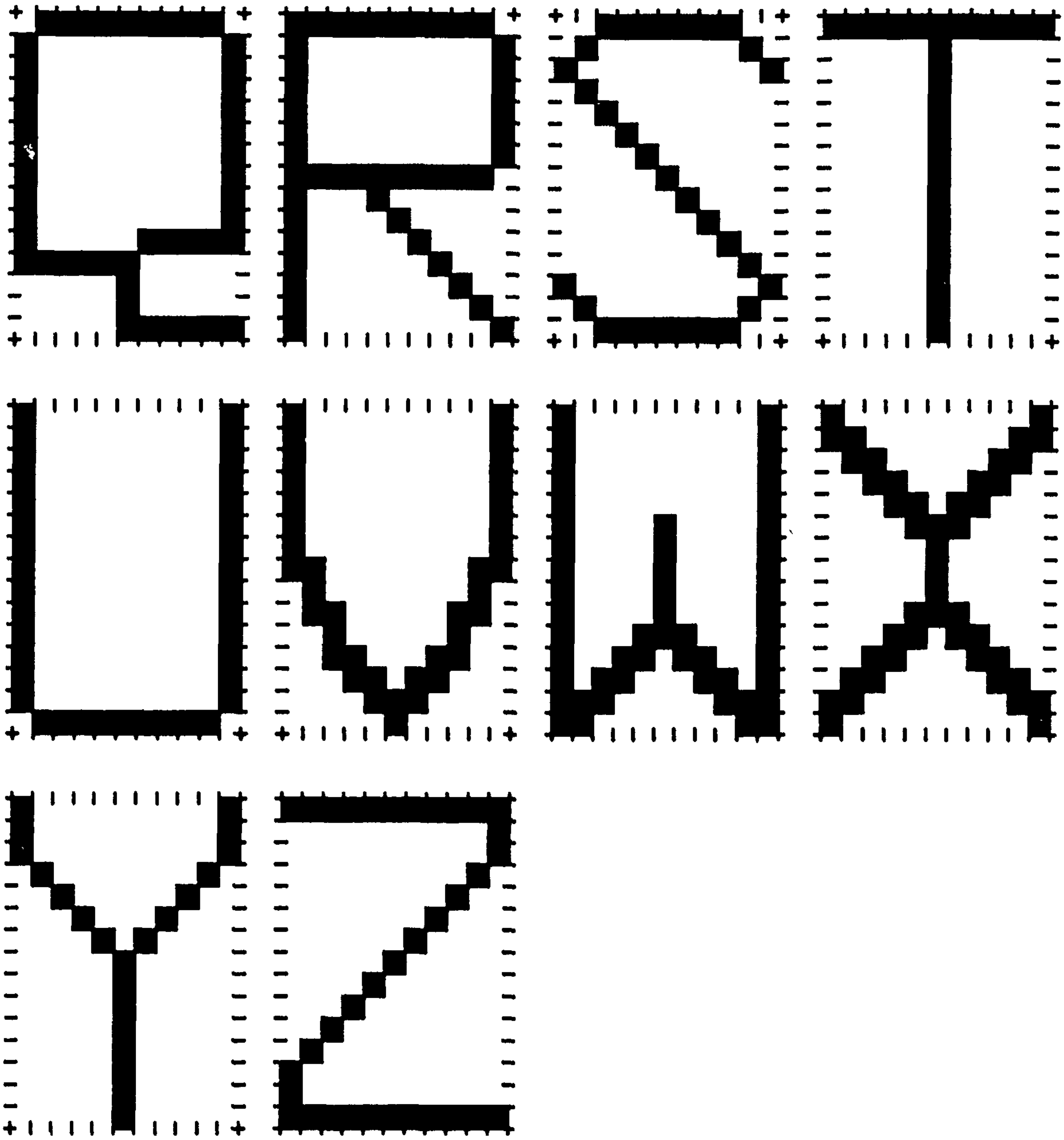

Figure 5. (continued)
Huddleston font upper case letters in 11 x 15 matrix size.

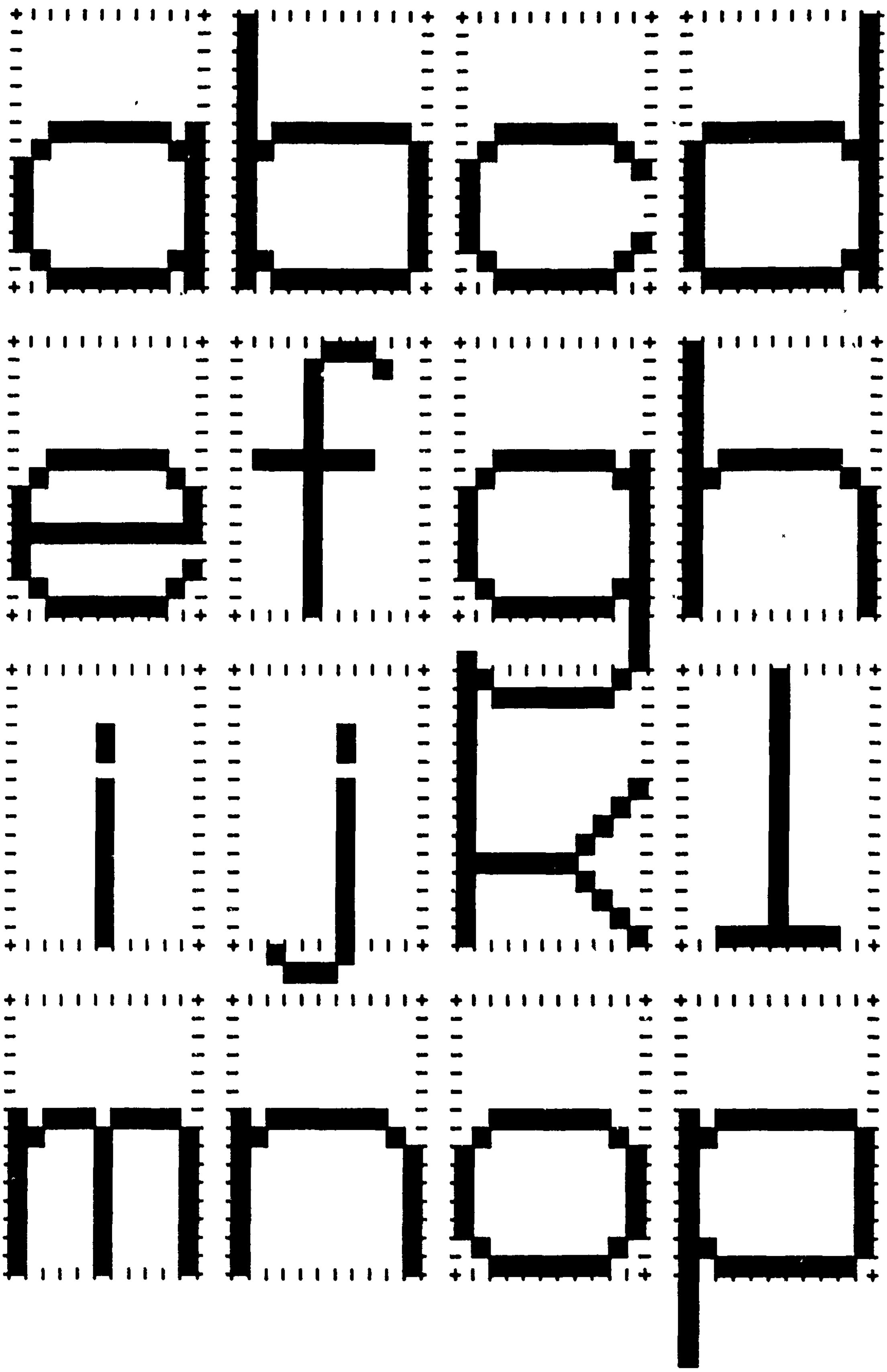

Figure 6. Huddleston font lower case letters in 11 x 15 matrix size.

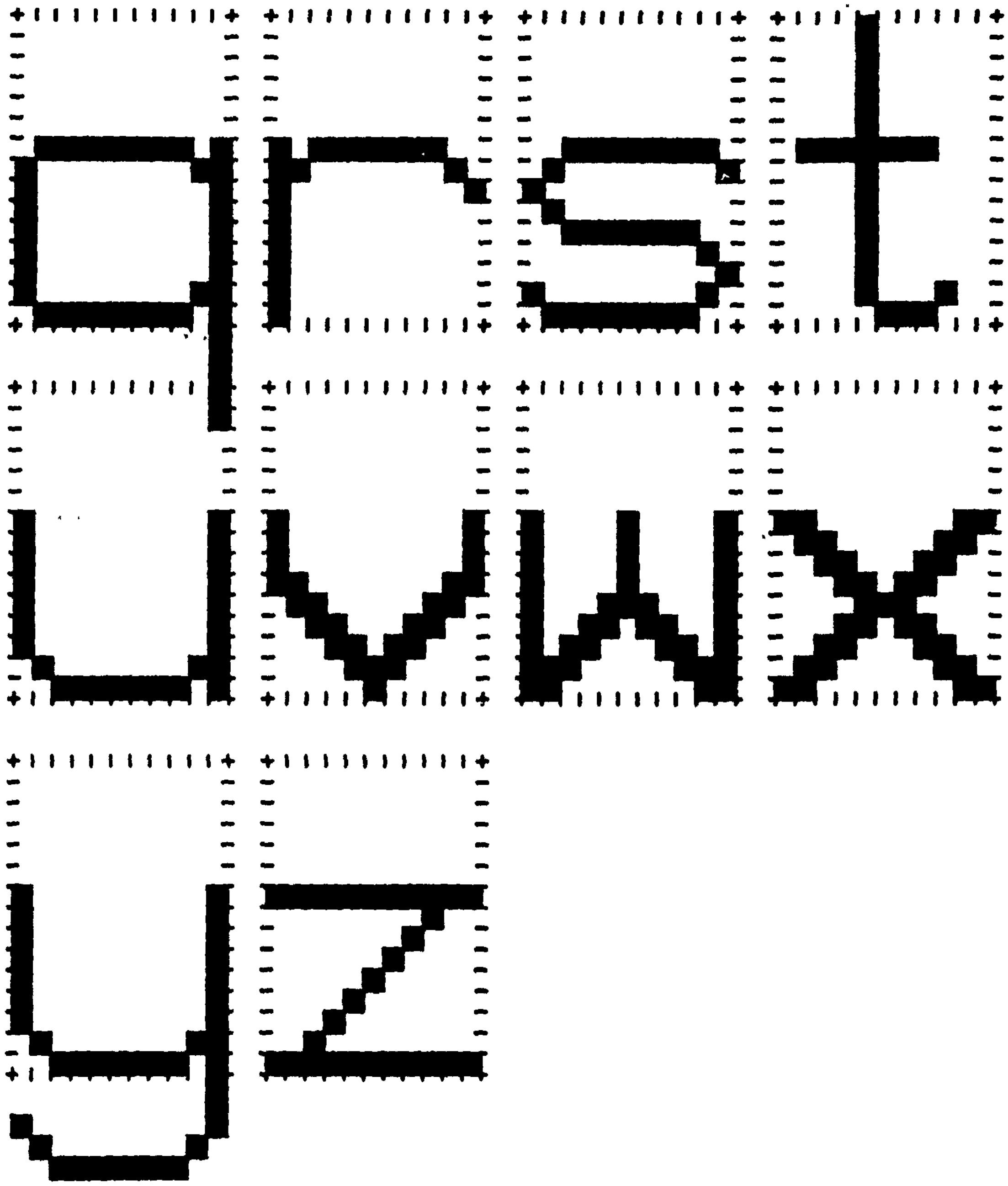

Figure 6. (continued)
Huddleston font lower case letters in 11 x 15 matrix size.

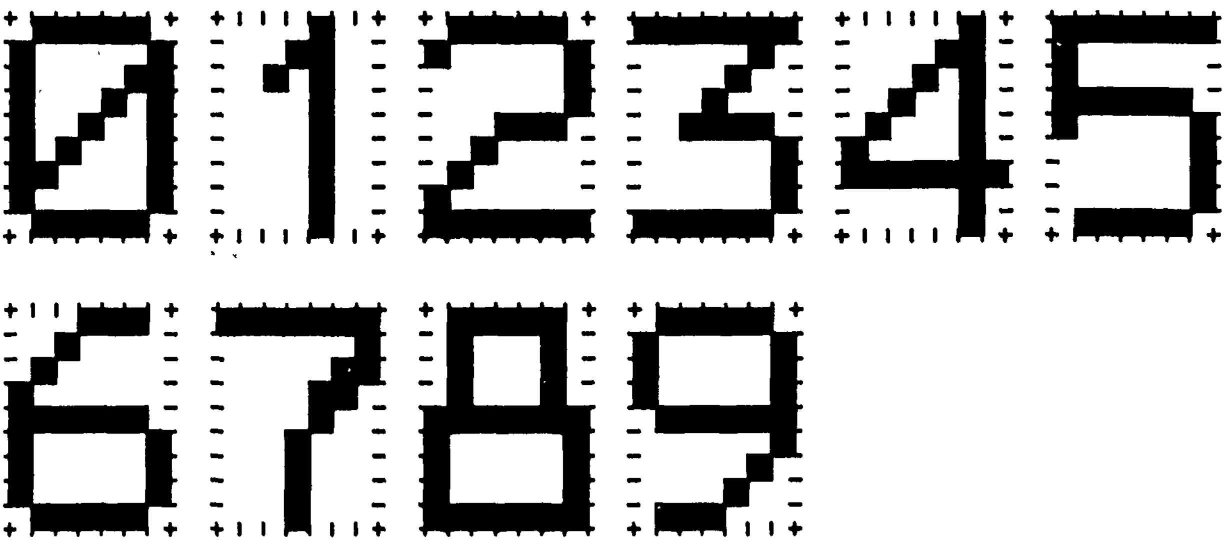

Figure 7. Huddleston font numerals in 7 x 9 matrix size.

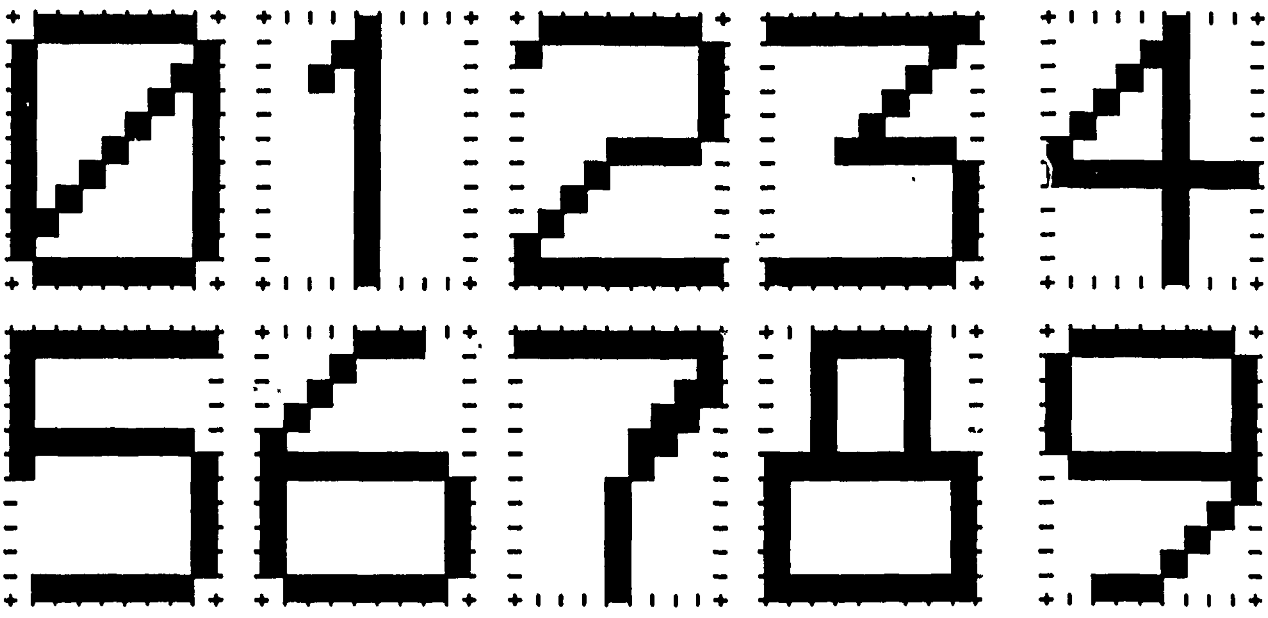

Figure 8. Huddleston font numerals in 9 x 11 matrix size.

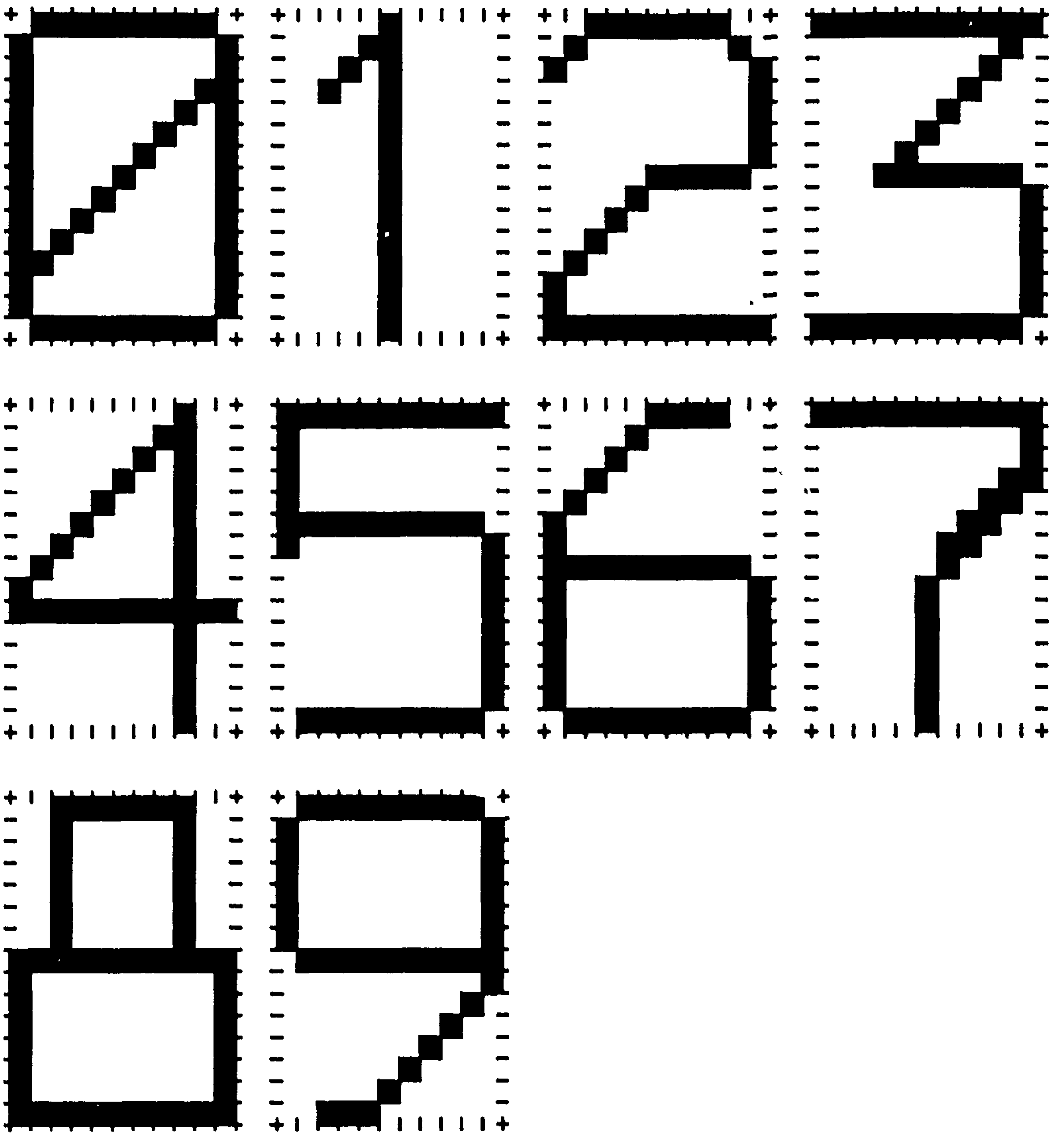

Figure 9. Huddleston font numerals in 11 x 15 matrix size.

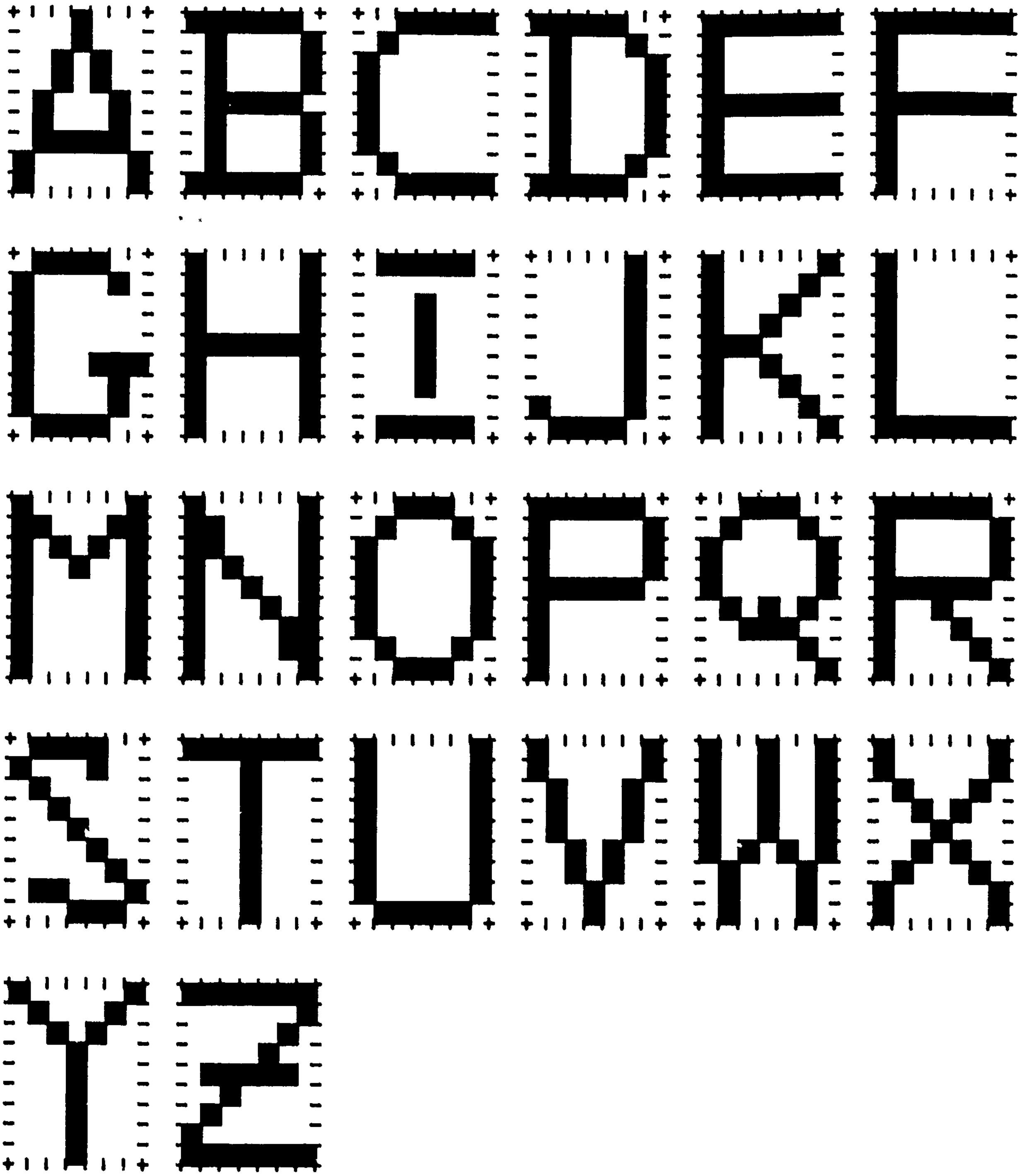

Figure 10. Lincoln/MITRE font upper case letters in 7 x 9 matrix size.

Figure 11. Lincoln/MITRE font lower case letters in 7 x 9 matrix size.

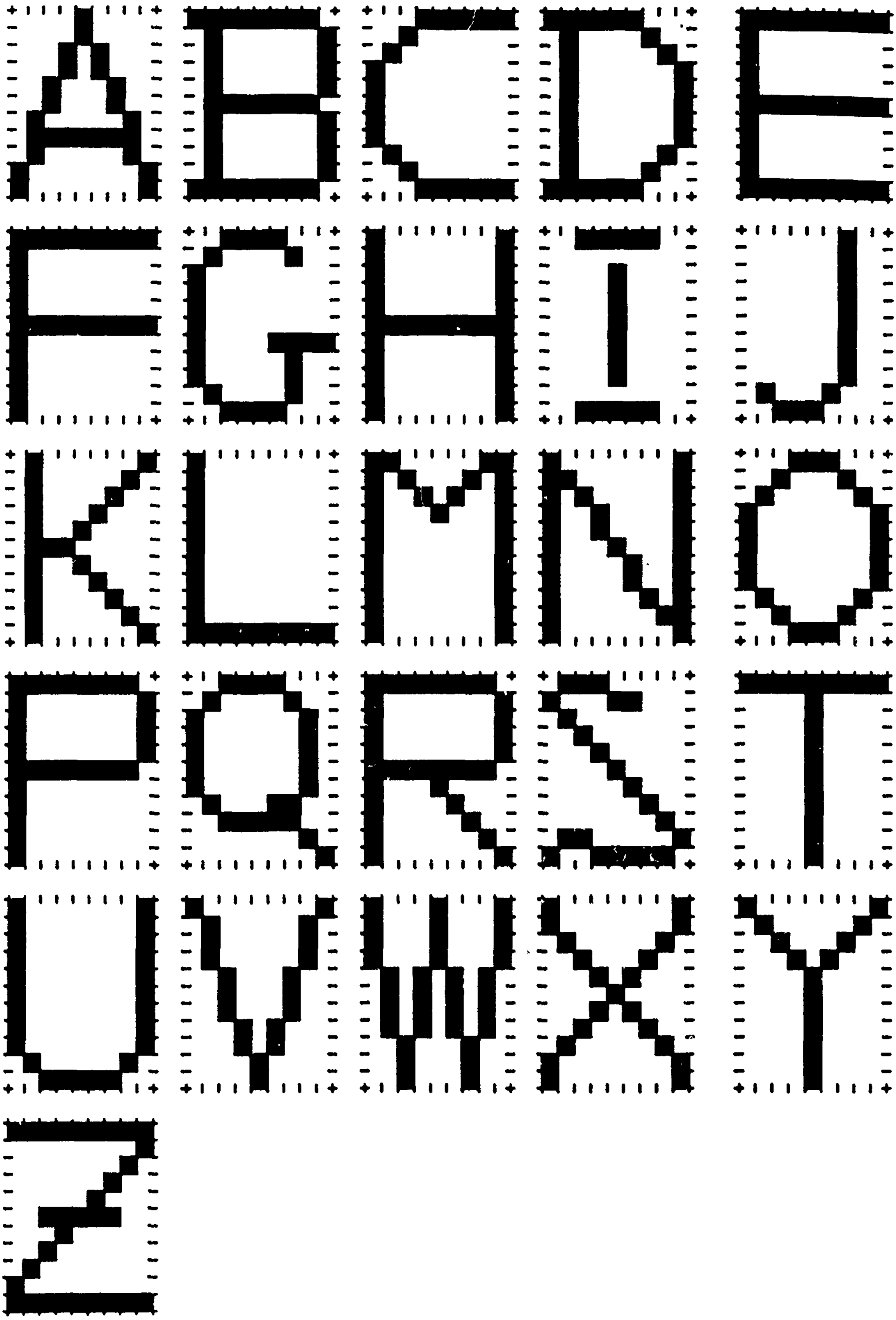

Figure 12. Lincoln/MITRE font upper case letters in 9 x 11 matrix size.

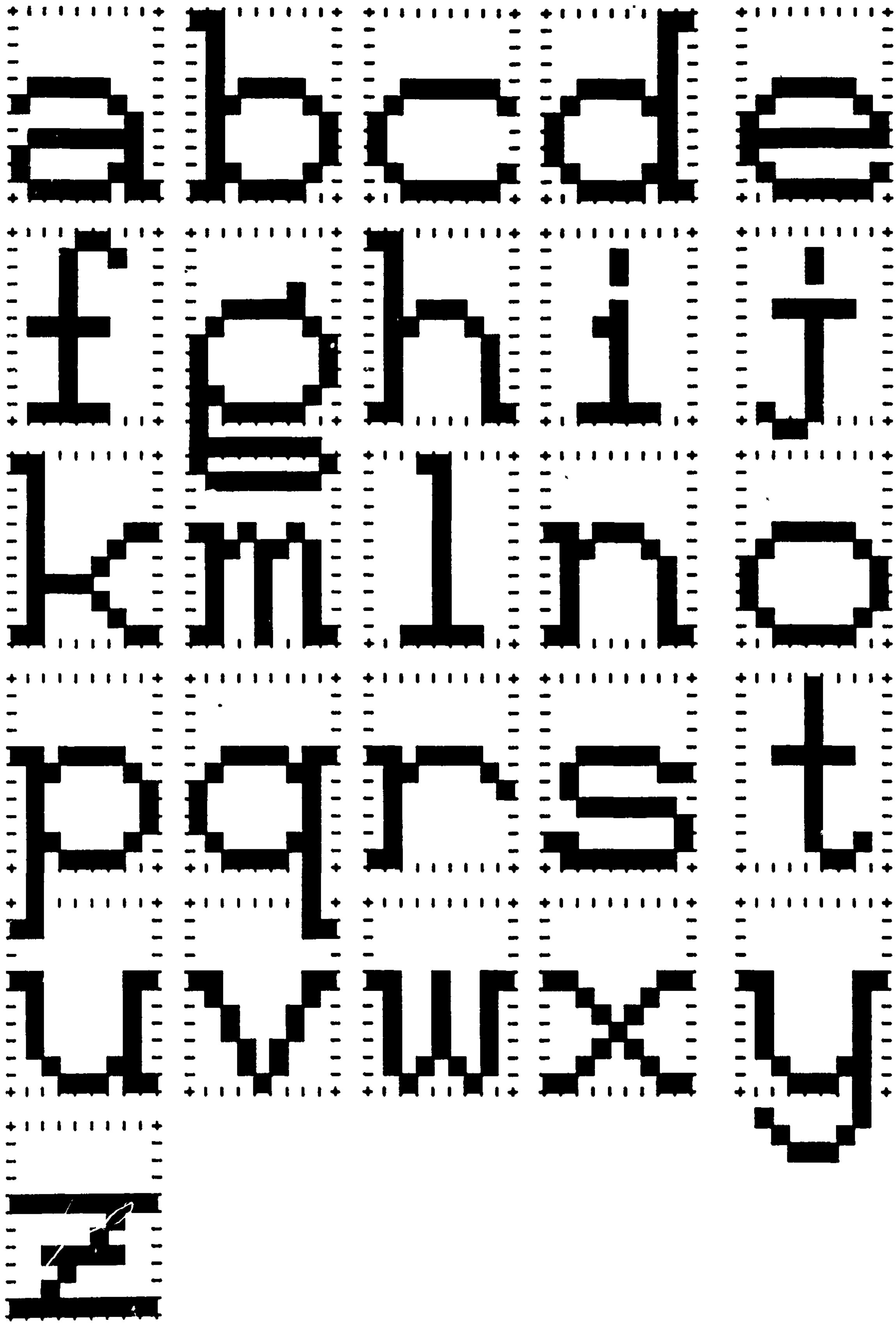

Figure 13. Lincoln/MITRE font lower case letters in 9 x 11 matrix size.

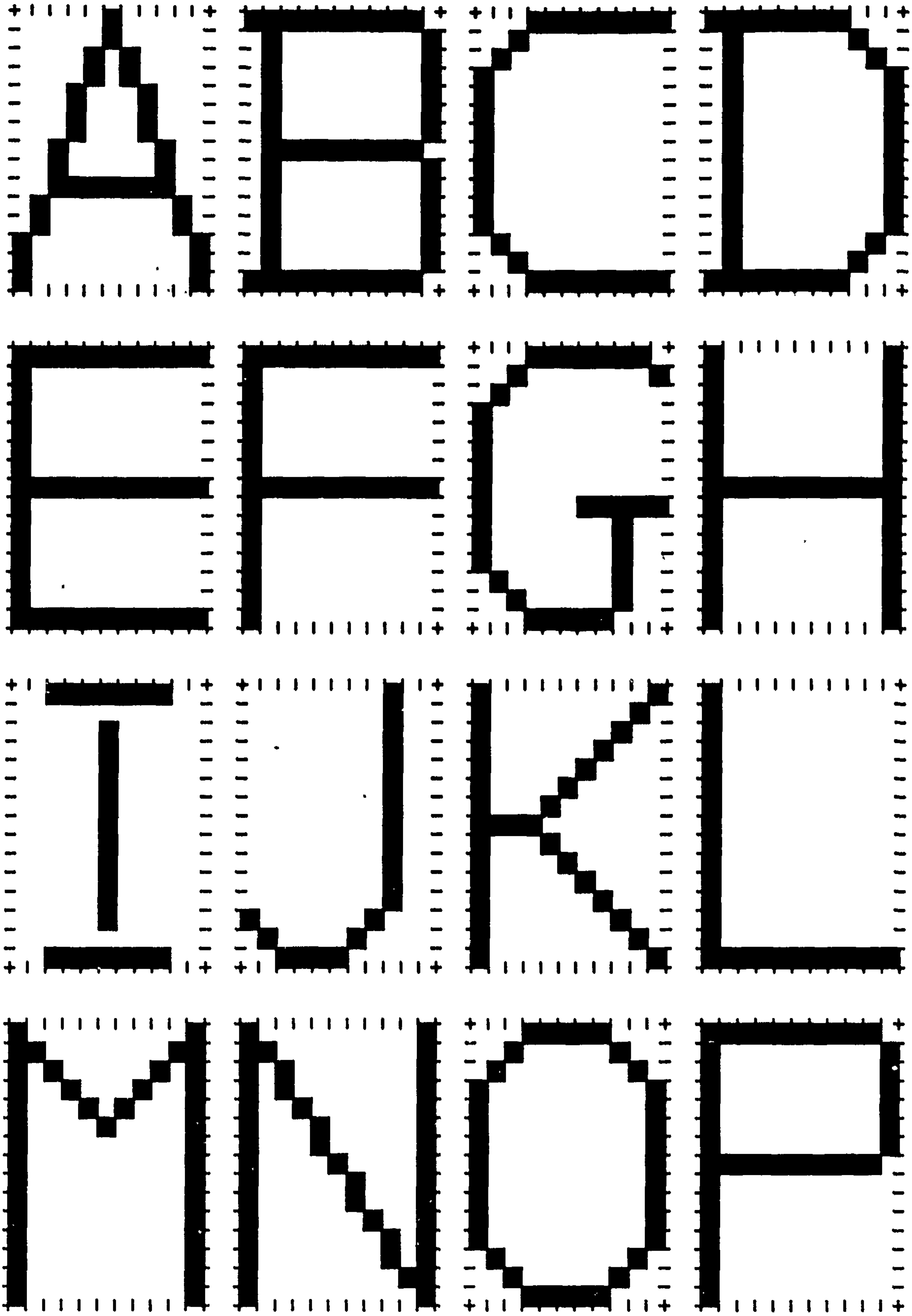

Figure 14. Lincoln/MITRE font upper case letters in 11 x 15 matrix size.

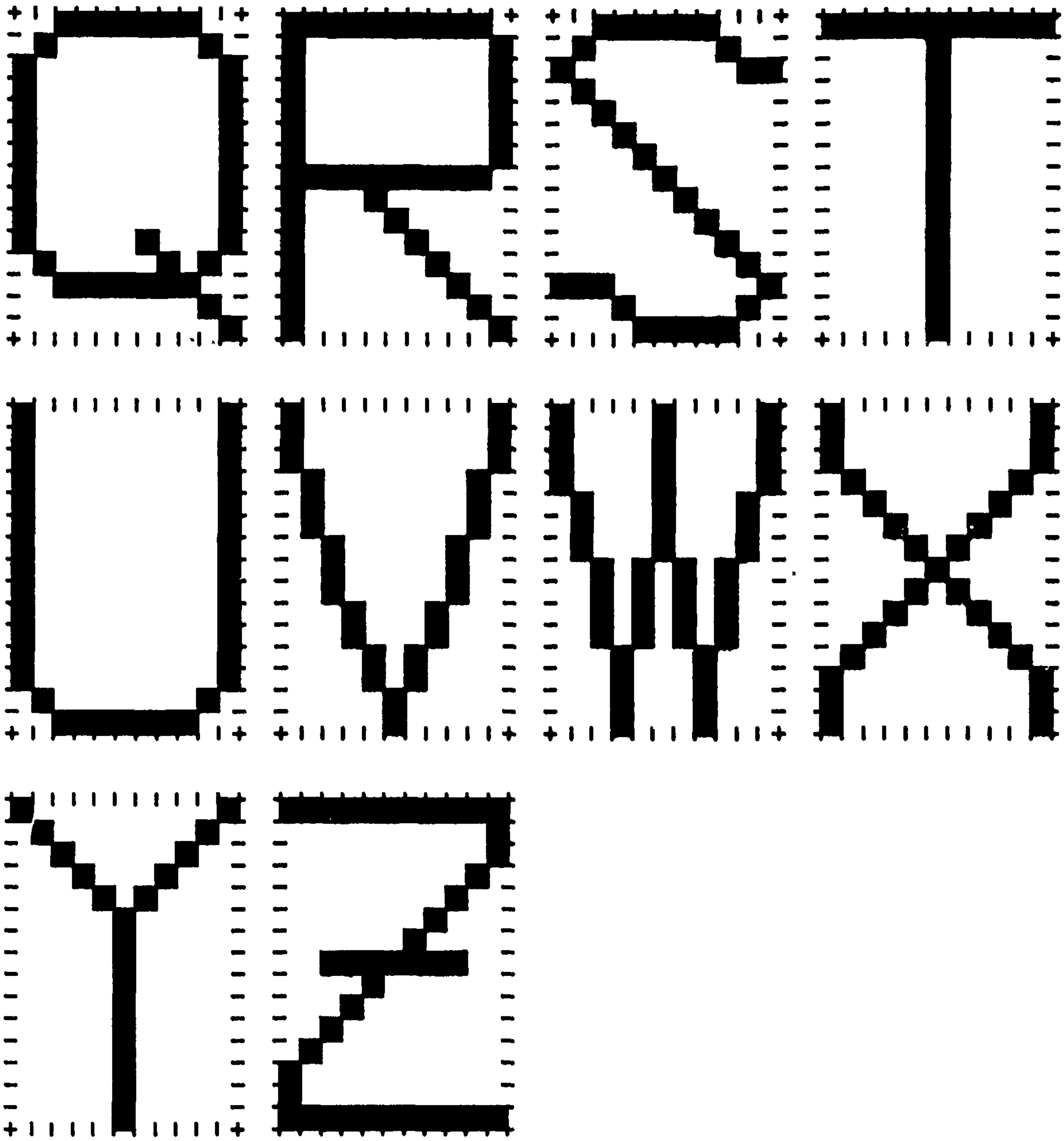

Figure 14. (continued)
Lincoln/MITRE font upper case letters in 11 x 15 matrix size.

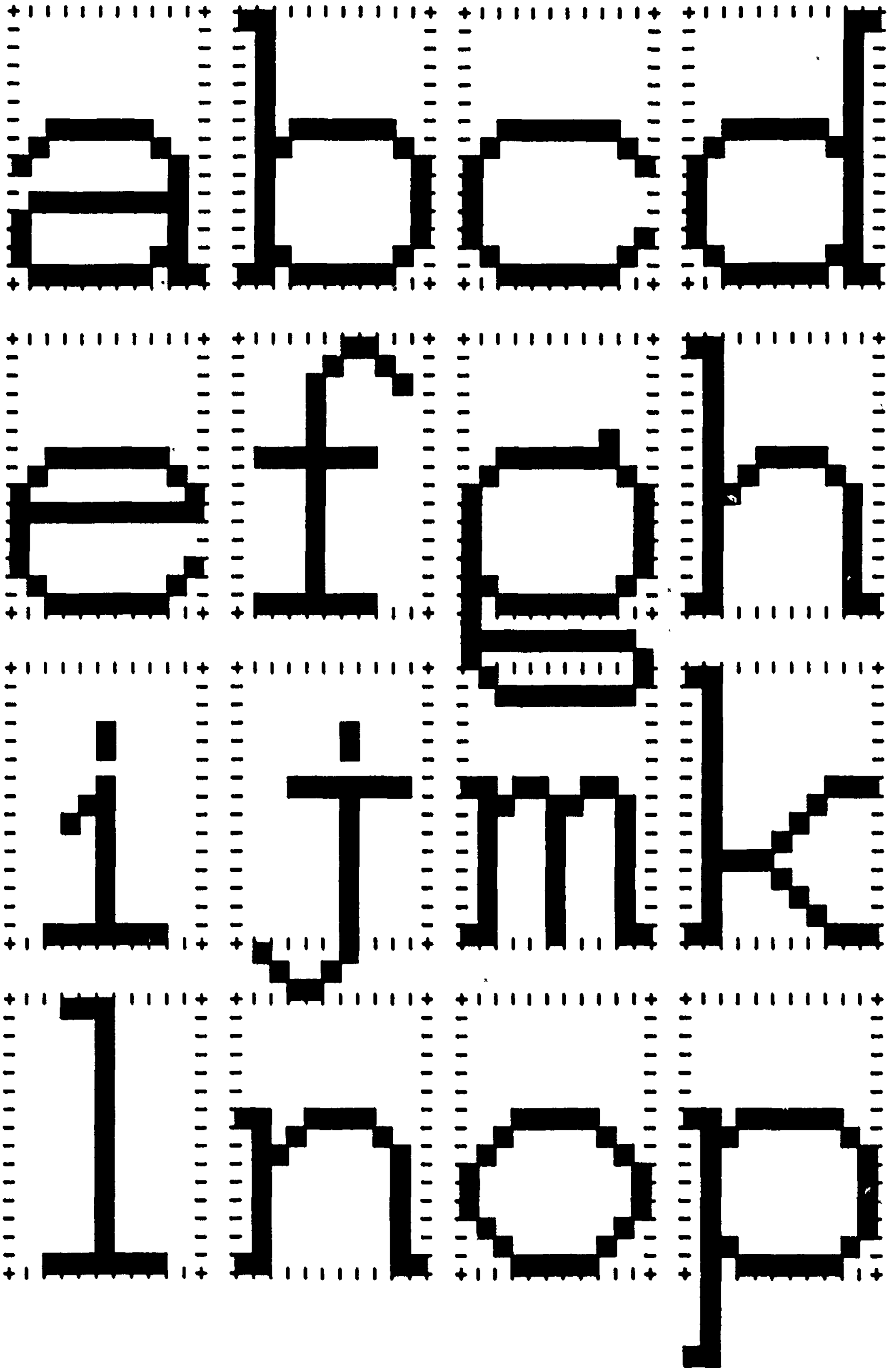

Figure 15. Lincoln/MITRE font lower case letters in 11 x 15 matrix size.

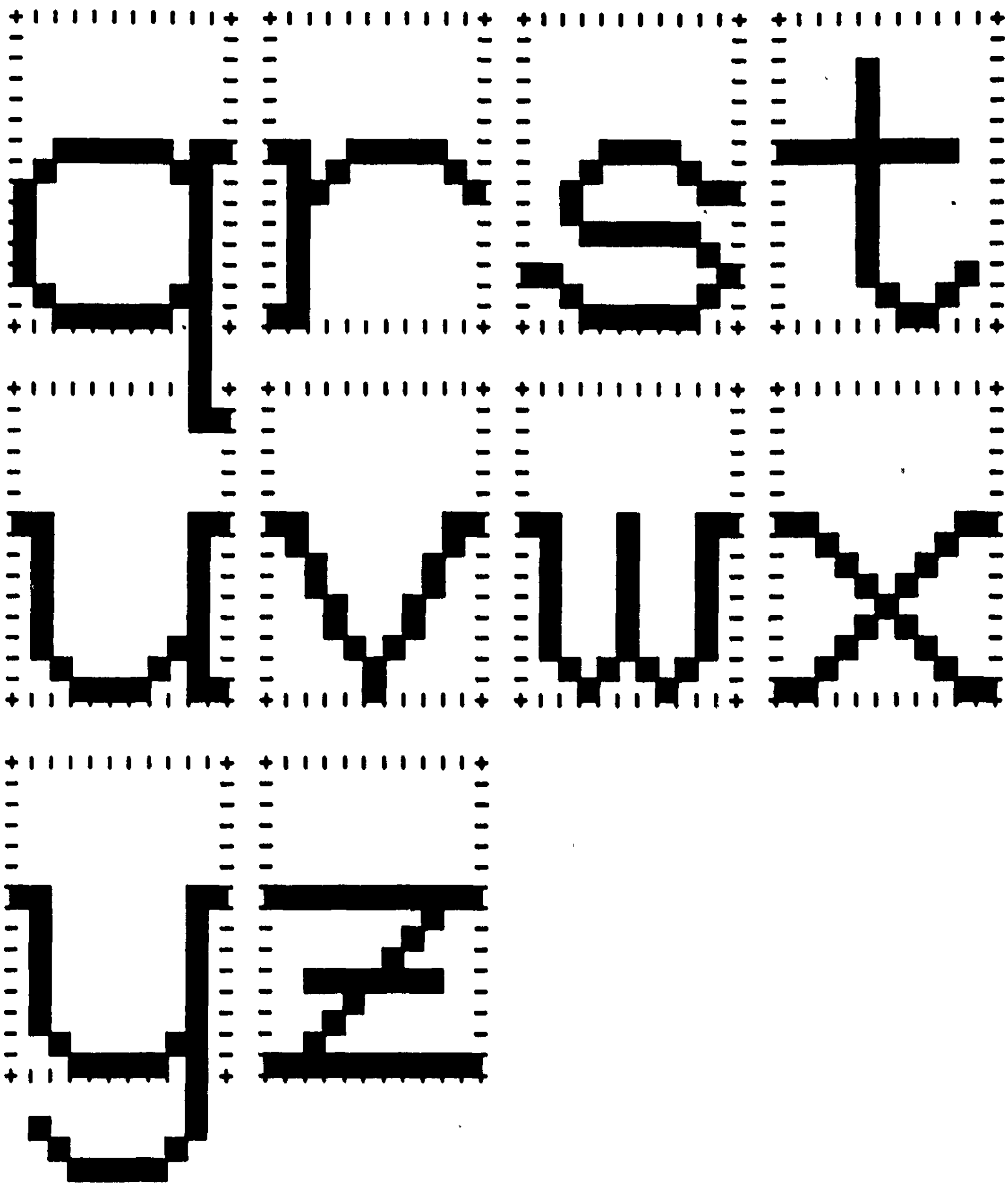

Figure 15. (continued)
Lincoln/MITRE font lower case letters in 11 x 15 matrix size.

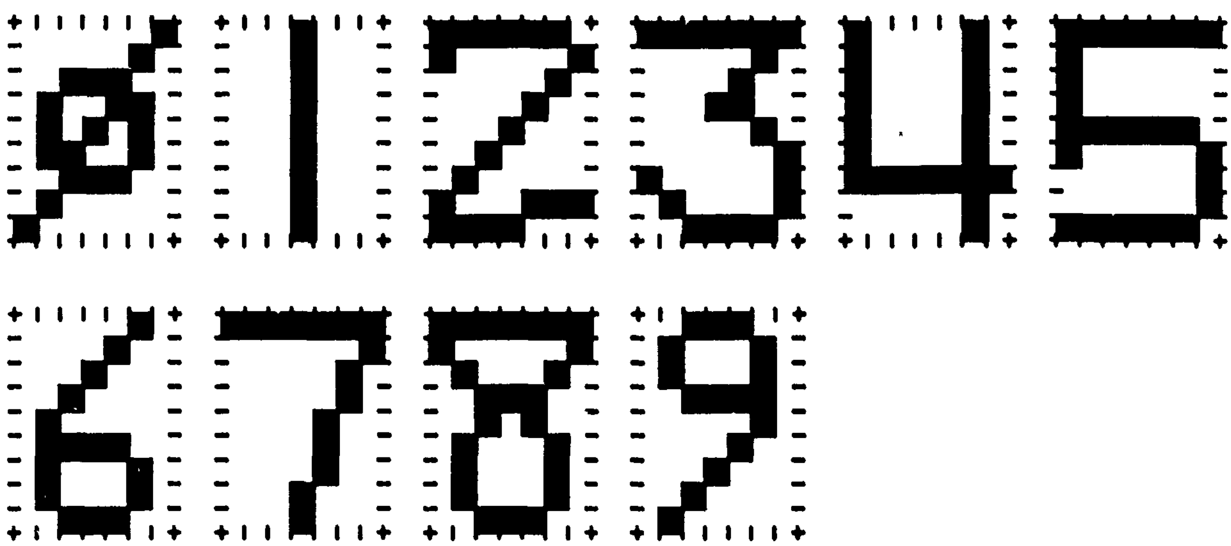

Figure 16. Lincoln/MITRE font numerals in 7 x 9 matrix size.

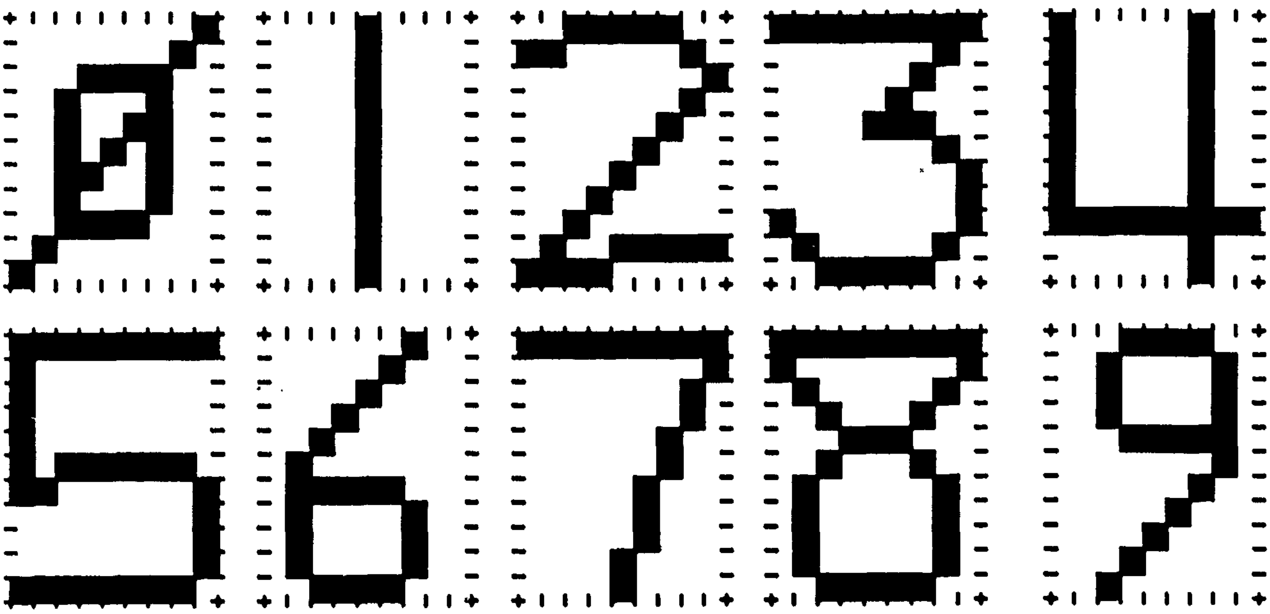

Figure 17. Lincoln/MITRE font numerals in 9 x 11 matrix size.

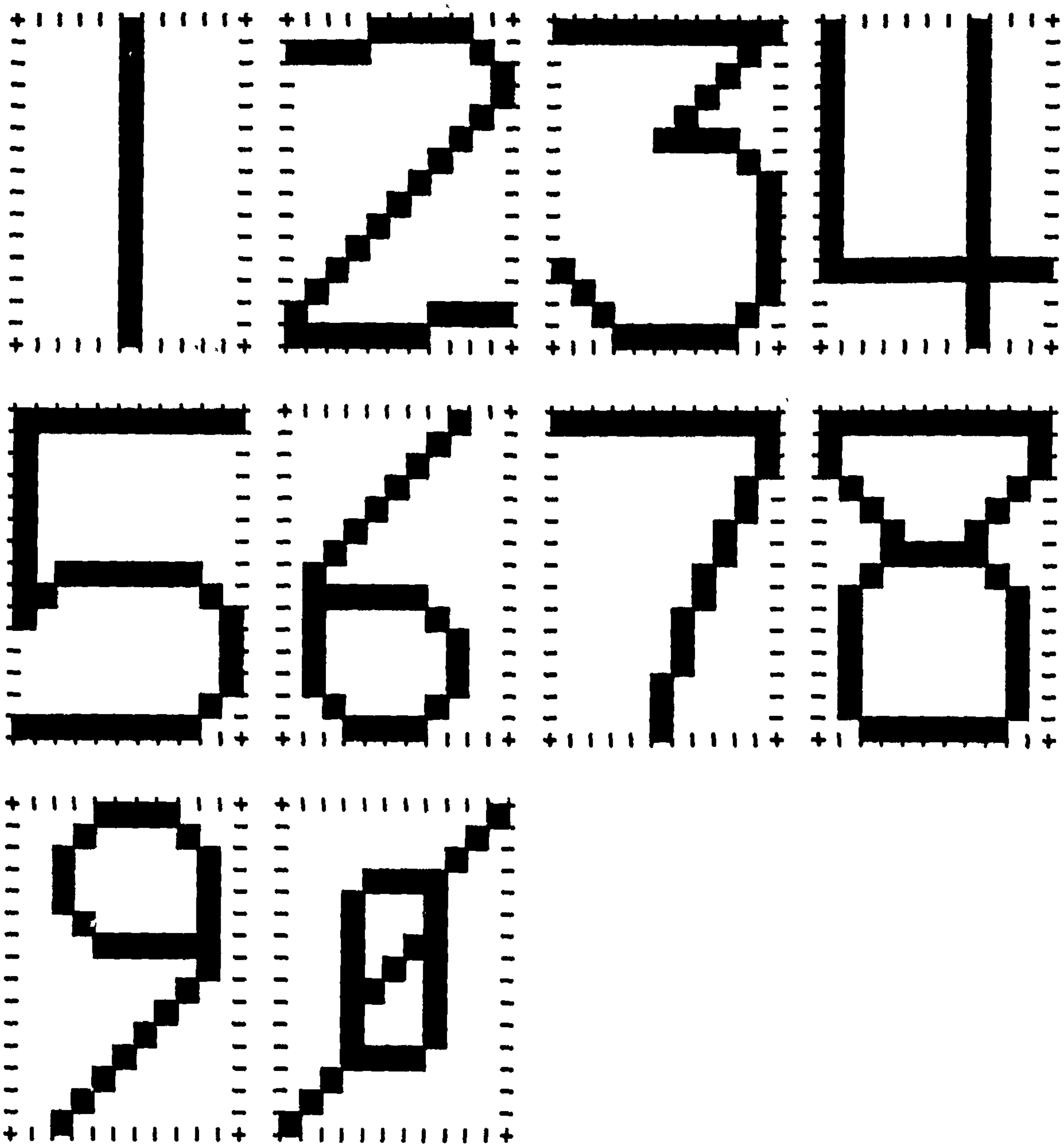

Figure 18. Lincoln/MITRE numerals in 11 x 15 matrix size.

Figure 19. Maximum dot font upper case letters in 7 x 9 matrix size.

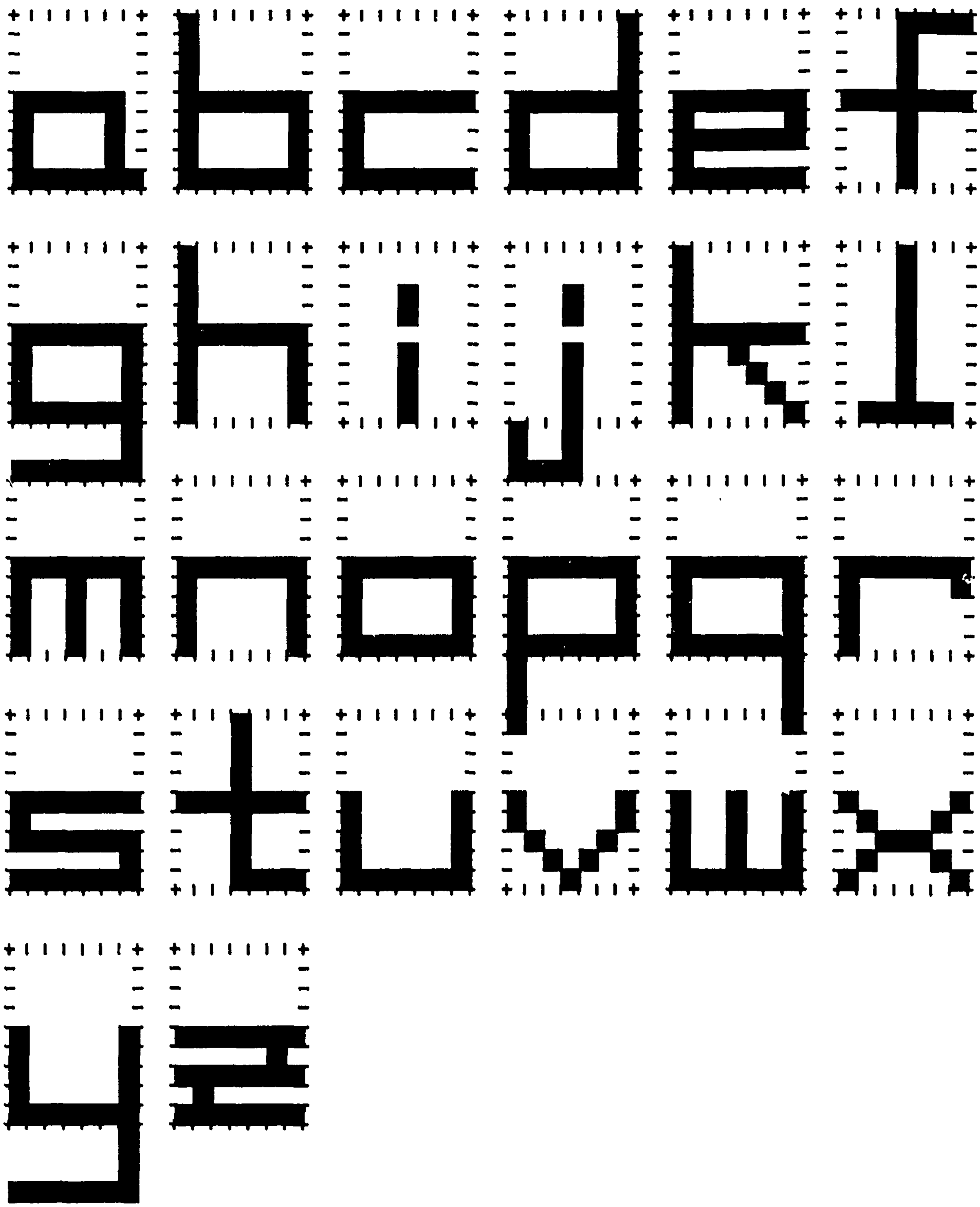

Figure 20. Maximum dot font lower case letters in 7 x 9 matrix size.

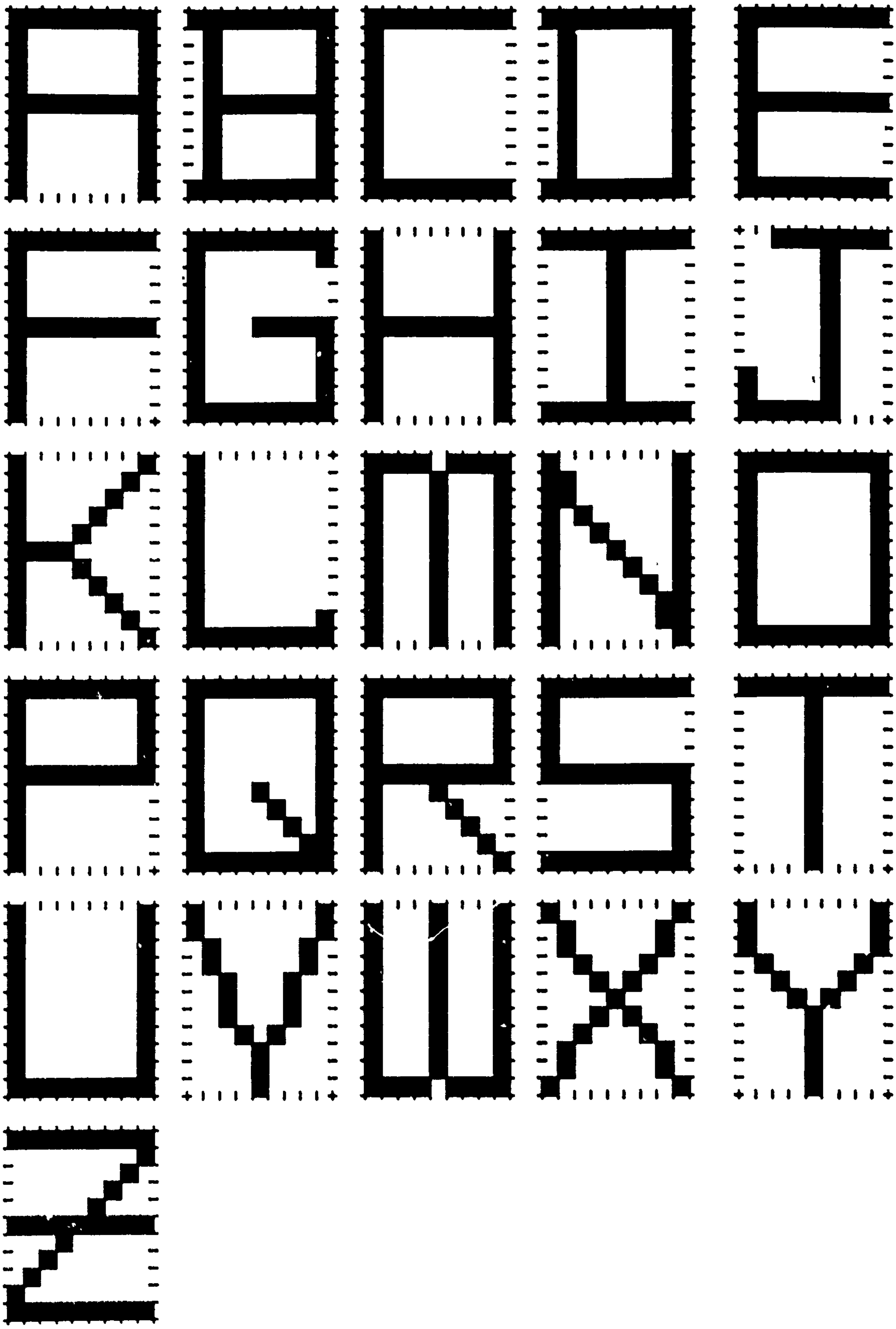

Figure 21. Maximum dot font upper case letters in 9 x 11 matrix size.

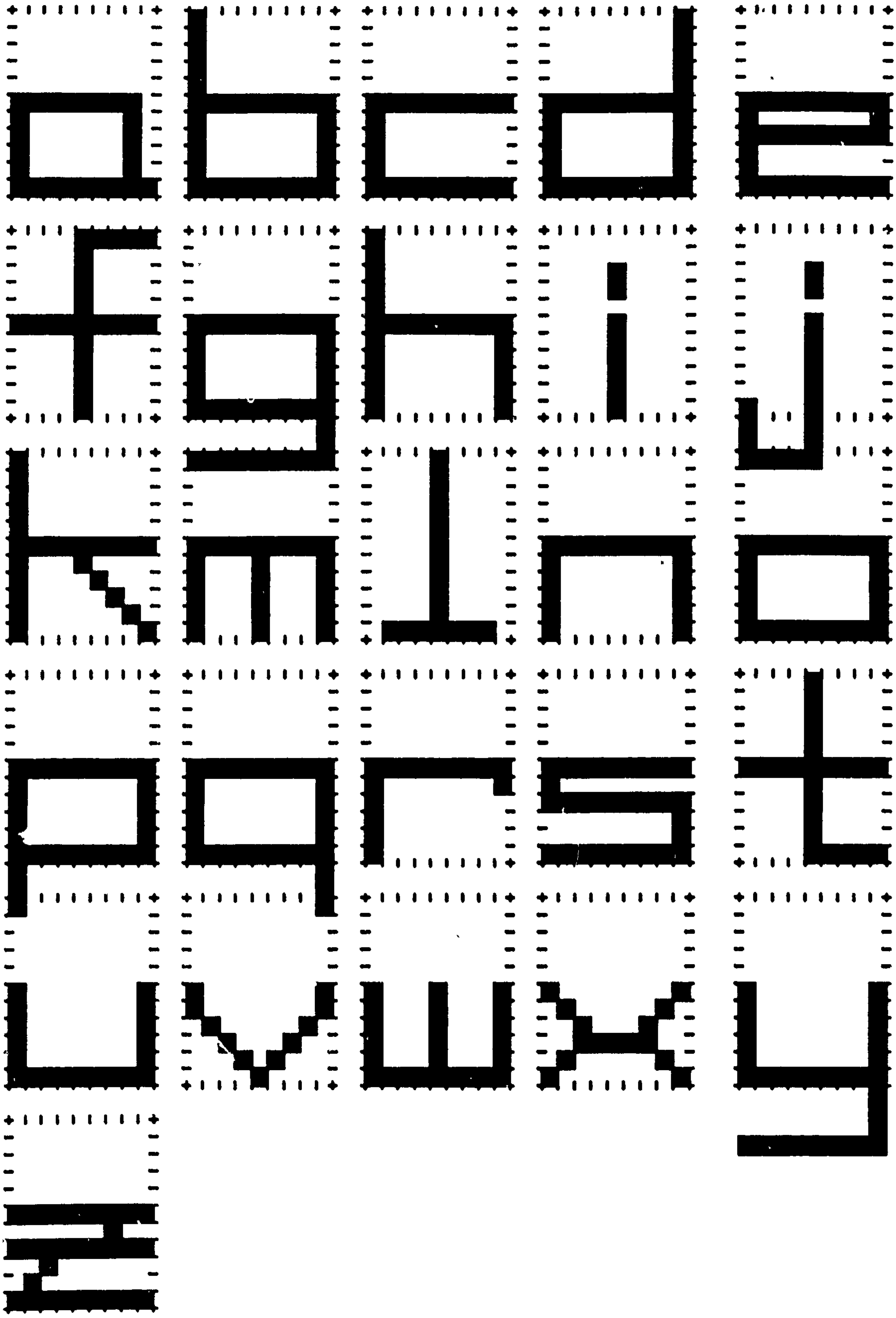

Figure 22. Maximum dot font lower case letters in 9 x 11 matrix size.

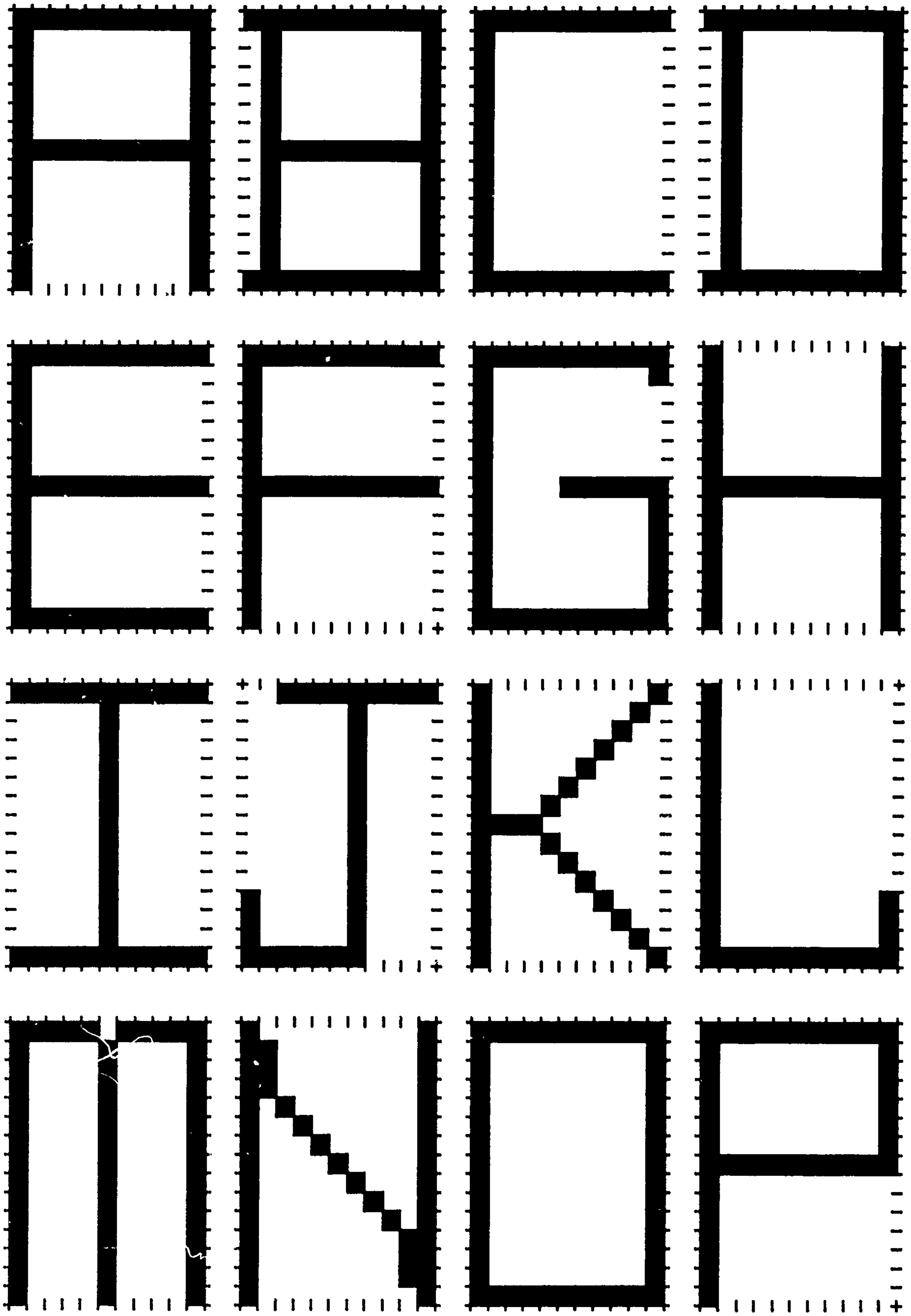

Figure 23. Maximum dot font upper case letters in 11 x 15 matrix size.

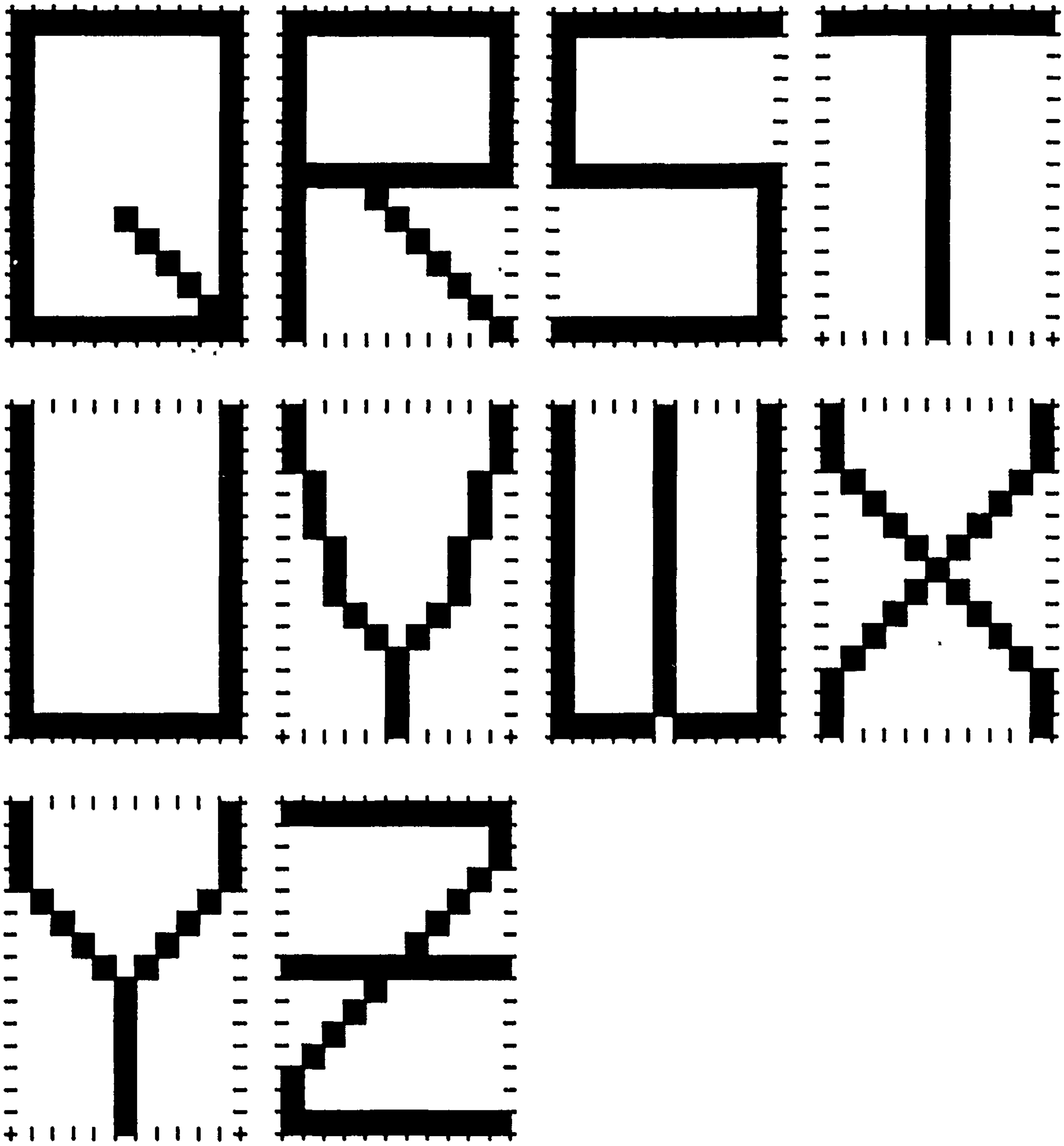

Figure 23. (continued)
Maximum dot font upper case letters in 11 x 15 matrix size.

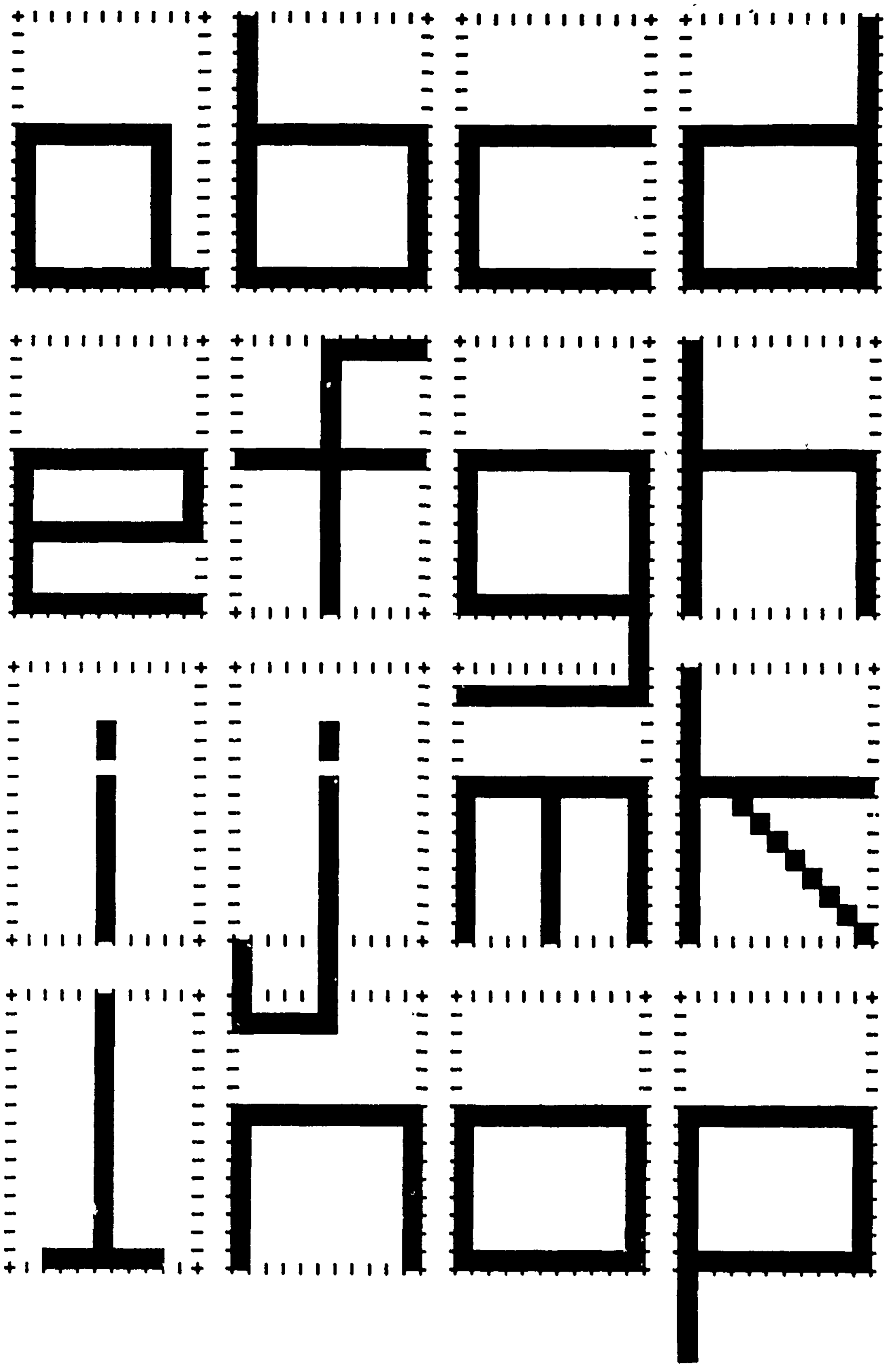

Figure 24. Maximum dot font lower case letters in 11 x 15 matrix size.

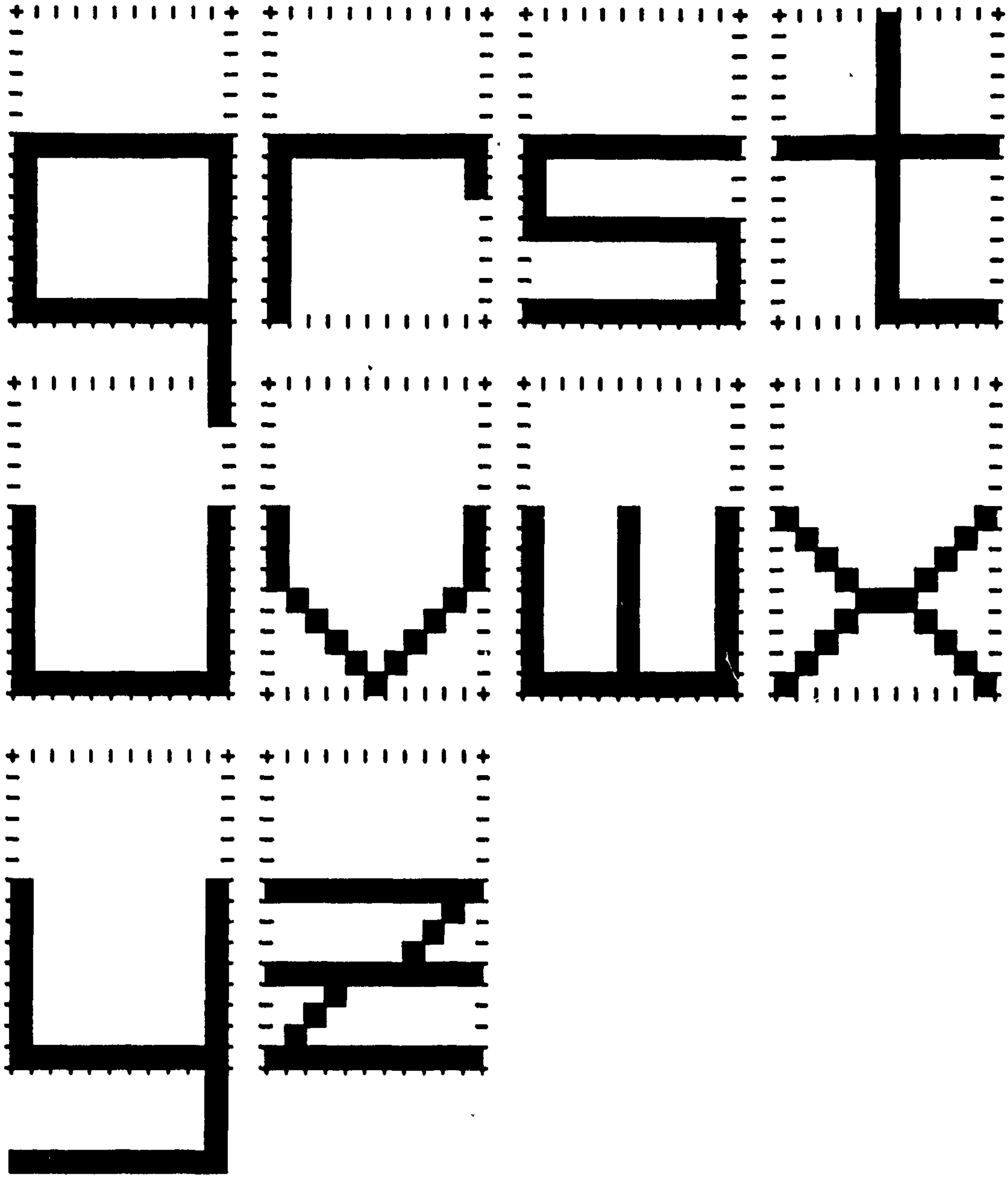

Figure 24. (continued)
Maximum dot font lower case letters in 11 x 15 matrix size.

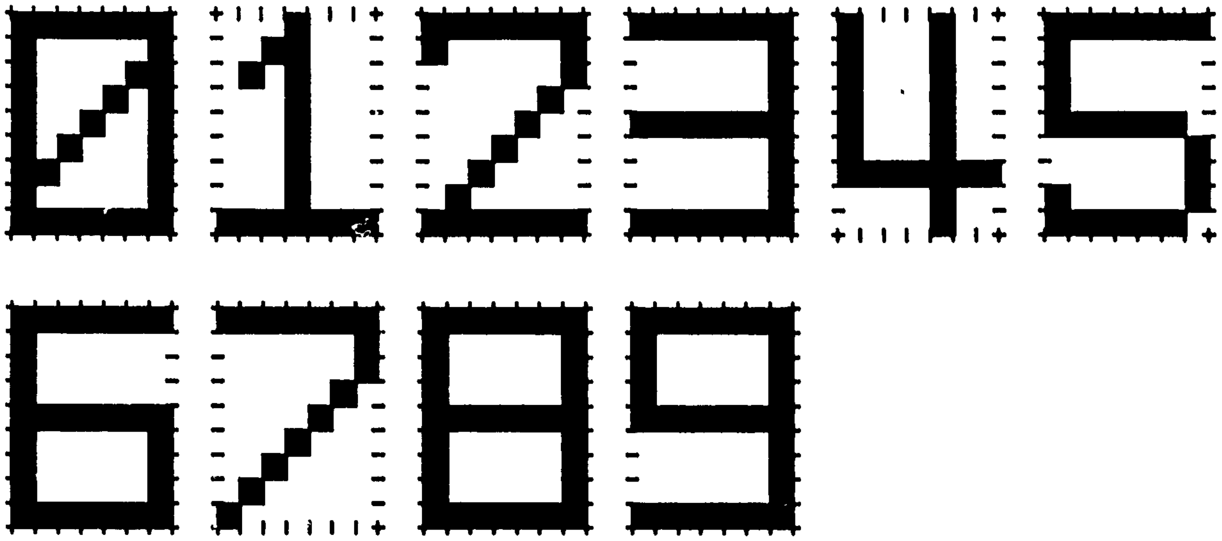

Figure 25. Maximum dot font numerals in 7 x 9 matrix size.

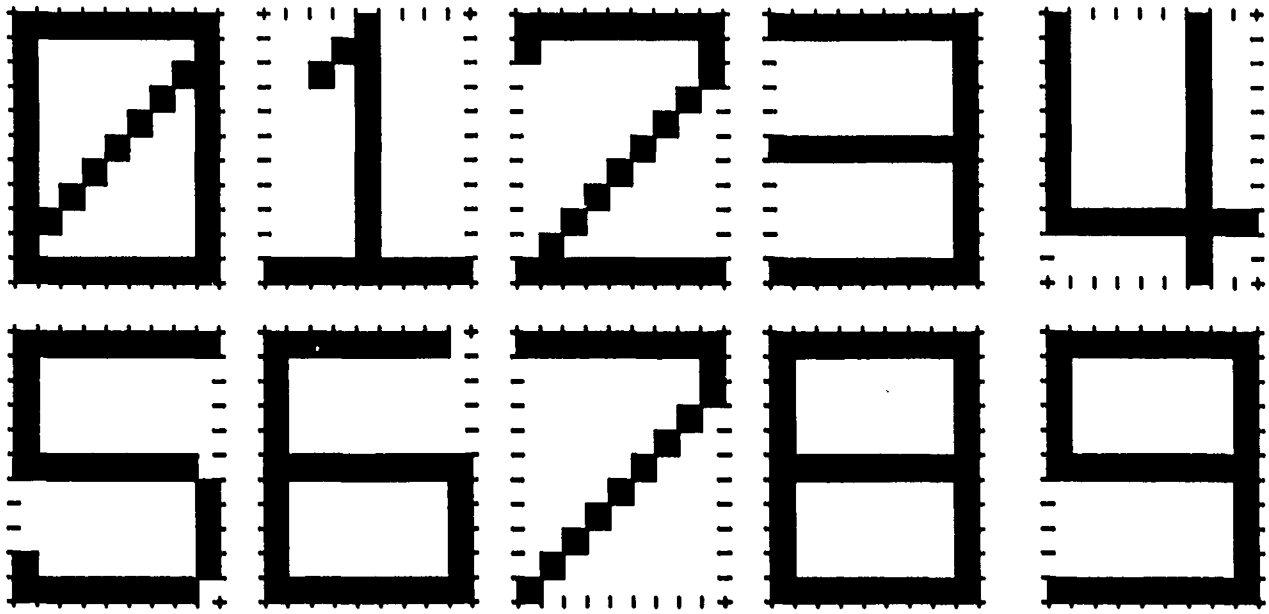

Figure 26. Maximum dot font numerals in 9 x 11 matrix size.

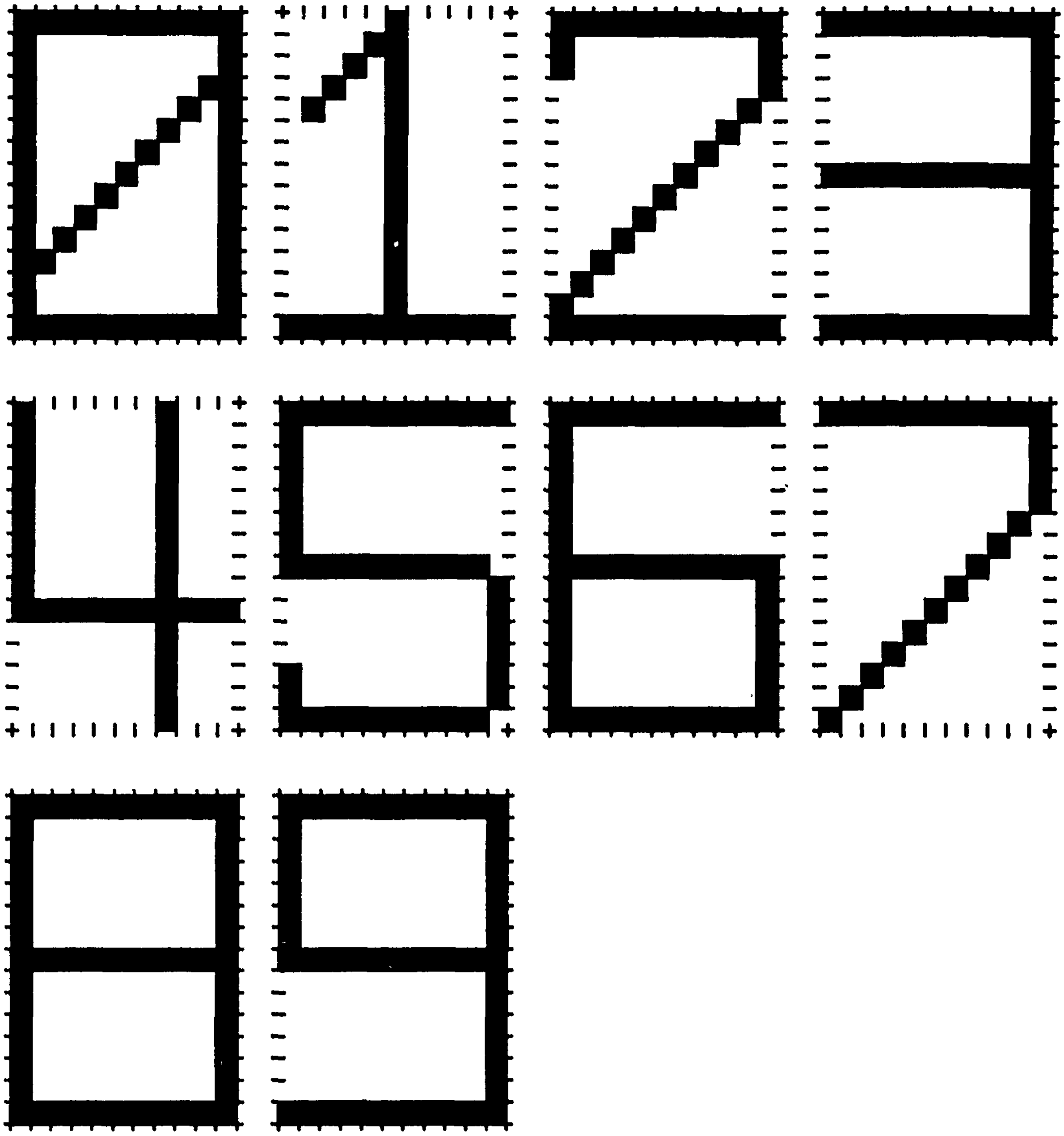

Figure 27. Maximum dot font numerals in 11 x 15 matrix size.

Procedure

Before each experimental session, the CRT was warmed up for at least 30 minutes. An all-on field (255 bits) was displayed, and the system was calibrated to a luminance of 49.4 cd/m^2. Indirect illumination was then set to achieve a luminance of 15 cd/m^2 on the wall directly behind the CRT.

Upon arriving at the laboratory, subjects read a brief description of the experiment and signed an informed consent form. Subjects then sat in front of the CRT, and the chair height and distance were adjusted. Detailed instructions were read aloud to the subject by the experimenter as the subject read along. The subjects performed practice trials to familiarize themselves with the apparatus and task. The practice session took approximately 10 minutes, a duration shown in prior experiments to bring subjects to asymptotic performance levels for this simple task. Subjects were encouraged to ask questions during and immediately following the practice session.

Approximately 20 minutes passed from the time subjects arrived at the laboratory until the regular experimental session started. Thus, subjects had a considerable amount of time to adapt visually to the luminance level of the laboratory.

At the beginning of each trial, the subject was prompted with a message that stated "Ready, the next target character is ___." Subjects initiated a trial by pressing the right button on the mouse input device to begin the timer. The screen was filled with a set of 70 randomly positioned letters and numerals (two of each nontarget letter and numeral) plus the one target. After locating the target, subjects pressed the left button on the mouse that stopped the timer and erased the screen. A two-pixel grid blocking pattern was displayed for 1 second to ensure that traces of the search pattern were not visible. Following the blocking pattern, a nine-cell grid resembling a tic-tac-toe pattern was displayed. Each of the nine cells was numbered. Subjects reported to the experimenter the number of the cell in which the target appeared. The experimenter entered the response into the computer after each trial.

An experimental session consisted of 54 blocks of five trials each (270 trials). Within each block, the font, size, polarity, and modulation conditions remained the same while the target character and its position changed from trial to trial. One 5-minute break was taken at the mid point of the session. The entire session took approximately 1 hour.

Experiment 2: Reading Task

Subjects

The same subjects who served in Experiment 1 participated in this experiment except for one female whose data were lost because of a power failure. This subject's data set was replaced with data from one additional male subject. Half of the subjects participated in Experiment 1 first while the other half participated in Experiment 2 first. Subjects were run on two consecutive days, one day per experiment.

Apparatus

The apparatus used in this experiment was identical to that used in Experiment 1. The only differences were procedural.

Stimuli

Stimuli consisted of modified Tinker Speed of Reading passages that are four-line, approximately 30-word passages that contain one word that does not make sense with respect to the rest of the passage. Following are two samples of the Tinker passages.

> 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.

The variables for the reading task were identical to those of the search task except for the addition of a mixed case along with all upper case, resulting in a 3 (fonts) x 3 (modulations) x 2 (polarities) x 2 (matrix sizes) x 2 (cases) within-subjects factorial experimental design.

Procedure

Calibration for this experiment was identical to that of Experiment 1. Subjects participated in 20 practice trials before beginning the experimental trials. (Prior experiments indicated that 20 trials were adequate for this task to have subjects reach asymptotic levels of performance.) At the beginning of each trial, the subject was prompted with a "ready" message. Subjects initiated the trial and started the timer by pressing the right button on the mouse input device. A reading passage was displayed, and subjects were asked to read the passage to themselves as quickly and as accurately as possible. After reading the passage, they pressed the left button on the mouse to stop the trial and the timer, and the passage was erased. Subjects then reported the incorrect word aloud to the experimenter who recorded whether the response was correct or incorrect.

An experimental session consisted of 108 blocks of four trials each. Within each block the font, size, contrast, modulation, and case remained the same. Three 5-minute breaks were taken during a session. A complete session took approximately 2 hours.

RESULTS

The results from both the random search task (Experiment 1) and the reading task (Experiment 2) are discussed together. Experiment 1 data were analyzed using a 3 x 3 x 2 x 2 repeated measures analysis of variance (ANOVA). Significant main effects were tested using the Student-Newman-Keuls test at an alpha level of 0.05. The summary results of this ANOVA are presented in Table 3. The data from Experiment 2 were analyzed identically except for the addition of the case variable. The summary results of this

ANOVA are presented in Table 4. In both 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 ε calculations were performed and the degrees of freedom were adjusted accordingly.

Table 3

Analysis of Variance Summary for Random Search Times

Source of variance	df	MS	F	*p*
Subjects (S)	19	66.15		
Font (F)	2	55.11	4.74	0.0145*
F x S	38	11.62		
Size (SZ)	2	219.85	37.04	0.0001**
SZ x S	38	5.93		
Modulation (M)	2	11.30	1.45	0.2481
M x S	38	7.81		
Polarity (P)	1	67.74	13.81	0.0015
P x S	19	4.91		
F x SZ	4	3.16	0.52	0.7215
F x SZ x S	76	6.08		
F x M	4	3.88	0.64	0.6364
F x M x S	76	6.07		
F x P	2	1.32	0.17	0.8411
F x P x S	38	7.60		
SZ x M	4	2.19	0.36	0.8394
SZ x M x S	76	6.17		
SZ x P	2	5.51	0.92	0.4067
SZ x P x S	38	5.98		
M x P	2	3.35	0.71	0.4971
M X P x S	38	4.71		
F x SZ x M	8	1.91	0.40	0.9168
F x SZ x M x S	152	4.71		
F x SZ x P	4	1.58	0.21	0.9332
F x SZ x P x S	76	7.61		
SZ x M x P	4	9.79	1.76	0.1455
SZ x M x P x S	76	5.56		
F x SZ x M x P	12	8.47	1.48	0.1325
F x SZ x M x P x S	228	5.72		
Total	1079			

Note. * $p < .05$ with lower bound Greenhouse and Geisser (1959) correction
** $p < .01$ with lower bound Greenhouse and Geisser (1959) correction

Table 4

Analysis of Variance Summary for Reading Times

Source of variance	df	MS	F	*p*
Subjects (S)	19	223.18		
Case (C)	1	10.41	10.14	0.0049
C x S	19	1.03		
Font (F)	2	26.01	24.08	0.0001**
F x S	38	1.08		
Size (SZ)	2	1.30	1.29	0.2867
SZ x S	38	1.01		
Modulation (M)	2	1.03	1.43	0.2520
M x S	38	0.72		
Polarity (P)	1	8.14	11.33	0.0032
P x S	19	0.72		
C x F	2	6.11	7.25	0.0021*
C x F x S	38	0.84		
C x SZ	2	0.65	0.65	0.5255
C x SZ x S	38	0.99		
C x M	2	0.58	0.66	0.5241
C x M x S	38	0.88		
C x P	1	1.57	2.53	0.1283
C x P x S	19	0.62		
F x SZ	4	0.22	0.24	0.9175
F x SZ x S	76	0.91		
F x M	4	1.31	1.69	0.1601
F x M x S	76	0.77		
F x P	2	1.51	2.53	0.0934
F x P x S	38	0.60		
SZ x M	4	0.41	0.77	0.5487
SZ x M x S	76	0.53		
SZ x P	2	0.84	0.72	0.4937
SZ x P x S	38	1.17		
M x P	2	0.10	0.11	0.8930
M x P x S	38	0.85		
C x F x SZ	4	0.65	0.94	0.4473
C x F x SZ x S	76	0.70		
C x F x M	4	0.52	0.57	0.6852
C x F x M x S	76	0.91		
C x F x P	2	2.48	2.98	0.0629
C x F x P x S	38	0.83		
C x SZ x M	4	0.56	0.71	0.5858
C x SZ x M x S	76	0.79		
C x SZ x P	2	0.81	0.07	0.9287
C x SZ x P x S	38	0.91		
C x M x P	2	2.18	3.29	>.05***
C x M x P x S	38	0.66		
F x SZ x M	8	0.87	1.10	0.3656
F x SZ x M x S	152	0.79		
F x SZ x P	4	0.20	0.22	0.9252
F x SZ x P x S	76	0.92		
F x M x P	4	0.33	0.37	0.8277
F x M x P x S	76	0.87		
SZ x M x P	4	0.95	1.02	0.4011

Table 4 (continued)

Source of variance	df	MS	F	*p*
SZ x M x P x S	76	0.93		
C x F x SZ x M	8	1.31	1.64	0.1179
C x F x SZ x M x S	152	0.80		
C x F x SZ x P	4	1.71	2.00	0.1036
C x F x SZ x P x S	76	0.86		
C x F x M x P	4	1.44	1.96	0.1090
C x F x M X P x S	76	0.73		
C x SZ x M x P	4	1.28	1.68	0.1638
C x SZ x M x P x S	76	0.76		
F x SZ x M x P	8	1.46	1.73	0.0946
F x SZ x M x P x S	152	0.84		
C x SZ x F x M x P	8	0.58	0.74	0.6583
C x SZ x F x M x P x S	152	0.78		
Total	2159			

Note. * $p < .05$ with lower bound Greenhouse and Geisser (1959) correction
** $p < .01$ with lower bound Greenhouse and Geisser (1959) correction
*** Greenhouse and Geisser (1959) $\varepsilon = .8237$, corrected df yield $p > .05$

As shown in Tables 3 and 4, the main effect of font was significant in both analyses. In both experiments, post hoc analyses indicated that the maximum dot font resulted in significantly longer response times, although the difference is much greater for the search task. However, in the random search task, the Huddleston and Lincoln/MITRE fonts did not differ significantly from one another (see Figure 28), whereas during the reading task (see Figure 29), the Lincoln/MITRE font resulted in significantly faster responses than the Huddleston.

The main effect of matrix size was statistically significant in the random search task, but did not reach significance in the reading task. The Student-Newman-Keuls test for the random search task indicated that search time decreased significantly ($p < .05$) with each increase in matrix size (see Figure 30).

The main effect of display polarity was found to be significant in both Experiments 1 and 2. During both tasks, positive contrast (light characters on a dark background) resulted in significantly longer response times than did negative contrast (dark characters on a light background), as illustrated in Figures 31 and 32, although the difference was not very large for the reading task.

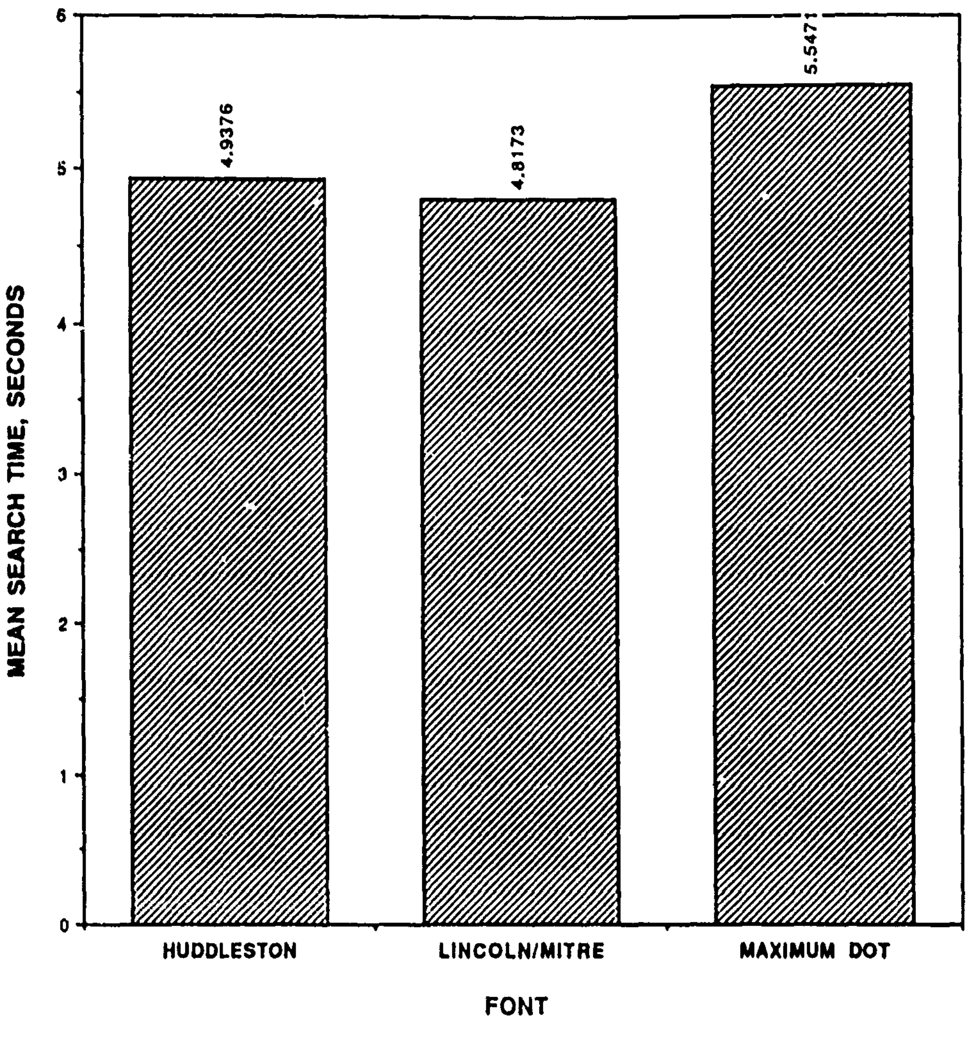

Figure 28. The effect of font on search time.

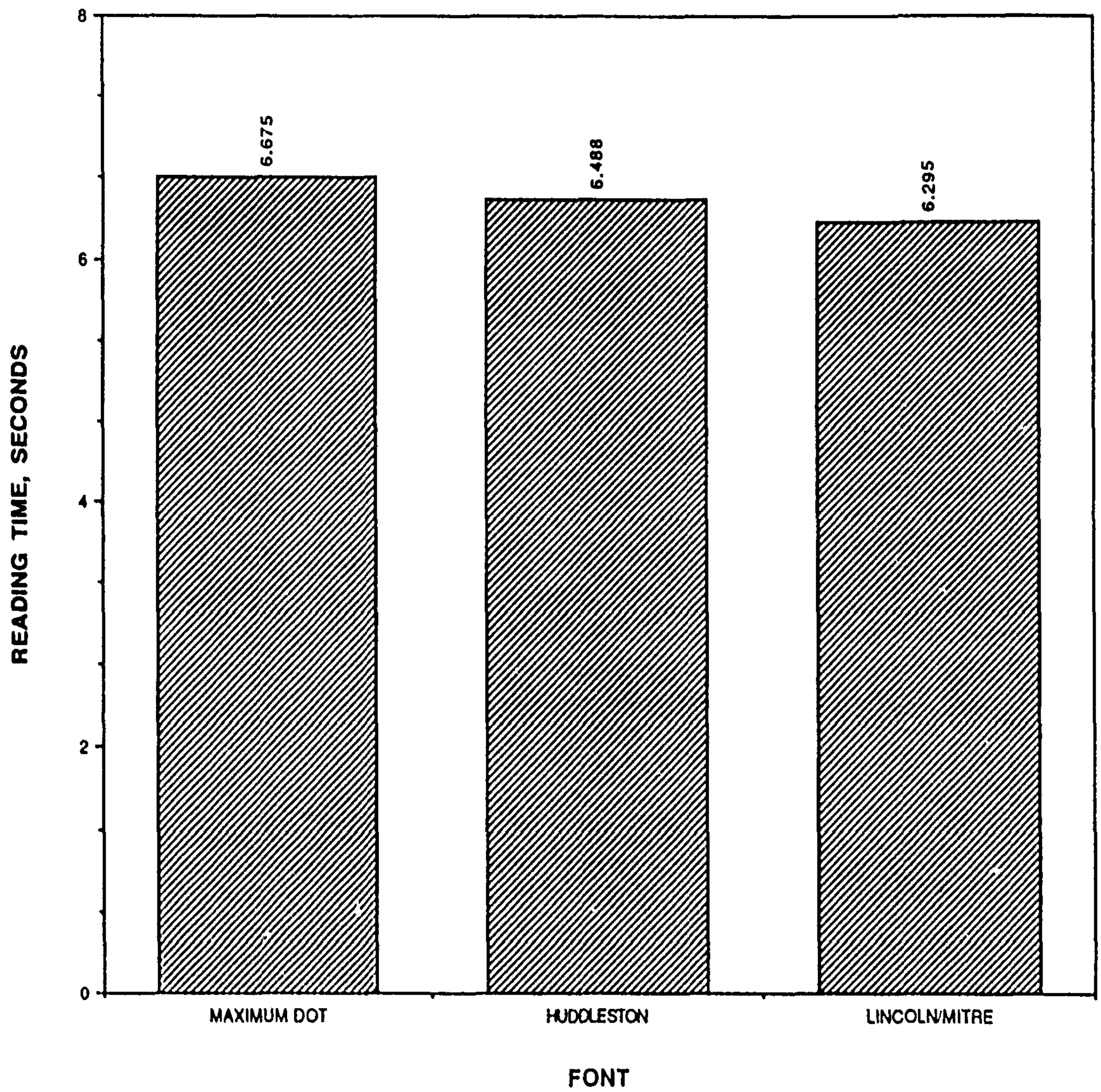

Figure 29. The effect of font on reading time.

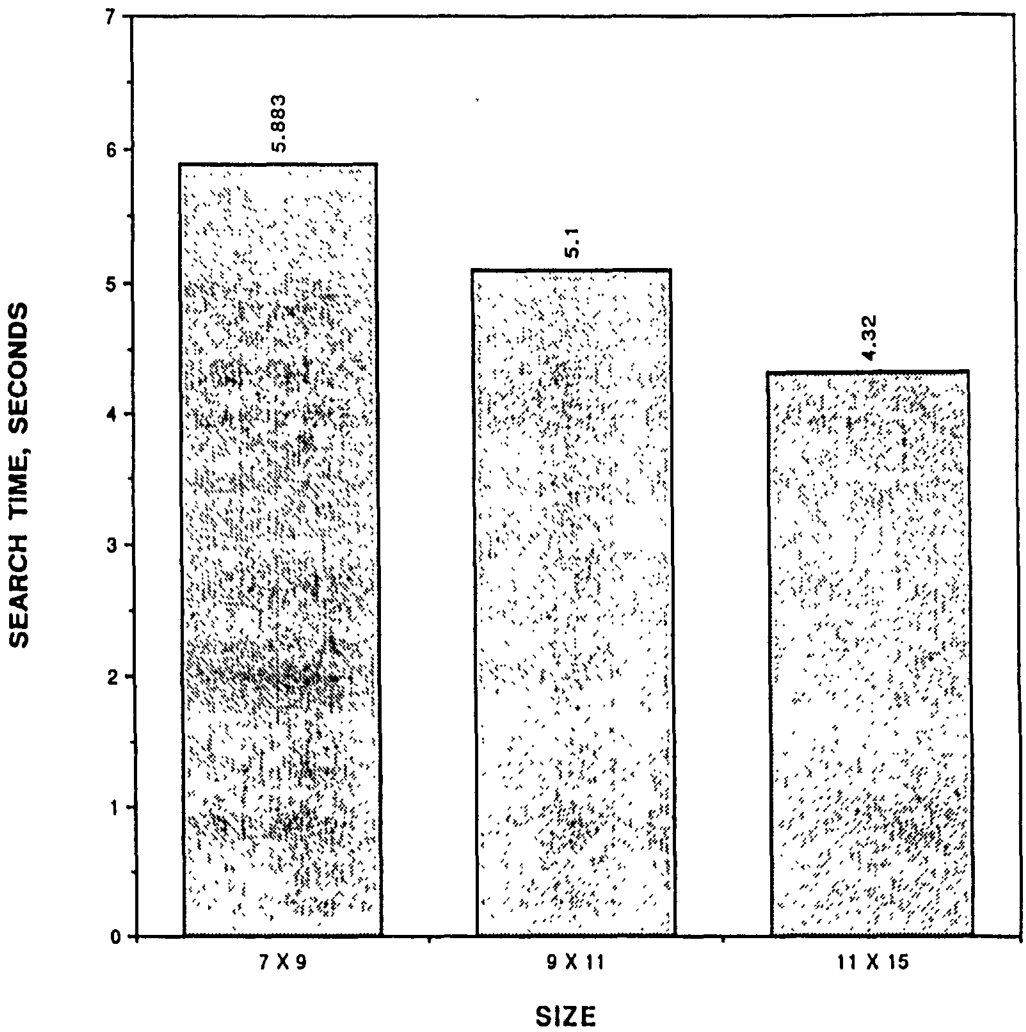

Figure 30. The effect of matrix size on search time.

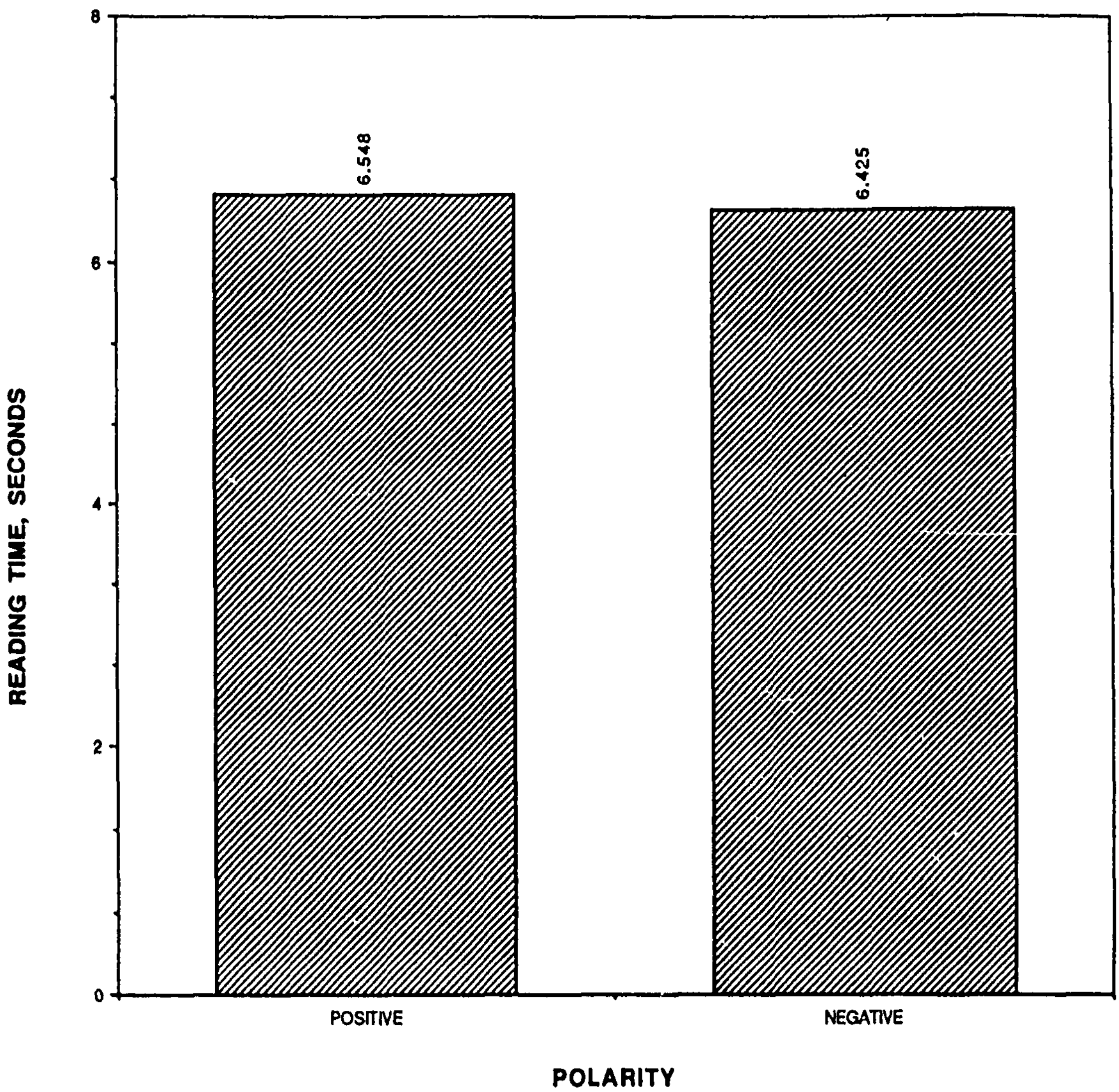

Figure 31. The effect of display polarity on reading time.

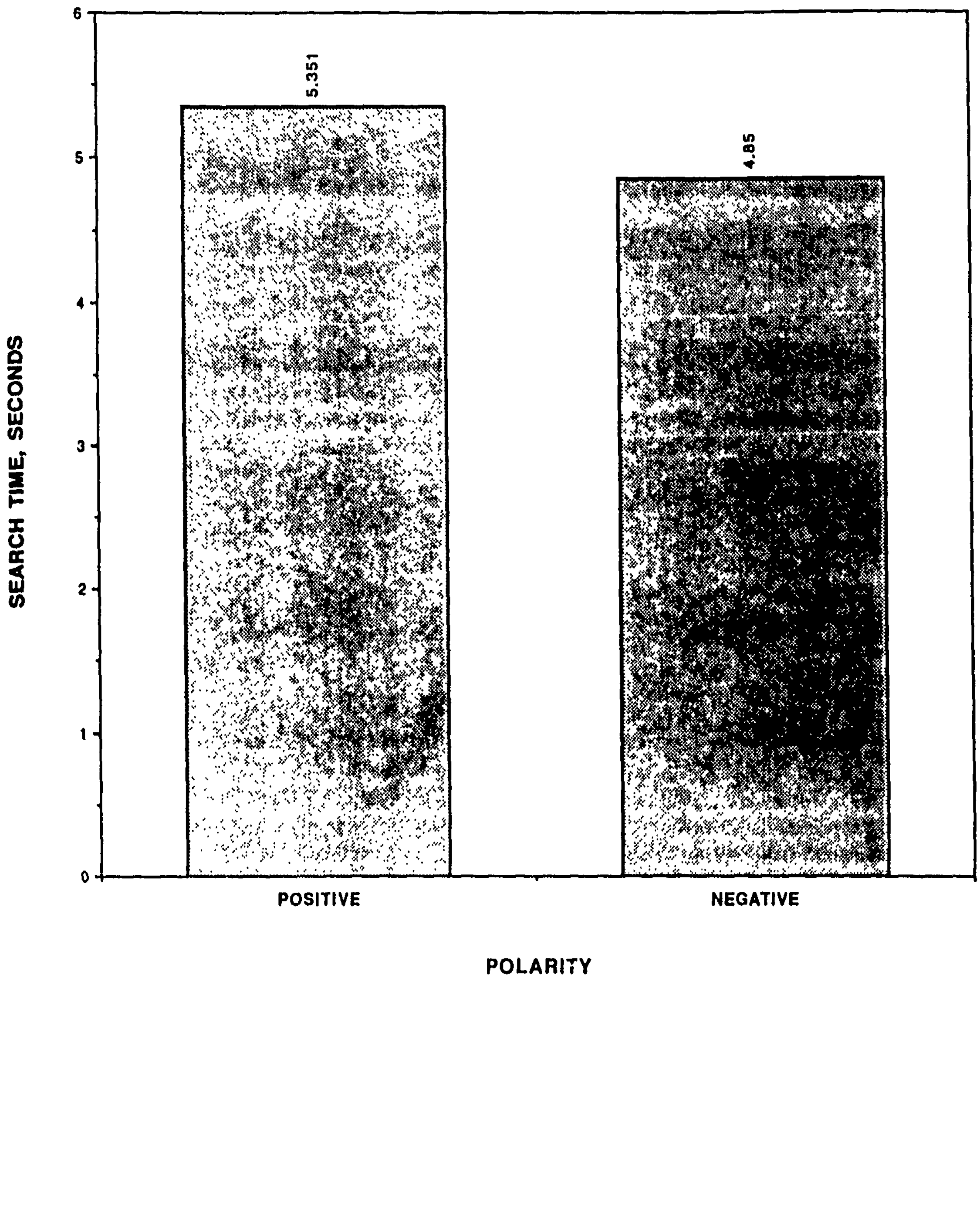

Figure 32. The effect of display polarity of search time.

No other significant effects were found of the random search task; however, the reading task showed a significant main effect for case (see Figure 33), with all upper case text resulting in significantly longer reading times than mixed case text. This variable, however, interacted significantly with the font, primarily because of the improved performance using the maximum dot font during mixed case conditions. As shown in Figure 34, the Lincoln/MITRE font resulted in the fastest response speeds in both cases. The Huddleston font showed no significant case effect, but it required longer reading times than the Lincoln/MITRE font, and the mixed case maximum dot font produced significantly shorter reading times than the upper case maximum dot. In fact, the mixed case maximum dot font approached the reading times achieved during the Huddleston mixed case font condition.

DISCUSSION

A possible explanation for the differences between polarities for both experiments is that the modulation and the spot size of the positive contrast condition differed slightly from those of the negative contrast condition. This possibility was investigated further.

Microphotometric measurements were made of the display for each modulation and polarity condition. The equipment used for these measurements is described in the method section. Measurements of a vertical and a horizontal line were made at the center of the screen. The spot size and modulation for each condition were calculated and are presented in Table 5.

These variables were entered into a multiple regression calculation to determine the correlation between performance and any contrast-related conditions, with the hypothesis that the modulation and spot size were different in at least one dimension between positive and negative contrast conditions and that such differences led to the differences in performance. The reading time data were used for the Lincoln/MITRE font because the reading performance is consistently faster when using this font.

Results of this analysis indicated no correlation between reading time and any combination of horizontal modulation and vertical and horizontal spot size ($R^2 = 0.0003$); therefore, it can be postulated that these factors were sufficiently well controlled and are not significantly influencing the results.

It is possible (and likely, from a hardware perspective) that previous studies that found no differences between the two polarities (Semple et al., 1971; Seibert, as cited by Shurtleff, 1980) did not stringently control for modulation and spot size for each contrast condition.

Bauer and Cavonius (1980) also found that negative contrast was faster than positive contrast; however, their negative contrast condition had a background luminance of 80 cd/m^2, well above recommended levels of 35 cd/m^2 (Decker, Pigion, & Snyder, 1987) and may have appeared too bright for the subjects. The positive contrast condition had a background luminance of 4 cd/m^2. The modulation values for these conditions may not have been equal.

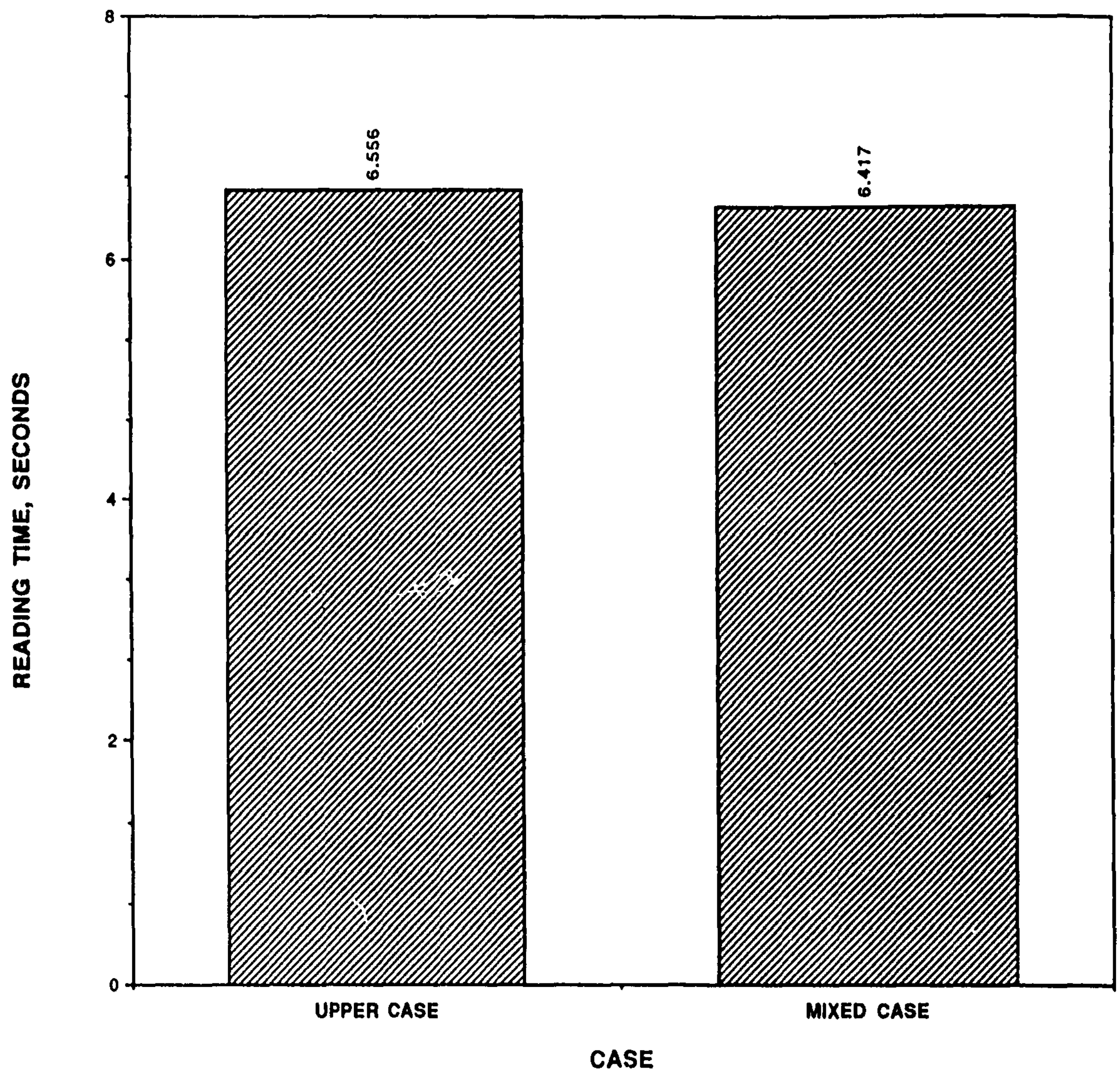

Figure 33. The effect of case on reading time.

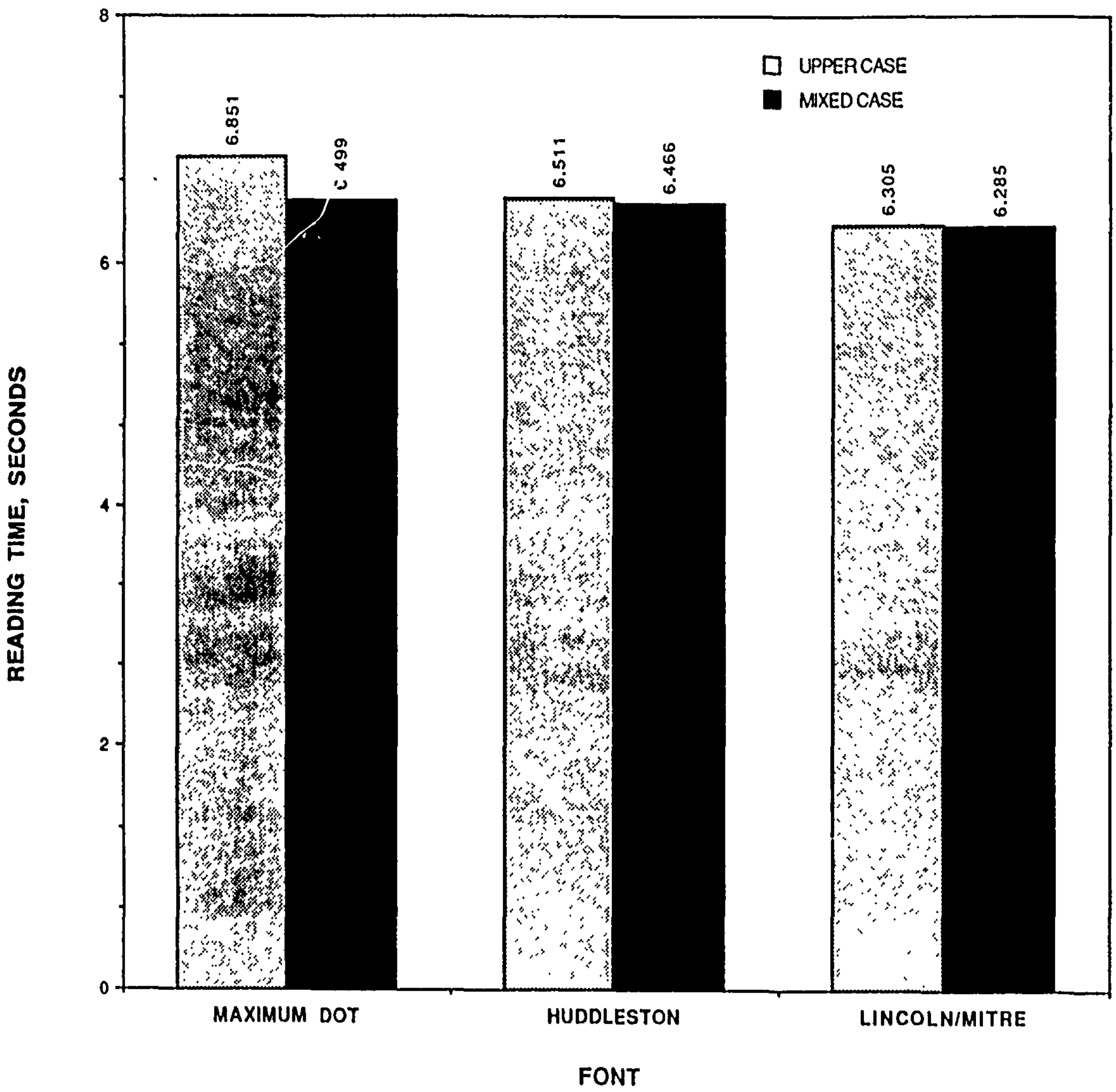

Figure 34. The effect of the font-by-case interaction on reading time.

Table 5

Modulation and Spot Size for Each Polarity Condition

	Negative Contrast				Positive Contrast			
Modulation	MODV	MODH	SSV	SSH	MODV	MODH	SSV	SSH
0.82	0.829	0.939	0.378	0.448	0.882	0.939	0.294	0.126
0.72	0.718	0.842	0.378	0.462	0.816	0.869	0.364	0.098
0.50	0.497	0.610	0.350	0.476	0.640	0.786	0.294	0.112

MODV = Modulation of a vertical line
MODH = Modulation of a horizontal line
SSV = Spot size for a vertical line, mm
SSH = Spot size for a horizontal line, mm

The results of the random search task differ somewhat from those of other researchers. Snyder and Maddox (1978) found the Huddleston and Lincoln/MITRE fonts to produce superior performance; however, by comparison, the present study found no interaction of font with character size. Response time was found to improve with increases in character size, as found by Snyder and Taylor (1979). Negative contrast (dark characters on a light background) resulted in shorter response times than positive contrast, similar to the improved accuracy with negative contrast found by Bauer and Cavonius (1980).

SUMMARY AND RECOMMENDATIONS

These results clearly support other literature and add to our understanding of the polarity variable. From the results, the following recommendations can be made regarding the investigated variables and their effects on visual task performance.

Font

The Lincoln/MITRE font was once again found to be superior to both the Huddleston and maximum dot fonts. At this time, no dot-matrix font is known to consistently outperform the Lincoln/MITRE font for either reading or search tasks.

Modulation

Greater modulations have been found to generally produce better visual task performance. Character luminance modulations between 0.50 and 0.80 produced no reliable performance differences in these two experiments. Based on existing data, however, modulations of 0.80 are still recommended.

Polarity

These two experiments clearly support the prior results of Bauer and Cavonius (1980) in recommending negative contrast displays. Significant superiority was shown for both reading and search tasks.

Character and Matrix Size

A matrix size of 11 x 15 (19 x 25 arcmin) is superior to 7 x 9 (12 x 15 arcmin) and 9 x 11 (15 x 19 arcmin) for search tasks, as has been found previously. Reading time was unaffected by matrix and character size within these limits. Since the larger (19 x 25 arcmin) size is not a disadvantage for reading, although the characters are slightly larger than often recommended, it appears logical to select the larger matrix size (11 x 15) and permit the character subtense to approach 25 arcmin vertically for all visual task applications.

These two experiments did not investigate the effects of various types of dot-matrix display failures on performance, nor the effects of interactions between failures and the selected experimental variables. Future studies in this program will address those issues.

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