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THE EFFECT OF ROTATION ON LEGIBILITY OF DOT-MATRIX CHARACTERS

Ko Kurokawa, Jennie J. Decker, and Harry L. Snyder
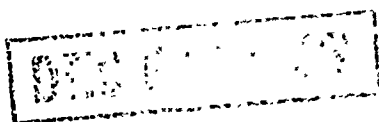Virginia Polytechnic Institute and State University

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When dot-matrix characters are rotated, as may be in a moving map display, their dot-matrix patterns are distorted and their legibility is thus affected. In this experiment, 16 subjects performed a random search task in which they were asked to look for a target in a random character pattern. The independent variables were (a) the direction (clockwise or counterclockwise), (b) the angle of stimulus image rotation, and (c) the target character's distance from the center of the screen, which was also the center of rotation. The dependent variables were response time and response correctness.

Significant effects were found for the angle of rotation, the target character's distance from the center, and the target character. The results indicate that (a) no angle-dependent mechanism is involved in performing this
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task and the angle of rotation influences recognition mainly through the distortion of dot-matrix patterns; (b) the target character's radial distance from the center of the screen is the determining factor for search time, while the x and y coordinates of the target contributed to dot-matrix pattern distortion; and (c) the target characters interacted differently with the angle and distance factors to determine the extent of distortion and their legibility. Means to quantify the extent of distortion are discussed and the direction for future research is suggested.

THE EFFECT OF ROTATION ON LEGIBILITY OF DOT-MATRIX CHARACTERS

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February 1991

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INTRODUCTION

Recent developments in digital electronics have made numerous applications possible that had previously been products of only the designers' imaginations. Traditional media of communication, for instance, are rapidly being changed or replaced by various offspring of digital technologies. Digital storage media, such as magnetic disks and tapes and optical disks, provide far more efficient and reliable storage of information than do traditional printed materials and photographs. Along with superior storage media come more applications that had not been previously considered.

A moving map display is one such application that is enjoying newly found interest and has the potential for widespread use. Normally, an image of a conventional map printed on paper is digitized and stored in a digital form. This approach allows not only re-creation of the whole map through another medium (e.g., a visual display, a printer, or a plotter) but also selective re-creation of the map in any way a person desires. A digital map display system can thus be designed to show an area of interest with features of importance and in an orientation that will allow the users to visualize their locations most easily.

Moving map display systems are currently used in aircraft, both military and commercial, and in automobiles to provide the operators with pertinent vehicular information superimposed on the map background. Moving map displays are also used in military command and control systems, in which various tactical information is presented over a map to provide operators with an integrated picture of the situation. The main factor that is currently keeping moving map displays from being widely used is their cost. Costs of digital electronics, however, seem to go only downward and as the price of systems is reduced, moving map displays are likely to be encountered more often.

Whenever a continuous entity is represented as a collection of discrete elements, a problem of resolution arises--the larger the number of elements used to describe the continuum, the finer the resolution and the more accurate the description of the entity. Tradeoffs must always be made between the level of accuracy and the number of elements required to provide it. In digitizing a continuous image, such as a map or a photograph, the issue of resolution remains important. The finer resolution desired, the more bits of storage are required. The issue of resolution is rather complex since it exists in both spatial and temporal domains. The problem begins with the resolution of alphanumeric characters.

Characters in typeface are drawn in strokes, but when they are digitized, they are represented by a collection of dots positioned to best simulate the strokes. As digital technologies developed, dot matrices were developed to simulate various typefaces. In these character fonts, compromises were made between how closely they resemble the stroke characters and the size of the matrix (i.e., the number of dots available and thus the spatial resolution). To simplify the patterns further, each dot in the matrix consists of one bit (i.e., the least possible temporal resolution, simply on or off).

These fonts are quite suitable for presenting characters in an upright position since their dot-matrix patterns were created for that particular orientation. Unfortunately, when dot-matrix patterns are rotated, as they are likely to be in a moving map display, relative positions of dots are altered and the character pattern is thus distorted. The performance of human operators using such displays may then be affected by the degradation of the dot-matrix patterns.

One way to counteract the distortion of dot-matrix patterns has been offered by Crow (1978) who discussed algorithms that provide gray scale for rotated dot-matrix characters. By controlling the gray scale and thus the luminance of each dot, this approach simulates a spatial gaussian luminance distribution with its peak at the position where the optimal stroke of a character should be. The result is the smoothing of artificial features that might be created by the rearrangement of dots. Another means of correcting the distortion involves the use of spatial or temporal dithering, neither of which is easier to implement than gray scale. Spatial dithering is not practical for fonts with a smaller matrix, while temporal dithering requires a higher sampling frequency (refresh rate).

These "exotic" means of compensating for the distortion of dot-matrix patterns caused by image rotation can be effective but are only attainable at substantial cost, both in terms of hardware and software. Furthermore, the question arises about whether they are even necessary.

Because applications that must contend with potential problems with rotated dot-matrix characters are still few and not widely used, there 'as been very little research investigating the effects of rotated dot-matrix characters on human performance. Clearly, a systematic effort is needed to define the problems and to assess their severity and consequences. Once the issues involved in rotating digitized characters and their effects on human performance are identified and understood, corrective means can be developed and tested.

Two issues must be considered in investigating the effect of rotated dot-matrix characters on human performance. The first issue deals with how human performance is influenced by rotation in tasks requiring recognition of (non-dot matrix, stroke) characters. The second issue involves the distortion or degradation of dot-matrix character patterns and how those might affect human performance.

Rotation of Characters

The effects of rotation in shape recognition tasks have been extensively investigated. By understanding the way humans look at and recognize visual patterns, underlying cognitive processes might be revealed. Studies have focused on recognition of shapes and patterns (two-dimensional and three-dimensional) and characters. Issues involved with pattern recognition are many and complex. The process by which identification and discrimination are conducted, however, is an issue central and most critical in the case of rotated patterns.

In 1971, Shepard and Metzler reported a study in which the idea of mental rotation was introduced. Their task involved inspection of pairs of perspective line drawings of three-dimensional shapes, and subjects were to determine whether the shapes were the same or different. They found that the subjects' reaction times were a linear function of the angular differences

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among the shapes, and this resu_t was interpreted to suggest the existence of a mental rotation process in which a person mentally rotated an image of one shape and compared it with the other.

Shepard and Klun (as reported by Cooper & Shepard, 1973) performed two experiments in which they investigated mental rotation with alphanumeric characters. Subjects were presented with 1 of 12 characters (F, G, J, R, e, j, k, m, 2, 4, 5, or 7) in various rotations, and they were asked to determine whether the presented character was normal or the mirror image of normal. The main difference between this study and the previous study by Shepard and Metzler was that this study required comparison of a mentally rotated image with a familiar pattern stored in long-term memory instead of with another simultaneously presented image. It should also be noted that the task was to discriminate between normal and mirror images rather than to simply identify a character that might be performed on some orientation-free features of the character without mental rotation. Shepard and Klun found that (a) reaction time was a monotonically (although not linearly) increasing function of angular deviation from the upright; (b) the normal orientation resulted in faster response than the mirror image; and (c) if both the identity and orientation of the upcoming character were provided, the reaction time function became flat, while either piece of information alone did not affect the reaction time. The last result indicated that matching of a rotated stimulus character with the internal representation was made constant by prior mental rotation of the character and that discrimination between normal and mirror images required mental rotation.

Cooper and Shepard (1973) further examined this issue of mental rotation in discrimination of alphanumeric characters. Of the two experiments reported, the first one addressed issues of interest to this research. The task was to discriminate between normal and mirror images of six characters (G, J, R, 2, 5, and 7) rotated in multiples of 60°. There were eight levels of advance information regarding the identity and the orientation of the stimulus that influenced the subjects' reaction time.

The results agreed with the earlier Shepard and Klun study in that (a) reaction time with no advance information increased monotonically but not linearly with the angular deviation from the upright; (b) with either identity or orientation information alone, reaction time was essentially parallel to that without advance information, and approximately 100 milliseconds less, which the authors attributed to the time needed to determine the identity or orientation; (c) when both types of advance information were provided separately and for an adequate amount of time to integrate them, the resulting mentally rotated image of a character was as effective as the memory image of a physically rotated character in producing a constant reaction time irrespective of rotation; and (d) there appeared to be two types of mental rotation: pre-stimulus and post-stimulus.

When the subjects were given enough time to integrate the advance information regarding the identity and orientation of the upcoming character, the authors postulated that the resultant mental image was created by rotating the normal upright image to the specific orientation and matched against the stimulus. When the mental rotation was initiated after the stimulus was presented, as in the case of no advance information, the resulting mental image was created by rotating the stimulus image to the normal upright and matching it against the image in long-term memory. Both types of mental rotation were said to occur at the same rate.

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In the second experiment, it was found that when the mentally rotated image did not match the stimulus, reaction time increased monotonically and linearly with the angular difference, which agreed with the results of Shepard and Metzler's (1971) study of unfamiliar three-dimensional shapes.

It is important to note that Cooper and Shepard (1973) intended to prevent subjects from responding to a stimulus character on the basis of its features and to force them to do mental rotation by discriminating between the normal and mirror images. As the results indicated, identification of the stimulus character and its orientation was a prerequisite for mental rotation. The task required mental rotation to compare the stimulus image with the internal image stored in the subjects' long-term memory.

Issues related to the types of mental rotation addressed by Cooper and Shepard (1973) were examined by Koriat and Norman (1984). They defined the term "image rotation" to be "a strategy in which the image of the stimulus is rotated until it attains its normal, upright orientation," and according to this strategy, response time depends on the angular deviation from the upright. According to the frame rotation strategy, "the perceiver's system of coordinates (or frame of reference) is rotated until it matches the orientation of the stimulus," and response time is a function of the angular deviation between two images, for example, an internal image and the stimulus image. In their second experiment, Cooper and Shepard applied the latter strategy to explain the linear relationship between reaction time and the angular deviation between the mentally rotated image and the stimulus. Koriat and Norman performed several experiments following the Cooper and Shepard paradigm, except that Hebrew letters and strings of five Hebrew letters were used in discrimination tasks. (Hebrew was the primary language of the subjects who participated in this study.) The results strongly favored the image rotation strategy and raised a question about the nonlinear nature of mental rotation found in the Cooper and Shepard study.

Koriat and Norman (1985) then investigated the idea of broad orientation tuning as an explanation for the nonlinearity, which they called "a quadratic trend." A discrimination task between the normal and the mirror image using four Hebrew letters presented in orientations in multiples of 60° was repeated for their first experiment. They found that for the mirror image characters, response time increased linearly with the angular deviation from the upright, whereas response time was significantly quadratic with the normal letters, which might indicate that the sensitivity to the deviation (from the upright) is lower near the upright. The second experiment was repeated with four artificial characters replacing Hebrew letters and showed a systematic increase in the quadratic component with practice, that is, the functions for both the normal and the mirror image began as linear. These results suggest that broad orientation tuning developed as the result of extensive practice or exposure and was responsible for the nonlinearity in discrimination of the normal character.

The sequence of cognitive operations in identification and discrimination of a rotated character, which appeared to involve mental rotation, was also investigated by Corballis, Zbrodoff, Shetzer, and Butler (1978). In the first of their three experiments, they asked subjects to identify stimulus characters (G, J, R, 2, 5, or 7) presented normally or backward (mirror image) for 1 second in orientation multiples of 60°. Although this task was not expected to require mental rotation, the results showed that the reaction time depended on angular deviation from the upright orientation. The authors added, however, that the significant effect was

confined to the backward characters and decreased as the subjects gained experience. They explained that the subjects occasionally performed mental rotation to check their decision.

In their second and third experiments, subjects were assigned one of the six characters or one of the six orientations as the target and responded whenever the target was presented. Their aim was to look at the sequence of identification of the character and the orientation, and they found that it took longer to determine orientation than characters. Thus, identification of a character required information about its orientation and was likely to take place before orientation was determined. The results of these experiments were somewhat contradictory and did not clarify whether identification of a character required mental rotation and was thus completely independent of orientation; they appear to at least support the concept that identification of orientation precedes mental rotation.

White (1980) reported an experiment that supported the idea that mental rotation was not necessary for identification of characters. He followed the general paradigm of Cooper and Shepard, using G, J, R, 2, 5, and 7 presented at orientations in multiples of 60°, except each 4-second presentation of the character was preceded by target information. During the "version" condition, the target information advised the subjects to look for either the normal or the mirror image of a character, and they responded only when the stimulus matched the information. Reaction times for correct responses were measured. Trials were repeated for the "name" condition in which the target character was specified and for the "category" (letter or number) condition. The results clearly showed the absence of an orientation effect in the latter two conditions, whereas the version condition was affected in a fashion similar to that reported by Cooper and Shepard (1973) and Corballis et al. (1978). White thus concluded that mental rotation to the upright orientation was necessary only when discriminating between the normal and mirror images of characters and that the information needed to create an internal image with which to compare the stimulus was "invariant with respect to angular orientation."

It seems clear from the results of the studies discussed thus far that mental rotation, which is a function of orientation, is involved in the normal versus mirror image discrimination of characters and other visual forms, but that identification alone does not require mental rotation. Yet, is it safe to assume that identification is completely independent of orientation? The studies summarized thus far used reaction time as the dependent variable to examine the effect of orientation. Jolicoeur and Landau (1984) argued that reaction time was not sensitive enough to measure the effect of orientation on identification and thus identification appeared to be independent of orientation.

In Jolicoeur and Landau's (1984) experiment, the task was to identify alphanumeric characters (A, B, E, F, G, K, R, T, 2, 3, 4, and 5) rotated in multiples of 30°. In this study, the identification error rate was measured instead of response time. They found that the error rate was a linearly increasing function of the angular deviation from the upright and based on the mean stimulus exposure duration, they estimated that approximately 15 milliseconds would be sufficient to compensate for a 180° rotation (or a rate of 12° per millisecond). This low rate of rotation in identification was then attributed to the lack of a significant effect of rotation in identification tasks. Jolicoeur and Landau further stated that features detected in pattern recognition might not be "orientation invariant."

It should also be noted that identification of some rotated characters might require mental rotation, since discrimination is involved in the process of identification. For example, the orientation of letters b, d, p, and q and numerals 6 and 9 must be known to identify them (Corballis, 1988; Corballis & Cullen, 1986); these characters are, however, an exception.

In summary, in the task requiring recognition (identification) of (non-dot matrix, stroke) characters, the effect of rotation on human performance is of such small magnitude that it might be negligible if the task is composed of other components, for example, searching for the target character.

Distortion of Dot-matrix Characters

The research about recognition of rotated characters summarized in the preceding section used stroke characters that were tachistoscopically presented to subjects. Most other research that pertains to characters has also been done using stroke characters; however, as Maddox, Burnette, and Gutmann (1977) pointed out, "It has not been satisfactorily demonstrated that the conclusions from stroke font research are directly transferable to dot-matrix fonts." Issues involved in the rotation of dot-matrix characters and particularly the resultant distortion of dot-matrix patterns need to be examined separately.

Research about dot-matrix characters has focused on such characteristics as their matrix and physical sizes; element shape, size, and spacing; and font (Decker, Pigion, & Snyder, 1987). An American National Standard (Human Factors Society, 1988) was developed to define recommended values for certain characteristics of visual display terminals. There has been little research, however, studying the effects of dot-matrix pattern degradation on legibility of the characters. Abramson, Mason, and Snyder (1983) investigated the effects of dot and line failures on dot-matrix displays. Three 7- x 9-matrix fonts were used in a reading task with various display failures, and the effect of font on performance was not found to be significant. One type of dot pattern degradation was represented in this study, that is, the dot-matrix patterns of characters remained constant, while certain dots in the pattern were omitted or extraneous dots added as the result of display failures. The results of their study showed the complex effects and interactions of display failure type, mode, and rate and that below a certain failure rate, this type of dot-matrix pattern degradation does not affect performance in a contextual reading task.

Vanderkolk (1976) reported a study in which an attempt was made to investigate several parameters relevant to dot-matrix displays and legibility. The variables in this study were percent active area, contrast, display background luminance, matrix size, character and symbol orientation, and "motion parameters," each of which had two levels. (Characters and symbols used were I, N, Q, U, V, 1, 3, 8, n, and s.) The task was to identify a character or symbol, and reaction time and accuracy were measured. The fractional factorial experimental design assumed all three-way and higher order interactions to be negligible. Of interest were the effects of matrix size (5 x 7 and 8 x 11) and orientation (0° and 15°). The results showed that neither had an overall significant effect, but that the interaction between matrix size and orientation was significant (15° rotated 8 x 11 font produced the shorter reaction time, but the 5 x 7 font did better upright). Apart from noting that the effect of rotation on dot-matrix characters was considered, this study does not offer useful information. Its shortcoming

lies in that only two levels of each variable were examined and that the experimental design statistically confused most of the interactions, which are at least as important as the main effects.

The main difference between stroke and dot-matrix characters lies in the way the shape and contour of characters are created. While stroke characters are composed of continuous "strokes," dot-matrix characters are comprised of discrete dots that approximate the strokes as closely as the "resolution" of the matrix allows. For instance, consider a line five units long (could be centimeters, inches, etc.). In the stroke representation, a continuous line five units long is drawn. In the dot representation, the line would be a series of dots; the density of dots or the number of dots per length unit representing the five-unit-long line makes little difference in this case (see Figure 1).

When a circle of some radius is to be drawn, the difference between the stroke and dot matrix representations becomes more obvious. To represent the curvature, each dot is drawn in a matrix position nearest to the curvature. How close the dot can be to the actual curvature is determined by the density or the resolution of the dot matrix. Keeping the overall size constant, the larger (the more elements) the dot matrix, the finer the spatial resolution (for the sake of simplicity, interelement spacing is assumed to be held constant), and the matrix allows a closer "approximation" to the actual curvature (see Figure 1). The point to be emphasized is that dot-matrix patterns are approximations of the actual patterns except for the horizontal, vertical, and 45° diagonal lines.

Characters in most fonts consist of lines and curves, and their dot-matrix patterns are thus approximations, the extent of approximation depending on the character's curvilinear characteristics. When such dot-matrix patterns are rotated, each dot is transformed to a new matrix position which can, once again, be an approximation (the closest available dot). The new position is not necessarily where the actual stroke drawing would be when rotated, but rather is an approximation of the original dot position which was itself an approximation of the stroke drawing. The resulting dot-matrix patterns can thus be quite distorted, since the relative positions of dots can be exaggerated through the series of transformations.

OBJECTIVES

How such distortions of dot-matrix characters affect the user's ability to recognize them is the question central to this research. As indicated earlier, although potential problems in applications requiring the rotation and the consequential distortion of dot-matrix characters are anticipated, the nature of the problems and factors involved has not been identified and is not understood.

Recognition of rotated dot-matrix characters is made complex because it is affected not only by the rotation of characters themselves but also by the distortion of their patterns. This investigation manipulates the direction (i.e., clockwise or counterclockwise), the angle of stimulus image rotation, and the target character's distance from the center of rotation, all of which were thought to influence character recognition performance. The experiment is intended to observe and measure these factors' effects on human visual task performance and to gain a better understanding of the problems.
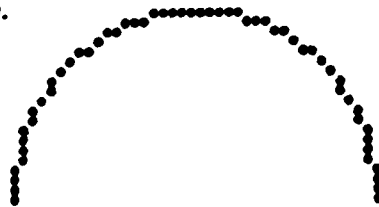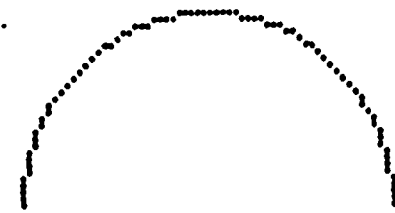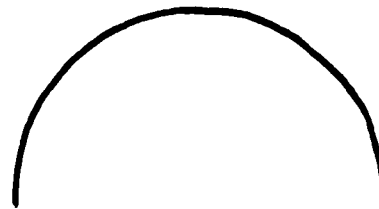
Figure 1. Dot matrix representations of a line and an arc during various conditions.

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Once the problems associated with the rotation of dot-matrix characters are firmly defined and understood, effective means to counter and correct them can be developed. Ultimately, this effort will lead to the larger and more complex issues involving digitized discrete element images.

METHOD

Experimental Design

A 37 x 2 x 4 full factorial within-subjects design, using 16 subjects and 4 repeated measures per cell, was chosen for this study (see Figure 2). Three parameters (angle of image rotation, direction of image rotation [clockwise and counterclockwise], and target character distance from the center of rotation) were varied (see Figure 3).

Experimental subjects were screened for normal visual acuity (correctable to a minimum of 20/30) and phoria (both horizontal and vertical). Their ages varied from 18 to 27 years with a median age of 20 years. There were 11 male and 5 female subjects, and all were university students.

Factors held constant throughout the experiment were alphanumeric characters in the 7- x 9-element Lincoln/MITRE font, all screens were presented in positive contrast ("on" characters on an "off" background), and the display luminance output was measured and adjusted to the standard value at the beginning of each session. The luminance of "on" pixels was approximately 49.4 candelas per square meter (cd/m^2) and the "off" pixels 4.8 cd/m^2, resulting in a luminance modulation of 0.823. The primary dependent measure was response time, although response accuracy was also recorded.

Each combination of the three independent variables was repeated four times using different target characters for each subject. A random pattern was created for each trial by selecting 71 sets of random coordinates, and no pattern was repeated for any trial or subject.

Apparatus

The experimental stimuli, random character patterns each of which consisted of 26 upper case letters of the alphabet and 10 numerals, were presented on a high resolution (1024 by 1024 picture element) cathode ray tube (CRT) display. The display imagery was generated by a high resolution graphics processor interfaced with a microcomputer (see Figure 4). Experimental sessions were controlled by the microcomputer with interactive links to the through the keyboard and the experimenter display and to the experimental subjects through the optical mouse input device.

Experimental subjects were seated approximately 40 centimeters from the display so that the vertical angular subtense of a displayed character was 20 arcminutes at the subject's eye. To prevent subjects from moving their heads during the experimental sessions, restraints were provided for the forehead and back of the head of subjects.

The data collected during experimental sessions were stored by the microcomputer, and when a subject completed all the sessions, the data files from each session were combined and transferred to a mainframe computer where all statistical analyses were performed using the Statistical Analysis System (SAS Institute, 1982).
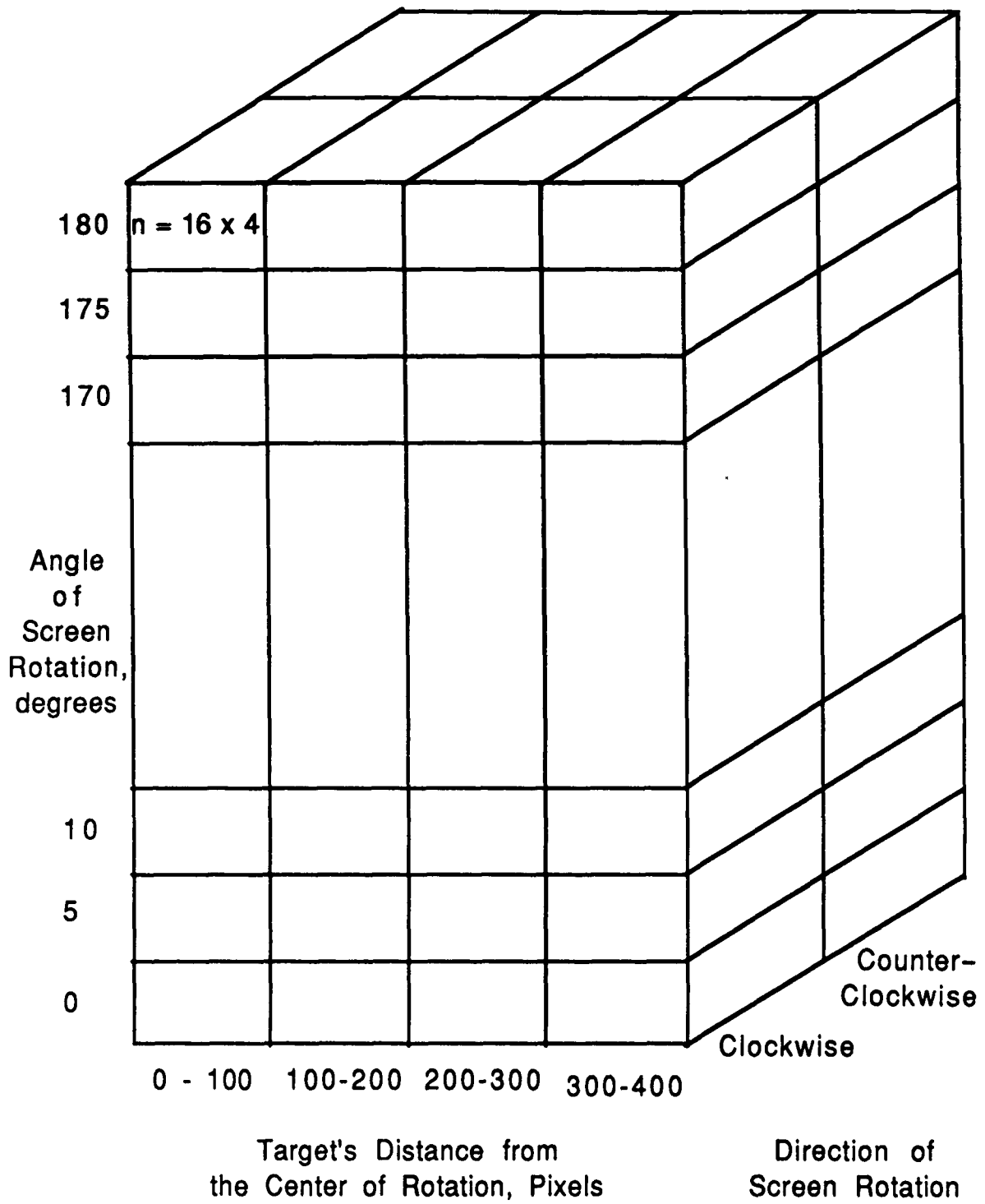
Figure 2. Experimental design.
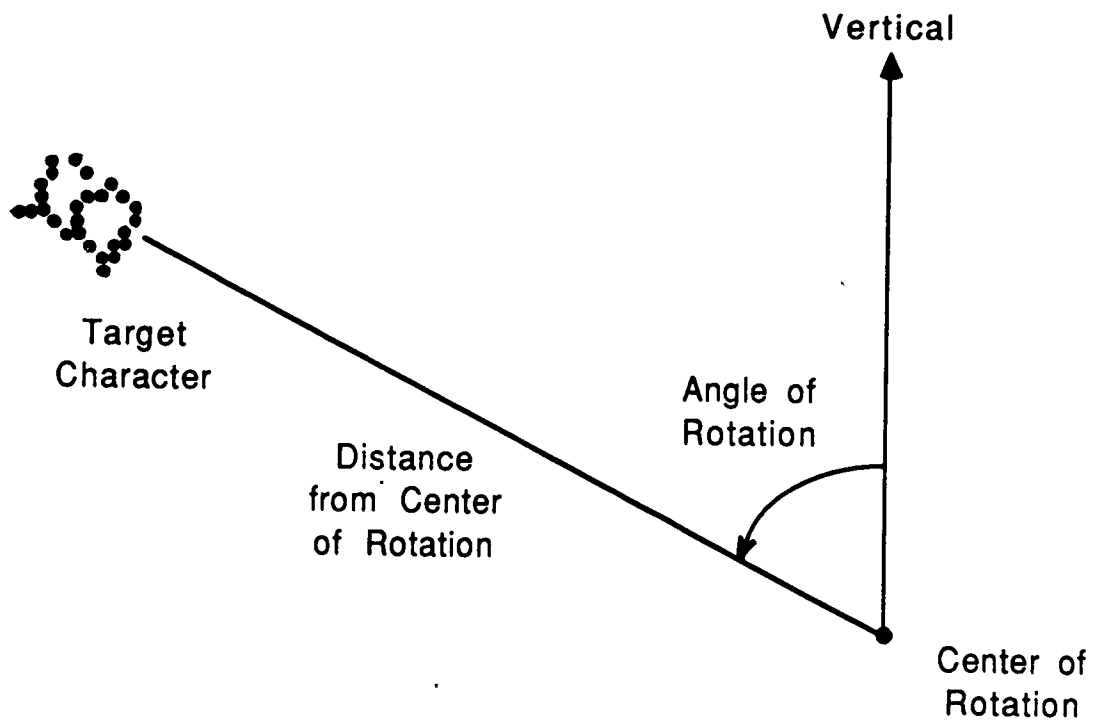
Figure 3.   Independent variables.
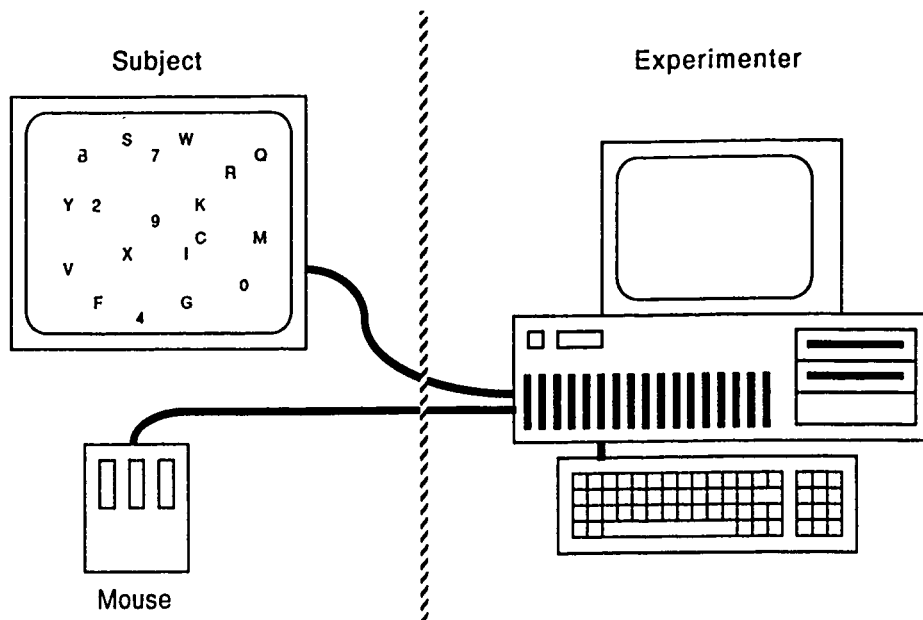
Figure 4. Experimental apparatus configuration.

Task and Procedure

The subject's task was to search for a specific character in a random
character pattern. The three independent variables determined how much and in
which direction the stimulus patterns were rotated and the position of the
target character in the stimuli. While the stimulus condition and thus the
legibility of the target character were varied, the task required subjects to
search for and identify the target character.   The objective was to measure
the effects of these variables and their interactions in a task when
difficulty was influenced solely by the factors being manipulated; in a
reading task, on the other hand, subjects might recognize a character or a
word based on the context.

Each experimental session started as the experimenter entered the
numbers identifying the subject and the session (day).   Each stimulus was
preceded by a screen indicating the next trial target character.   The
character was presented at the center of the screen in an upright orientation,
and it also served to guide the subject's eyes to fixate at the center of the
screen before the onset of the stimulus.   As the subject pressed the right
button on the mouse input device, a stimulus pattern was presented. The task
was then to search for and visually identify the target character in the
random pattern as quickly and accurately as possible.   The random pattern
contained one of the target character and two each of the remaining
alphanumeric characters (i.e., the pattern contained 71 characters).   When the

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subjects located the target character, they pressed the left mouse button and the target pattern was removed. A high spatial frequency blocking pattern, intended to remove any afterimage, was then shown for approximately 800 milliseconds, followed by a 3 x 3 numbered grid that covered the entire screen. The subjects identified the sector of the grid where they had located the target and verbally responded with the number corresponding to the sector, which was entered by the experimenter. Their response times, that is, the time between pressing the right and left mouse buttons (or the time the stimulus was presented) and the responses that determined whether the subjects correctly identified the location of the target character were recorded.

Each subject participated in three experimental sessions scheduled over 3 consecutive days at about the same time of day. During the first session, the subjects familiarized themselves with the task during 20 practice trials, and 480 recorded trials followed. During the second and third sessions, each subject completed 500 trials per session. Trials were presented in blocks of four; the direction and angle of rotation were held constant for these four trials, but the target characters and their distances from the center were varied. Rest breaks, about 5 minutes each, were given after every 125 trials or at the subject's request. The sessions typically lasted from 2-1/2 to 3 hours, and all subjects were paid by the hour for the average total of 7-1/2 hours.

Experimental Variables

Random Character Pattern Generation

In creating a rotated random character pattern, two distinct ways were considered. One approach is, given a set of coordinates for a character, to rotate the character at the coordinates. A reference point in the character's dot-matrix pattern, for example, the lower left corner of the matrix, remains fixed at the coordinates, while the other dots in the pattern rotate the specified angle around the reference point. New coordinates for each dot are determined by its relative coordinates from the internal reference point and the angle of rotation. One might refer to this approach as individual character rotation.

The other approach used for this study was to rotate a whole screen image around some common point of rotation, for example, the center of the screen. As each character rotated around some reference point, which was unlikely to be within its dot matrix, all dots in the pattern must have received new coordinates to perform the rotation. Each dot's coordinates were determined by its relative coordinates or distance from the center of image rotation and the angle of rotation.

The difference in these two approaches lies not in the extent of each character's distortion but in the number of factors determining the distortion. Given that the same size characters of the same font were used, in the former approach, the (rearranged, distorted) dot-matrix pattern resulting from character rotation was determined only by the angle of rotation. So long as the rotation reference point remained constant, the distorted pattern was identical regardless of its position in the random character pattern. In the latter approach, the resulting dot-matrix pattern was determined not only by the angle of rotation but also by the coordinates of the character pattern relative to the rotation point.

The rotated images created through the latter approach are more representative of rotated images in actual applications such as moving map displays. In a moving map display, for example, an original image (e.g., a map, including alphanumeric characters in its legends) is digitized upright and, in a heading-aligned mode, the image is rotated around some reference point. The characters would obviously not rotate individually around their own reference points. The stimulus patterns used in this study were thus rotated at the center of screen, and the coordinates of the target character were randomly selected for each pattern, so as to provide a broad sample of dot-matrix distortion.

Angle of Image Rotation

Although the angle of rotation is a continuous variable, only angles in increments of $5°$ between $0°$ and $180°$ were investigated in this study, for a total of 37 levels. When combined with the direction of screen rotation variable, all angles in $5°$ increments around $360°$ were covered. Two important assumptions were made regarding the nature of this independent variable. As summarized earlier, research concerning non-dot matrix characters concluded that mental rotation was not involved in recognizing familiar shapes, such as alphanumeric characters, and that the effect of rotation on the time to identify a character is negligible. These conclusions were assumed to be correct and transferable to this study that involved dot-matrix characters in a random search task. The only effect that the angle of rotation would therefore exert on the response time measure was then assumed to be through the distortion and degradation of the dot-matrix character patterns, and not through the process of character identification.

Distortion of dot-matrix characters was considered to be a function of the angle of rotation as well as of distance from the center of rotation. Dot-matrix patterns remained intact at $0°$, $90°$, and $180°$ from the vertical. At $45°$ and $135°$ from the vertical, some distortions were encountered. While vertical, horizontal, and $45°$ diagonal lines in the original upright pattern would remain straight, other dots in the pattern were displaced from the optimal positions. At angles between vertical, horizontal, and $45°$ diagonal, all dots were positioned at their nearest available matrix positions, likely away from the optimal, and varying distortions were expected. Hence, the extent of distortion, measured in terms of displacement (or deviation) from the optimal (i.e., the distance between the actual dot position and the ideal position where the dot would be if not constrained by available matrix positions) should be zero at $0°$, $90°$, and $180°$, local minima at $45°$ and $135°$, and peaks between these minima (see Figure 5).

Assuming that the response time would be influenced only by the distortion of dot-matrix characters, images rotated between $0°$ and $90°$ (right side up) and between $90°$ and $180°$ (upside-down) were expected to produce similar results, as the extent of distortion would be identical (mirrored along the horizontal). If, however, the resultant function were monotonically increasing toward a peak at $180°$, that would suggest the involvement of mental rotation or some other process that depended on the angular departure from the upright.
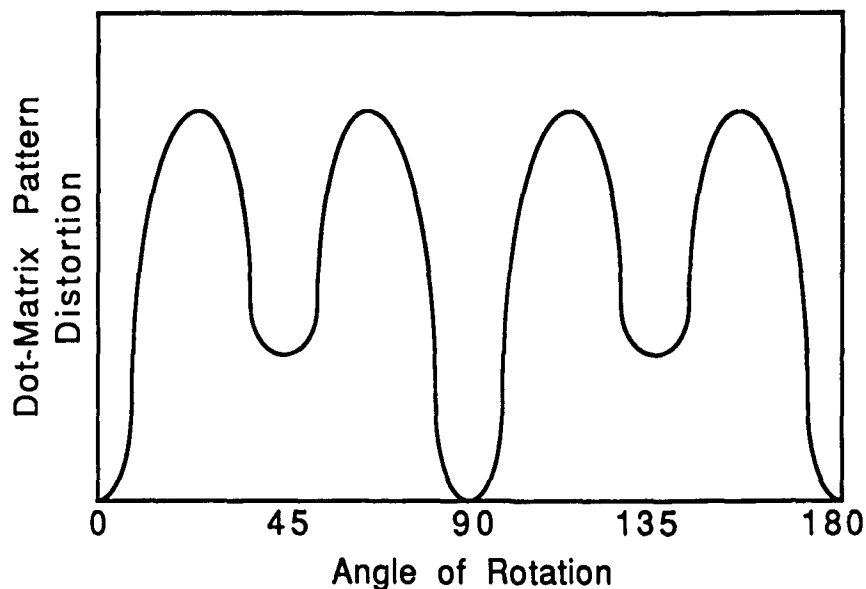
Figure 5. Expected distortion as a function of the angle of rotation.

Direction of Image Rotation

This variable compared a clockwise rotation with a counterclockwise one. There has been no report in the literature that a clockwise rotation resulted in either superior or inferior performance. A question remained concerning the symmetry of characters. Based on their symmetry, characters in the 7- x 9-element Lincoln/MITRE font (see Figures 6 & 7) can be categorized as follows. (These categories are mutually exclusive and are in increasingly restrictive order.)

Symmetrical about only the vertical axis (8)--A, M, T, U, V, W, Y and 8.
Symmetrical about only the horizontal axis (5)--B, C, D, E, and K.
Symmetrical about both vertical and horizontal axes (5)--H, I, O, X, and 1.
Rotatable (i.e., either same character when rotated 180° or another meaningful character when rotated 180°) (5)--N, Z, 0, 6, and 9.
Asymmetrical and nonrotatable (13)--F, G, J, L, P, Q, R, S, 2, 3, 4, 5, and 7.

Characters in Categories 1 and 3, for example, are not affected at all by the direction of rotation, as their dot-matrix patterns would be distorted identically whether rotated clockwise or counterclockwise from the vertical. Similarly, the distortion of characters in Categories 2 and 3 would be identical along the horizontal. In these cases, if a character is rotated a certain number of degrees from the axis of symmetry, the sum of dot deviations from the optimal would be the same in either direction. Asymmetrical characters, on the other hand, would result in different amounts of dot deviations when rotated in different directions.
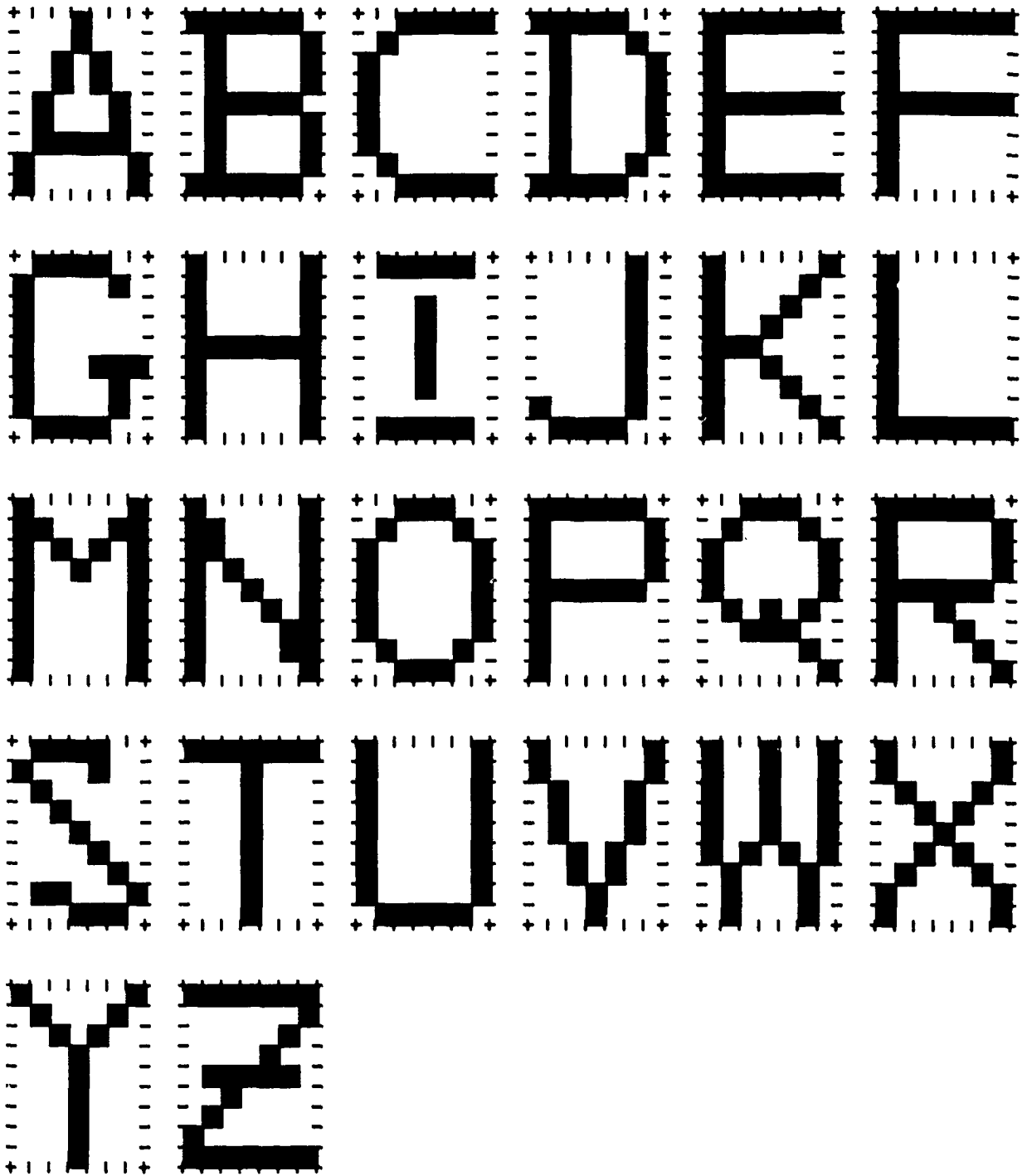
Figure 6. Lincoln/MITRE 7 x 9 letter characters.
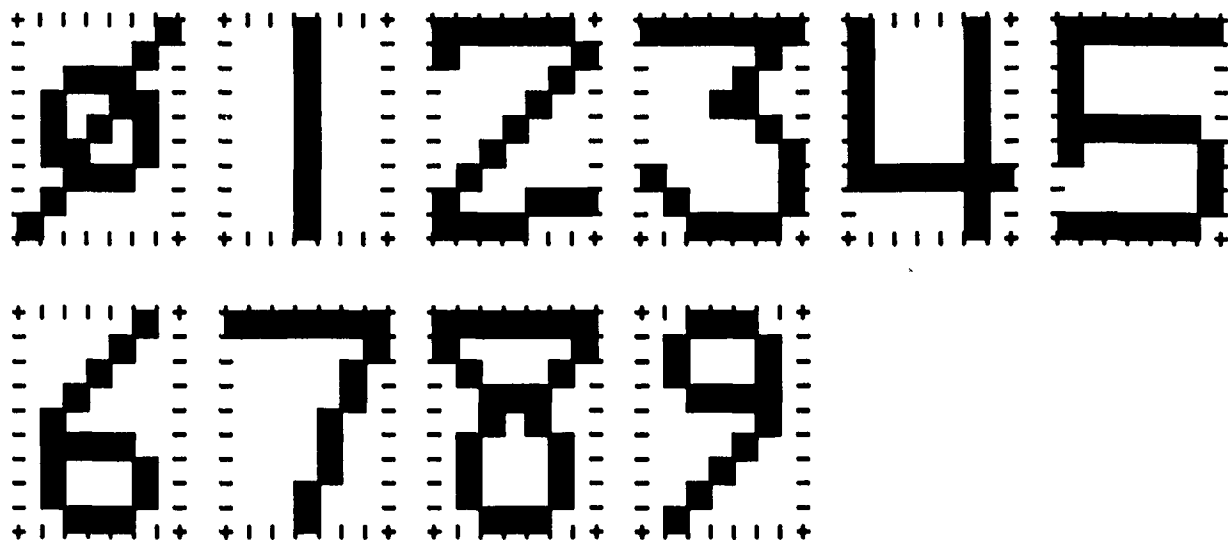
Figure 7. Lincoln/MITRE 7 x 9 numeral characters.

In this experiment, each stimulus pattern used all 36 alphanumeric characters, regardless of their symmetry, and the effect of asymmetry was expected to be marginal so that, overall, the effect of direction of image rotation was predicted to be nonsignificant. If a statistical analysis of experimental data later showed this variable to be nonsignificant, the data would be collapsed across the variable, doubling the number of observations in each condition (for each subject) from 4 to 8. This approach allows the data to be reanalyzed including the target character as another independent variable, and it provides insights about how dot-matrix distortion affects individual characters.

Distance from Center of Rotation

As stated earlier, all coordinates for the characters in the search patterns were randomly selected, and the characters' distances from the center of rotation, which was the center of the screen, varied continuously. This variable, however, was analyzed as a discrete variable by categorizing the distance in terms of four equally spaced intervals. Four concentric circles, with their centers at the center of rotation and their radii in increments of 100 dots (pixels), defined the distance zones; targets falling in radial distance between 0 and 100 pixels were assigned in zone 1, and so forth. No characters were more than 400 pixels away from the center of screen (beyond zone 4).

This variable might influence the response time in at least two ways. First, subjects' search strategies could be potentially significant. As their eyes were fixated to the center of the screen when the target stimulus was presented, if their strategy to search for the target was to start from the center and to gradually move outward, the time to find the target might have depended on its distance from the center. Second, the search strategy was to scan across the screen from the top to the bottom, for example, the response time would have been independent of this variable.

Issues involving search strategies are many and beyond the scope of this research. Hence, two issues potentially critical to this experiment were considered. First, interindividual differences in search strategy were assumed to be negligible. Significant differences among subjects could contribute to a larger subject variance, causing a loss of power; the effects of independent variables were, however, expected to be robust enough even in such a case. Second, intra-individual differences (change over time, e.g., learning and fatigue) could also be significant. Standardization trials, discussed later, were included and placed randomly among the "condition" trials to monitor the subject's "base line" performance; this factor was not expected to be significant.

The target character's distance from the center of rotation was expected to affect response time mainly through its effect on distortion of dot-matrix patterns. The equations for a rotated set of coordinates are

$$X \text{ rotated} = \text{round}(X \text{ original} \cos \theta - Y \text{ original} \sin \theta), \text{ and}$$

$$Y \text{ rotated} = \text{round}(X \text{ original} \sin \theta + Y \text{ original} \cos \theta).$$

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

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As can be seen in these equations, the new x and y coordinates are determined by the original x and y coordinates and the angle of rotation. To determine a new x coordinate, the difference between (1) the product of the original x coordinate and the cosine of the angle to be rotated, θ, and (2) the product of the original y coordinate and the sine of the angle is calculated and rounded to the nearest integer. Similarly, a new y coordinate is determined by combining the original x and y coordinate components weighted by the sine and cosine functions. The weights vary from -1 through 1 and act to "pull" the dot position differentially to a new rotated position. When rounding the product of the weight and the coordinate component, keeping the weight constant, the larger number the coordinate component is, the closer the rounded value of the product will be to the actual product. In other words, the larger value of a coordinate component provides better resolution. The greater distance from the center of rotation, that is, the larger valued x and/or y coordinates, would therefore provide the dot position closer to the ideal position and would distort a dot-matrix pattern less.

Both the angle of rotation and the target character's distance from the center of rotation determined the distortion of the dot-matrix patterns of characters and were thus expected to affect response time. Each variable was expected to have a significant effect; however, their interaction was not well understood, although predicted.

Font and Matrix Size

A 7- x 9-element Lincoln/MITRE font was used in this study. Smaller size fonts composed of fewer elements are more susceptible to distortion, resulting in poorer performance, as shown by Vanderkolk (1976). In larger matrix sizes, as each dot's contribution in forming the character shape is less, the dots' deviations from their ideal positions affect the character shape less drastically; thus, there should be less distortion. As this study tries to investigate the effect of such distortion, a smaller matrix size was considered more appropriate. In addition, given the spot size of the CRT display to be used and general recommendations made about character size and viewing distance (Decker, Pigion, & Snyder, 1987; Human Factors Society, 1988), the 7- x 9-element size was considered most appropriate for use in this study. Furthermore, as this matrix size is used by most "good" quality video display terminals, it might better represent the matrix size currently used in relevant applications.

The Lincoln/MITRE font is one of the more commonly used fonts in computer display applications, since it is closer to the regular typeface seen in printed materials than many other fonts. The latter point is desirable in that characters will better simulate the digitized image of printed characters. In this font, shapes of characters are so designed to make them unique and more distinct from each other, thus minimizing the likelihood of confusion among characters. Studies comparing different fonts have consistently shown that the Lincoln/MITRE font resulted in better performance (Decker et al., 1987).

Target Character

Only numerals and upper case alphabet characters were used in this study; lower case characters were not desirable as their sizes, mostly in height, were not constant across characters and the issue of resultant visual angles would have been complex. This study also treated characters as a

random effect variable. Characters are distinct from each other, as their geometric compositions, that is, the ways in which they are comprised of lines and arcs, are extremely complex. No means exist to quantify their characteristics systematically.

Geyer and DeWald (1973) reviewed three sets of "feature lists" of upper case (stroke) alphabet characters and compared them in their attempt to explain the underlying human information processes in character recognition. They correlated the information processing models based on these sets with confusion matrix data from another study. In Gibson (1969) feature lists (see Table 1), characters are represented based on the presence or absence of 12 common features. On the other hand, Geyer and DeWald's lists of characters are described by the number of 15 features present (see Table 2). Based on their results, such lists provide some insights about how a person recognizes a (stroke) character; however, they are neither predictive or quantitative.

A similar list of dot-matrix characters may be constructed in an attempt to categorize their features. The task is, however, considerably more difficult than with stroke characters. As noted earlier, except for vertical, horizontal, and 45° diagonal lines, the dot-matrix patterns are only approximations of the character's shape. These approximations result in irregularities in the positioning of dots which are difficult to be seen as a (regular) feature.

Considering the absence of a convenient list to categorize the dot-matrix characters based on their features, an alternative would be to treat the characters as a fixed effect variable. Unfortunately, if characters were to be treated as a fixed effect variable, every character would have to be included to investigate the effect of dot-matrix pattern distortion. Such a comprehensive effort would mean adding another variable with 36 levels, which would make the size of a factorial matrix enormous and infeasible.

As a compromise, a sample of characters that represent the others in certain characteristics (e.g., their symmetry, curvilinearity, the number of dots in their patterns) was selected. While the experiment was kept at a manageable size, it was hoped that meaningful generalizations would be made regarding the interpretability and applicability of results.

Eight sample characters were selected for use as target characters, based on two criteria. The first criterion was the confusion matrix for the 7- x 9-element Lincoln/MITRE font determined by Snyder and Maddox (1978). In their study, single character legibility of four fonts in three matrix sizes was compared. The confusion matrix was constructed from their data about subjects' response errors, and it shows that numeral 1 was most likely to be confused with another character, or that numeral 2 was often mistaken for the character Z. By selecting characters likely to be confused with another, it was hoped that subjects would be forced to examine the character carefully before responding and to identify dot-matrix patterns that might be so distorted as to be indistinguishable when rotated. A summary of the confusion matrix is shown in Table 3.

The second criterion used in target character selection was to avoid character pairs likely to be confused when rotated, as constructed from the visual inspection of 7 x 9 Lincoln/MITRE dot-matrix patterns. For example, the matrix patterns of numerals 6 and 9 are identical, except that one is rotated 180° from the other; in the absence of any context, there is no way to distinguish an upside-down 6 from right side-up 9, and vice versa.

Table 1

Gibson Feature Set and Lists

Feature Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Straight																										
1. Horizontal	•				•	•	•	•				•								•						•
2. Vertical					•	•		•			•	•	•	•						•					•	
3. Diagonal (/)	•										•		•					•							•	•
4. Diagonal (\)	•		•																						•	
Curve																										
5. Closed		•		•											•	•	•	•								
6. Open, Vertical																	•									
7. Open, Horizontal										•																
8. Intersection		•														•	•	•								
Redundancy																										
9. Cyclic Change		•			•								•						•				•			
10. Symmetry		•	•		•								•									•	•			
Discontinuity																										
11. Vertical	•					•		•					•	•		•		•		•					•	
12. Horizontal						•														•						

Note. In reproduction of this chart, it was noticed that the letter T was not listed as possessing the property of Symmetry. The authors believe this is an error.

Table 2

Geyer Feature Set and Lists

Feature Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
External																										
1. Horizontal					2	1						1								1						2
2. Vertical			1		1	1				1		1				1	1			1	2					
3. Slant (/)		1		1						1																
4. Slant (\)																										
5. Convex Segment																										
Open																										
6. Horizontal			1				1												2							
7. Vertical																	1									
8. Wedged, Horizontal																					1					
9. Wedged, Vertical																										
10. Internal Protrusion		1									1						1	1						2		
11. Intersection, Internal											2						1							2		
12. Bar, Horizontal							1						1									1	1			
13. Bar, Slant Crossing											1		1								1					
14. Symmetry, Vertical		1																					1			
15. Symmetry, Horizontal				1																						

Note. In reproduction of this chart, it was noticed that the letters H and Y were not listed as possessing the property of Vertical Symmetry. The authors believe this is an error.

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Table 3

Summary of Target Character Selection

Distinct characters, that is, no identification error according to the confusion matrix (Snyder & Maddox, 1978)

    B, E, H, S, and 3

Characters likely to be confused with another, according to the confusion matrix (Snyder & Maddox, 1978)

    1 >>> 2 >> V >> 0 > I > 7 > C,J,Q > G,L > T,Z

Character pairs or combinations likely to be confused when rotated

    6, 9
    A, V
    C, U
    K, X
    L, 7
    N, Z, 2
    B, 8
    D, O
    M, W.

As stated earlier, the use of such confusing characters would likely require mental rotation in identification, which was to be avoided since it would confuse the effect of dot-matrix pattern distortion.   Other character pairs that were similar to a lesser degree were also eliminated on this basis.

Based on these criteria, eight characters (B, C, I, K, V, 0, Z, and 7) were used as the target characters in this study (see Figures 6 & 7). Each of the eight characters had at least one other character with which it was likely to be confused.   These eight characters were drawn to be representative samples of the 7 x 9 Lincoln/MITRE font "population."

Standardization Trials

As this study was to require a substantial amount of data collection from each experimental subject (average time 7.5 hours), task performance was likely to fluctuate during the subject's participation.   Of the various external factors that might affect the subject's performance, fatigue and learning were of greatest concern.   While efforts were made to keep each session as short as possible and to allow subjects rest breaks at various intervals, some effect of fatigue was considered inevitable.   Also, since the experiment was to be conducted over 3 days, the level of vigilance might vary (it was to be minimized by scheduling subjects for the same or close time of the day).   In addition, increased familiarity with the task and targets (learning) and changes in search strategy were expected.   Measures were therefore taken to minimize and to monitor changes in performance.

This experiment was organized to minimize the practice effect in two ways: (a) practice trials were given on the first day, familiarizing subjects with the task, before the actual data were collected, and (b) the four observations in the same condition were not administered consecutively, that is, they were randomly placed among the other trials. The assumption was that the practice effect over the four observations in the same condition was negligible. In addition, as a way to monitor such possible changes in subject's base line performance and as a way to address these issues if significant differences (intra- and interindividual) existed, one of the five trials in each block (there were 96 blocks on the first day and 100 on the second and third days) was designated a "standardization trial."

The standardization trial was placed randomly among the other four "condition" trials in each block and involved the identical random character search task, except that the pattern was always presented in the upright orientation and the target character was drawn from the complete pool of 36 alphanumeric characters appearing in the pattern, instead of the eight for the condition trials. The response time from these standardization trials was expected to provide the subject's base line performance throughout the sessions. Regression of these data by trial would indicate any change in the subject's performance over time, while other statistical analyses could be performed for the effects of target character and its distance from the center of screen.

Data Analysis

Each (non-standardization) condition was repeated four times using a different target character for each of the 16 subjects. All eight target characters selected for this study were assigned to every angle-distance combination (four were rotated clockwise and the other four counterclockwise). In the initial analysis of variance, a mean response time from these four observations in each condition was used. By using the means, the issue of the target character's effect on performance could be conveniently avoided for the time being, and the data could be tested for the main effects and interactions of the three independent variables.

If the effects of and interactions involving the direction of rotation were shown to be nonsignificant as predicted, the data could then be reanalyzed as a 37 x 4 x 8 full factorial within-subjects design with a single observation per condition and tested for the effect of the target characters.

RESULTS AND DISCUSSION

A three-way repeated measures analysis of variance was performed for the mean response times using SAS. The results are summarized in Table 4. The Greenhouse and Geisser (1959) correction, ε, was made in numerator and denominator degrees of freedom to compensate for violations of the assumption of sphericity. Following these corrections, significant main effects for the angle of rotation and the target character's distance from the center of rotation were found, as predicted. The angle-by-distance interaction, which was also predicted to affect the extent of the target character's distortion, was not found to be significant. The three-way interaction among the direction and angle of rotation and the distance variable was not found to be significant following the ε correction.

Table 4

Summary of Analysis of Variance on Mean Response Times

Source	df	MS	F	p
Subject (S)	15	253.732		
Direction (D)	1	14.991	0.68	>.05
S x D	15	21.994		
Angle (A)	36	28.476	1.77	<.01
S x A	540	16.123		
Distance (L)	3	2512.591	47.36	<.01
S x L	45	53.058		
D x A	36	24.811	1.08	>.05
S x D x A	540	23.054		
D x L	3	10.949	0.96	>.05
S x D x L	45	11.401		
A x L	108	15.671	1.13	>.05
S x A x L	1620	13.810		
D x A x L	108	17.653	1.26	>.05
S x D x A x L	1620	14.058		
Total	4735			

Note. Greenhouse and Geisser ε values are 0.8127 for A and S x A; 0.7921 for L and S x L; and 0.7727 for D x A x L and S x D x A x L.

The effects of the direction of rotation and the interactions involving this variable were not expected to be significant, and the prediction was proven correct. As shown in Table 4, the main effect, the two-way interactions, and the three-way interaction are not significant. It thus appears that overall, rotation of the dot-matrix characters clockwise or counterclockwise makes no difference in the extent of their distortion as reflected by response time for this random search task.

Angle of Rotation

The angle of rotation was assumed to affect the extent of dot-matrix pattern distortion and thus, response time. It was also hypothesized that the extent of distortion, in terms of dot deviations from the optimal, formed a regular function, zero at 0°, 90°, and 180°; local minima at 45° and 135°; peaks between these angles; and that response time, influenced by the distortion, would closely follow this function in shape. The actual mean response time at each angle, as plotted in Figure 8, shows that the hypothesis was incorrect. Although the minimum mean response time was recorded at 0°, the response times at 90° and 180° were not quite as short as at 0°, as predicted. Curve fitting of the function was attempted and the best fit, in terms of a correlation value, was achieved with a quadratic function.
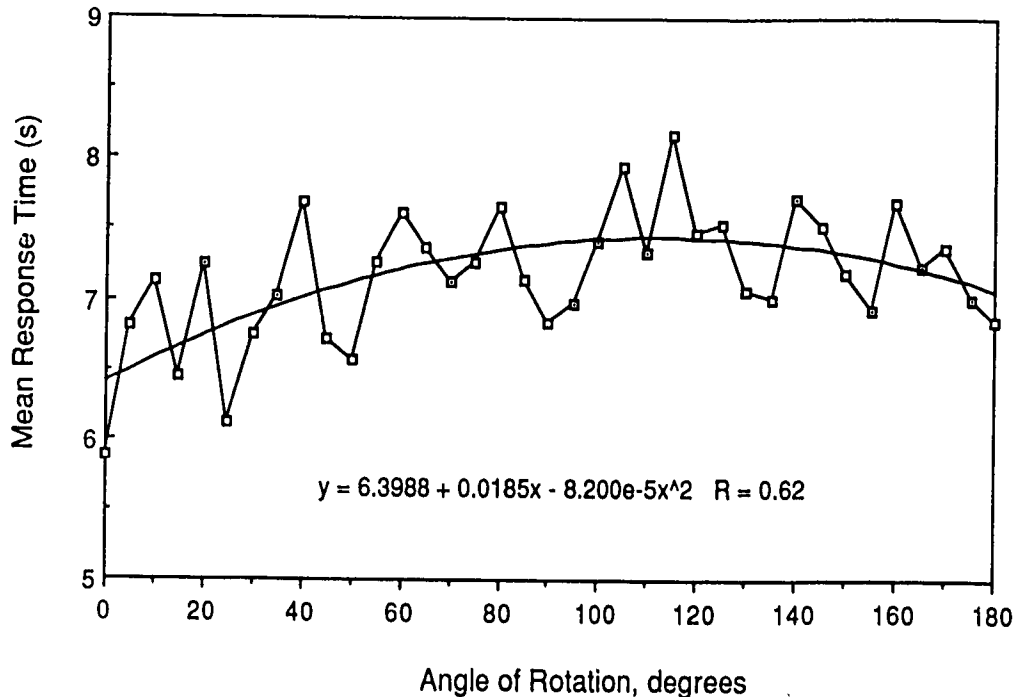
Figure 8. Mean response time as a function of the angle of rotation.

The irregular shape of this function supports the assumption that the angle of rotation does not contribute through some angle-dependent cognitive mechanism, such as mental rotation, but likely through the distortion of dot-matrix patterns. The lack of monotonicity in the function and the fact that the function hardly increases as the angle moved toward $180°$ are strong evidence against mental rotation, although it is an interesting coincidence that the best fitting curve was quadratic, as Koriat and Norman (1985) defined the mental rotation function to be (their function peaked at $180°$, however).

The irregular shape of the mean response time curve suggests several points: (a) If the response time is affected solely by distortion, the angle of rotation is certainly not the only factor in determining the distortion of dot-matrix characters (the character's distance from the center of rotation was also expected to be a factor); and (b) other factors, not necessarily through distortion, might be influencing task performance. The mean response times at $90°$ and $180°$ rotation, where there was no distortion of dot-matrix patterns, are not close to the response time minimum at $0°$.

The Student-Newman-Keuls test of the mean response times at each angle (see Table 5) indicates that there is no apparent pattern or grouping of angles. (The only significant differences are between $115°$ and both $0°$ and $25°$, and between $105°$ and $0°$) For instance, the mean response times at $90°$ and $180°$ were almost 1 second longer than the minimum at $0°$. If the difference were shown to be significant, it would raise a serious concern about the factors affecting the task performance. Also, the fact that the difference between $90°$ and $180°$ is quite small further supports the absence of some angle-dependent mechanism. The reasons for this particular ordering of angles, however, are not clear.

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Table 5

Student-Newman-Keuls Results Across Angles of Rotation (Angles sharing the
same vertical line are not significantly different [$p < 0.05$].)

	Angle	Mean response times (seconds)
I	115	8.172
I I	105	7.941
I I I	140	7.714
I I I	40	7.691
I I I	160	7.687
I I I	80	7.662
I I I	60	7.615
I I I	125	7.533
I I I	145	7.516
I I I	120	7.472
I I I	100	7.411
I I I	65	7.373
I I I	170	7.363
I I I	110	7.342
I I I	55	7.270
I I I	75	7.261
I I I	20	7.253
I I I	165	7.239
I I I	150	7.196
I I I	85	7.140
I I I	10	7.132
I I I	70	7.124
I I I	130	7.067
I I I	35	7.022
I I I	135	7.015
I I I	175	7.001
I I I	95	6.980
I I I	155	6.939
I I I	180	6.862
I I I	90	6.835
I I I	5	6.811
I I I	30	6.747
I I I	45	6.714
I I I	50	6.564
I I I	15	6.447
I I	25	6.113
I	0	5.870

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Distance From the Center of Rotation

This variable was expected to influence the response time in two ways--
through the subject's search strategy and the distortion of dot-matrix
patterns. This effect was found to be very significant. The mean response
time at each distance zone is shown in Figure 9 and Table 6. The target
character's distance from the center of rotation was predicted to influence
task performance through distortion and search strategy. The hypothesis that
the greater the distance from the center the less distortion and thus the
faster recognition was proven obviously wrong. The x and y coordinates of a
dot-matrix character pattern relative to the center of rotation unquestionably
affect the character's distortion (as discussed later), and distortion
influences the task performance. The previous poor understanding of this
distance variable is thus responsible for the false prediction concerning the
extent of distortion.

From the perspective of search strategy, the data suggest that the
subjects took longer to find a target farther away from the center. The
results support a search strategy that starts from the center, where the
subject's eyes are fixated, and moves outward. Curve fitting of the mean
response time data was performed, and a quadratic function resulted in a
better fit than a linear one (a cubic function would have been a perfect fit
because there are only four points in this case). This result might indicate
that the search time was a function more of the area to be searched than the
target's distance from the center (as subjects did not know in which direction
to look for a target). To test this hypothesis, regressions using the actual
(continuous) radial distances from the center were performed and are discussed
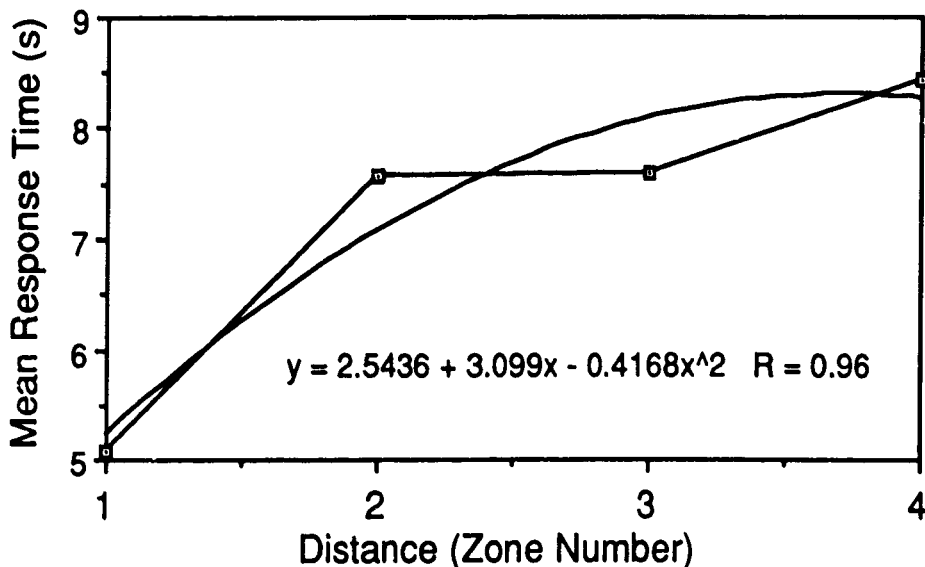later.

$y = 2.5436 + 3.099x - 0.4168x^2 \quad R = 0.96$

Figure 9. Mean response time as a function of distance zone.

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Table 6

Student-Newman-Keuls Results Across Distance Zones (Zones having a common
vertical line are not significantly different [$p < 0.05$].)

Distance zone	Mean response times (seconds)
4	8.432
| 3	7.604
| 2	7.559
1	5.064

Direction-by-Angle-by-Distance Interaction

Both the angle of rotation and the target character's distance from the
center of rotation distort dot-matrix patterns by displacing dots from their
optimal positions, and their effects are not independent of each other.
Hence, the interaction between these two variables was also expected to
influence distortion and task performance. It was not, however, found to be
significant, whereas a significant three-way interaction among these two
variables and the direction of rotation was found.

Effect of Target Character

Since the effect of the direction of rotation was not found to be
significant as expected, the data were collapsed across the direction of
rotation and reanalyzed (see Table 7). At each angle-by-distance combination,
four target characters were presented at clockwise rotation, while the other
four characters appeared in counterclockwise rotation. By removing the
direction of rotation variable, the data were restructured as a 37 x 4 x 8
design without repeated measures and allowing the effect of target characters
and its interactions with the angle and distance variables to be examined.
The Greenhouse and Geisser (1959) ε values were used to correct for violations
of the assumption of sphericity. Following these corrections, this analysis
of variance revealed the significant effect of target character and the
significant interaction between the target character and distance from the
center of rotation, in addition to the significant effects of the angle of
rotation and distance.

The significant effect of target character is not at all surprising.
The dot-matrix patterns of characters are composed of different numbers of
dots and their curvilinear characteristics vary. As stated above, the eight
target characters were selected on the basis of their greater likelihood to be
confused with other characters, and mental rotation should not be required for
their identification since subjects were familiar with these alphabets and
numerals. The number of dots in each target character pattern varied from 15
in character I and numeral 7, 16 in character V, 17 in character C, 19 in
character K and numeral 0, 21 in numeral 2, and 29 in character B. In terms
of the geometry of character dot-matrix patterns, character I consisted only
of vertical and horizontal lines, numeral 0 of diagonal lines and a circle,
while character B contained vertical and horizontal lines and arcs.

Table 7

Summary of Analysis of Variance Across the Direction of Rotation

Source	df	MS	F	p
Subjects (S)	15	1014.926		
Angle (A)	36	113.905	1.77	<.01
S x A	540	64.494		
Distance (L)	3	10050.365	47.36	<.001
S x L	45	212.231		
Character (C)	7	8985.851	48.80	<.001
S x C	105	184.136		
A x L	108	62.684	1.13	>.05
S x A x L	1620	55.238		
A x C	252	66.179	1.07	>.05
S x A x C	3780	62.054		
L x C	21	242.190	3.97	<.001
S x L x C	315	60.984		
A x L x C	756	59.930	1.07	>.05
S x A x L x C	11340	56.135		
Total	18943			

Note. Greenhouse and Geisser ε values are: 0.8020 for A and S x A; 0.7677 for L and S x L; 0.8293 for C and S x C; and 0.7623 for L x C and S x L x C.

The Student-Newman-Keuls test of characters reveals the differences among the eight target characters on the basis of their mean response times. Numeral 2 differed significantly from the rest, with the longest mean response time (see Table 8). One likely explanation for this difference might be the character's dot-matrix pattern. Subjects often spoke of its peculiar shape as unusual, and they evidently thought that their ability to identify it was affected, namely, the pattern's lack of curvature and the "step" in the bottom horizontal line made it different from the more familiar, rounded shape of numeral 2. Its number of dots (21) was only the second highest, after character B (29) for which mean response time was significantly less. Character I, which was composed of the least number of dots (15) and only of vertical and horizontal lines, resulted in a slow mean response time. The number of dots in a matrix pattern is evidently not a good measure of the character's geometry by itself. That is, even if two characters with the same number of dots are compared during the same condition, their distortion and the subject's ability to recognize them are likely different.

Another factor that might influence the distortion of dot-matrix patterns was reflected in the subjects' apparent dislike of numeral 0. Although the height of its pattern was 9 dots, as were the heights of the other characters, the dots in numeral 0 were concentrated in the center of the dot matrix. The proximity of dots probably made the central circular feature, which distinguishes numeral 0, degrade and become an indistinguishable and meaningless cluster of dots. There are the same number of dots in character K as in numeral 0, but the dots are well spread over the dot matrix. This difference in the arrangement of dots must be one of the factors responsible for the shorter response time for character K.

Table 8

Student-Newman-Keuls Results for Characters (Characters sharing a common
vertical line are not significantly different [p < 0.05].)

Character	Mean response times (seconds)
2	10.679
B	8.888
0	8.134
V	6.885
I	6.469
K	5.981
7	5.416
C	4.866

Distance-by-Character Interaction

As the target character's distance from the center of rotation affects
the extent of its dot-matrix pattern distortion, the interaction between it
and the target character was expected to be significant. Similarly, the
interaction between the angle of rotation, which also affects the extent of
dot-matrix pattern distortion, and the target character was predicted to be
significant. The distance-by-character interaction, however, was the only
significant interaction.

An analysis of variance for each target character (see tables in the
Appendix) showed that the effect of the character's distance from the center
of rotation was significant (p < 0.0001) for all eight target characters; the
characters were, however, affected differently by the variable (see Figure
10). For instance, the mean response time for numeral 2 peaked at distance
zone 2 (this was also true with character I, although in a less dramatic way),
while most other characters showed a gradual increase in response time as the
distance from the center increased.

The effect of the angle of rotation was found to be significant only in
character V and numeral 0. The mean response time varied considerably in
magnitude and in an irregular manner for character V (see Figure 11), while
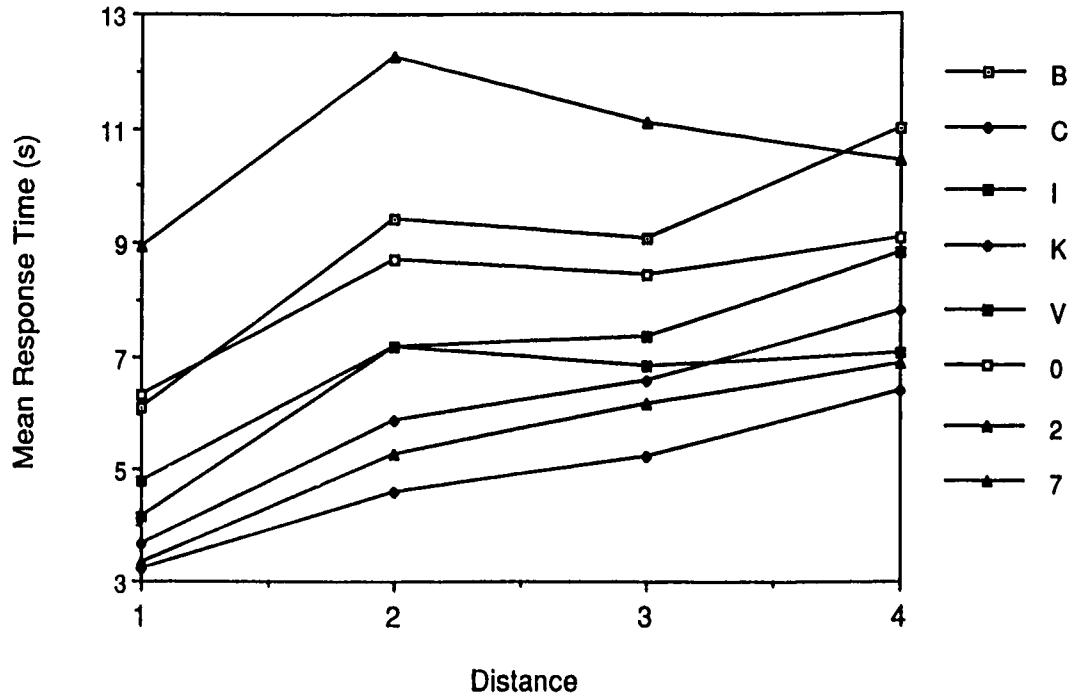character K showed a more moderate fluctuation.

33
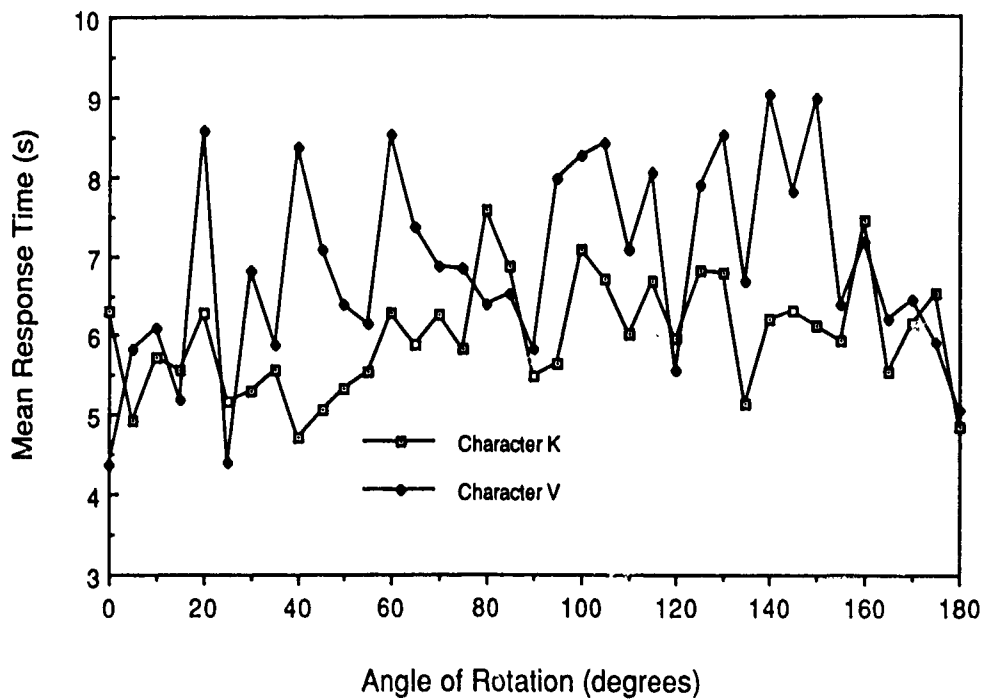
Figure 10. Distance-by-character interaction.

Figure 11. Angle-by character interaction

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Based on the comparisons of the analyses of variance, the distance variable appears to have exerted a stronger and more consistent effect on recognition of a target character. Assuming that the distorting effects of the angle and distance variables are comparable in magnitude, this difference in the strength of the effects might indicate that the target character's distance from the center influences task performance in additional ways. Other than through distortion of dot-matrix patterns, for example, search strategy and the combined effects may have contributed to the more pronounced change in performance. The angle of rotation, on the other hand, affected only response time through distortion and thus produced a significant effect only in some dot-matrix patterns, perhaps the ones more sensitive to distortion.

The ways in which the effects of the angle of rotation, target character, and distance from the center of rotation influence performance in a random search task are evidently more complex than originally anticipated. Not only was the distortion of the character's dot-matrix patterns affected by these variables, but other factors were also involved in determining the outcome.

Standardization Trials

The concept of standardization trials, although its rationale appeared sound, was disappointing in reality. In many trial blocks, the response time for a standardization trial was not faster than the response times for rotated (condition) trials. Subjects may have been distracted by the standardization trials, which were presented randomly in any part of a trial block. Response times for the standardization trial and the condition trial immediately following it tended to be longer than the others, since subjects were forced to search in different orientations from the preceding trials in the same block. The standardization trials did not prevent subjects from discovering that only eight characters were used as targets in the condition trials.

The data from the standardization trials were analyzed separately, and regressions were performed for two variables--the trial block number and the (radial) distance from the center of the screen. The trial block number varied from 1 through 296--1 through 96 from the first session (day), 97 through 196 from the second, and 197 through 296 from the third. The radial distance (in pixels) from the center of screen was calculated from the coordinates of the left lower corner of the target character's dot matrix and varied from 0 through 400. Response speed, the reciprocal of response time, was regressed against these variables.

The trial block number variable was expected to reflect a practice effect, while the radial distance variable might provide information about the subject's search strategy. For instance, if a subject searched systematically outward from the center of the screen where his or her eyes were fixated when the stimulus was presented, the response time would be a monotonically increasing function of radial distance, and the shape of the function might reflect some underlying strategy.

The data from each subject were analyzed separately. The results were that neither variable was significant and the fit was very poor for all subjects (R^2 for the best fitting subject was 0.0383). There were evidently no systematic shifts in the subject's performance over time during standardization trials and no consistent search strategy. The data from all subjects were then pooled and regression against these two variables was

repeated. A first order linear model resulted in an R^2 (0.1846, see Table 9) that was better than individually but still poor (a second order model, adding the squared distance, was no better). The effect of trial block was not significant ($p = 0.1052$), while the effect of radial distance was found to be significant ($p < 0.0001$).

Table 9

Regression Analysis Summary for Standardization Trials
(The dependent variable is response speed.)

Source	df	MS	F	p
Model	2	32.101	535.907	0.0001
Error	4733	0.0599		
Total	4735			

Variable	df	Parameter estimate	t	p
Intercept	1	0.6084	51.692	0.0001
Radial distance (pixel)	1	-0.001214	-32.720	0.0001
Trial block	1	0.000178	1.620	0.1052

Note. $R^2 = 0.1846$

In standardization trials, the stimulus patterns were always presented upright, so there was never any distortion of the characters' matrix patterns. The data from these trials reflect the subjects' base line performances, and if there was a fluctuation in the performance, whatever factors that caused it were also present in the condition trials. The significant effect of the target character's radial distance from the center adds strong support to the relative importance of search strategy in the task performance. The nonsignificance of the trial block, on the other hand, indicates that there was little change in the subjects' performances over time, and thus such external factors as fatigue and learning had negligible effects on performance. Hence, the results of the standardization trials were useful at least in showing the consistency of subjects' performances over time.

Simulation of Dot-matrix Pattern Distortion

To understand the issue of dot-matrix pattern distortion better, that is specifically how the angle of rotation, the target character, and its distance from the center of rotation influenced the level of distortion, a simulation was made of dot-matrix patterns during various conditions. Following this, attempts were made to quantify the dot-matrix patterns of characters, and additional statistical analyses were performed.

The simulation program was developed to investigate separately the effects of the angle of rotation and the character's distance from the center of rotation. First, character B was rotated in increments of 5° from 5° through 85° around the lower left corner of its dot matrix (see Figure 12). The distance between the actual dot position, after rotation, and the ideal position where the dot would be if not constrained by available matrix positions was calculated for each dot, summed for each angle, and plotted (see Figure 13). This sum for each character was termed "sum of dot deviations" and was measured in pixels. A close examination of the rotated patterns indicated that the extent of distortion, judged visually, was not monotonic and did not appear to vary systematically. The plot clearly demonstrated that in terms of the sum of dot deviations, the effect of the angle of rotation did not vary systematically. (Its similarity with the expected distortion function, [see Figure 5] is limited to the points at 0° and 90°.)

A simulation was repeated for the effect of the character's distance from the center of rotation. Shown in Figure 13, the x coordinate of the lower left corner of character B's dot matrix was varied from 0 through 16, while keeping the y coordinate at 0, and the dot-matrix pattern was then rotated 45°. The sum of dot deviations was also calculated and plotted for each distance (see Figure 14). Once again, the patterns did not appear to change systematically.

Several points must be noted about these simulations. To look separately at the effects of the angle of rotation and the character's distance from the center of rotation, one variable was held constant while the other was varied. For instance, in the angle of rotation simulation, the character's dot-matrix pattern was always rotated at its lower left corner and at distance 0 (this convention is used hereafter when defining the character's distance from the center of rotation).

This constraint was not the case during the experiment, when the whole screen was rotated about the center of the screen; thus, each character's distance from the center of rotation varied. That is, if two dot-matrix patterns of the same character rotating the same number of degrees were compared, they would likely be distorted differently, as their distances from the center might be different. The patterns that were presented to the subjects during the same combinations of variables were most probably different, and thus their task performance would necessarily vary. The effect of the angle of rotation became much clearer in this simulation, as a character was rotated at the same distance from the center of rotation.

The distorting effect of a character's distance from the center of rotation was further simplified as only one coordinate component was varied while the other was held constant. As discussed earlier, a new coordinate is determined by both the original x and y coordinates weighted by the sine and cosine functions. Therefore, even at the same radial distance away from the center of rotation and the same angle of rotation, different combinations of the x and y coordinate components result in different dot-matrix pattern distortions. In addition, an equal increase or decrease in the x and y coordinates produces no change in dot deviation, although the radial distance from the center changes. The target character's distance from the center does not determine the amount of dot deviations; rather, the x and y coordinates do.
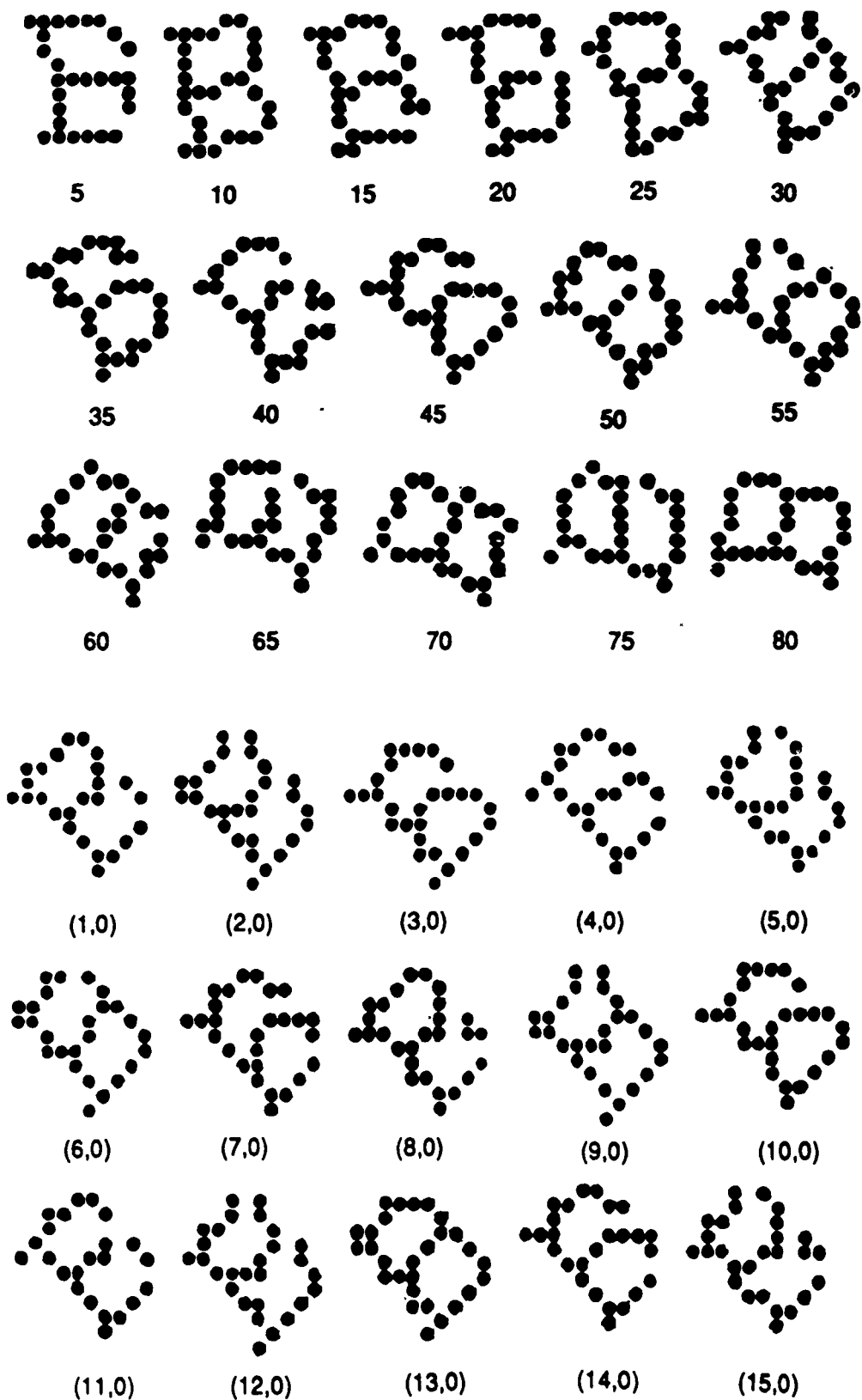
Figure 12. Character pattern distortion. (top) Character B rotated different angles at (0,0); (bottom) Character B rotated 45° at different x coordinates.
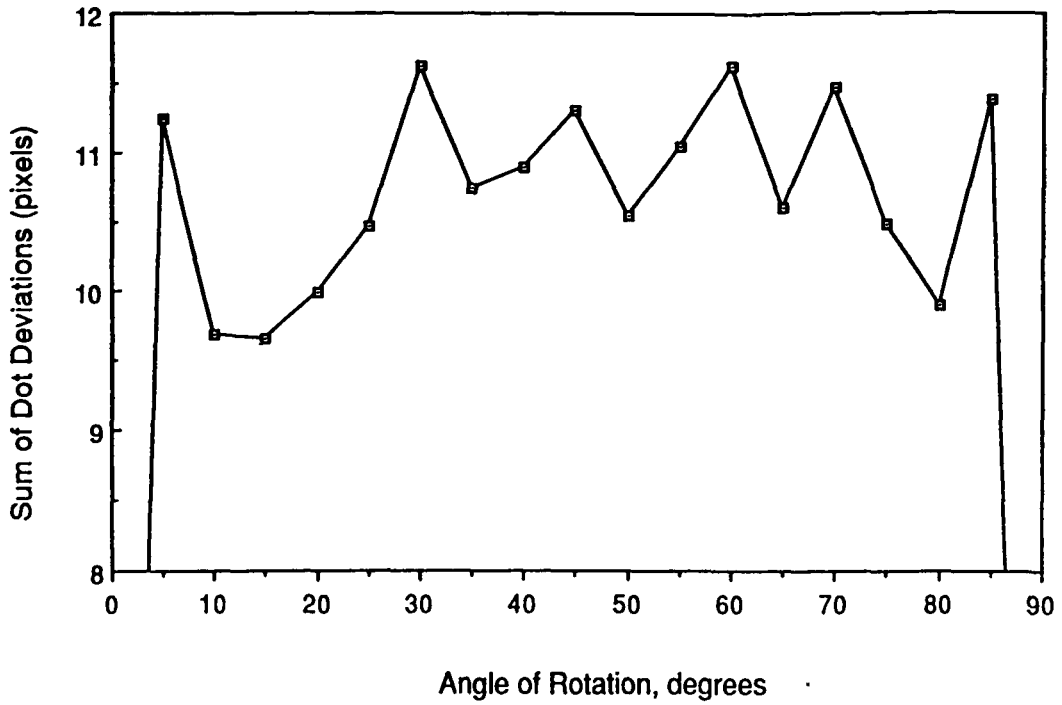
Figure 13. Sum of dot deviations in character B by the angle of rotation.
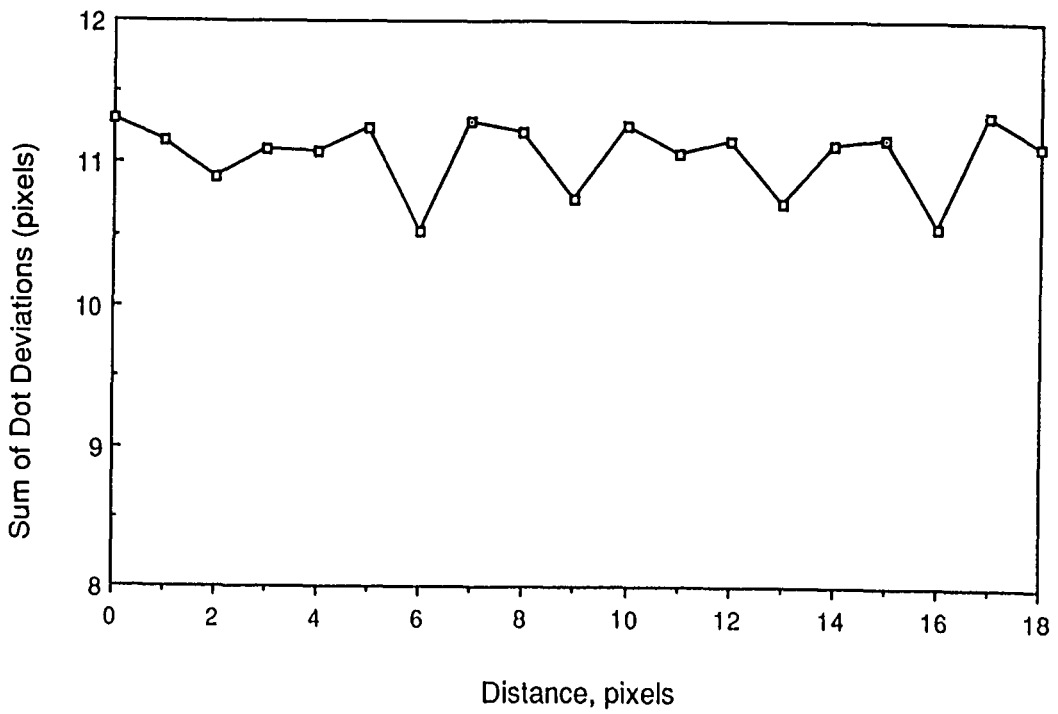

Figure 14. Sum of dot deviations in character B by the x coordinate.

In a comparison of the two figures (see Figures 13 & 14) of simulated distortion, the sizes of changes in the dot deviation appear to be greater during the varying angles of rotation (even if the points at $0°$ and $90°$ are excluded [see Figure 13]) than during the varying x coordinate (see Figure 14). This result suggests that the angle of rotation variable contributed to the greater amount of dot-matrix distortion than did the distance variable. Yet, the distance variable exerted the stronger effect on the task performance. This apparent contradiction reiterates the relative importance of the search component of the distance variable.

Finally, these distorting effects of angle and coordinate components act differently on different characters, since characters are composed of different numbers of dots, to be moved, and different curvilinear characteristics. Figure 15 illustrates all eight targets rotated $25°$ at distance 0. Some characters are more readily recognizable than others during various rotation conditions. Curvilinear characteristics of dot-matrix patterns of characters are difficult to quantify, as demonstrated in the earlier discussion of the effect of target character.

Regressions on Response Time and Response Speed

A revised list of factors that might have influenced the task performance was considered. The angle of rotation was assumed to affect the character pattern distortion. The x and y coordinates of the target character were assumed, based on the previously presented results, to also affect the distortion, while the character's (radial) distance from the center seems to determine the search time (i.e., the time spent to locate a target whether or not distorted). The number of dots in the character pattern is one of the measures, certainly the simplest one, to quantify the geometry of a character. The sum of the actual dot deviations was calculated for each target character pattern used in this experiment (the x and y coordinates of each target had been recorded along with the trial condition information). The mean dot deviation was also calculated by dividing the sum by the number of dots. Taking these factors into account, the data were then reanalyzed.

Regression analyses were performed using various combinations of regressors. The best fit (R^2 = 0.2184) was achieved when the response speed, the reciprocal of response time, was regressed against the angle of rotation, the x and y coordinates, the radial distance, the number of dots in the matrix pattern, the average dot deviation, the sum of dot deviations, and the trial block number (see Table 10). A comparable fit (R^2 = 0.2136) was achieved when the response speed was regressed against the angle of rotation, the radial distance, the sum of dot deviations and the trial block number. In this latter model, all regressors were found significant ($p < 0.0001$). The poor fit of this model was another reminder that other measures more accurately quantify the character's geometry and the extent of its distortion and that the mechanism of random search must be better understood.

Having failed to quantify the character's pattern adequately, it seemed more appropriate to treat characters as a fixed effect variable. Regression analyses were then repeated for each character separately. The results were disappointing; the R^2 values varied among characters, with even the best fitting character failing to provide a significantly better R^2 value.

B   C   I   K   V   0   2   7
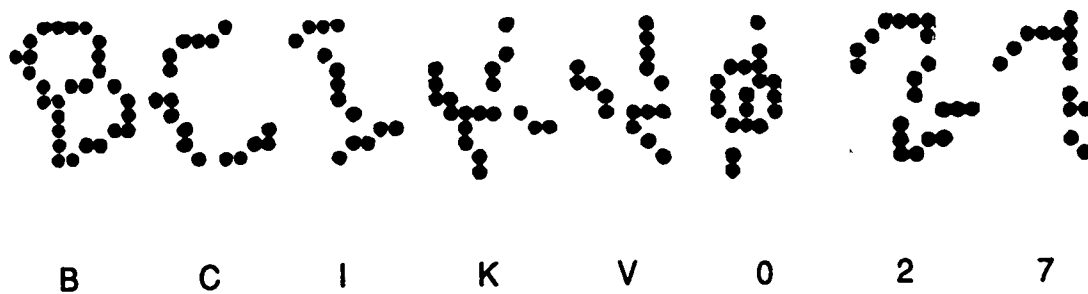
Figure 15. Configuration of all eight target characters rotated 25°.

Table 10

Regression Analysis Summary Using Response Speed

Source	df	MS	F	p
Model	4	110.160	1285.991	0.0001
Error	18939	0.0857		
Total	18943			

Variable	df	Parameter estimate	t	p
Intercept	1	0.6814	78.581	0.0001
Angle of rotation	1	-0.000159	-4.000	0.0001
Radial distance (pixel)	1	-0.001410	-70.459	0.0001
Sum of dot deviations	1	-0.009554	-11.715	0.0001
Trial block	1	0.000420	6.385	0.0001

$R^2 = 0.2136$

Source	df	MS	F	p
Model	8	56.311	661.246	0.0001
Error	18939	0.0852		
Total	18943			

Variable	df	Parameter estimate	t	p
Intercept	1	0.76441	22.571	0.0001
Angle of rotation	1	-0.000160	-4.019	0.0001
x coordinate	1	-0.00000144	-0.110	0.9122
y coordinate	1	-0.00000554	-0.427	0.6696
Radial distance (pixel)	1	-0.001409	-70.403	0.0001
Number of dots	1	-0.006407	-3.871	0.0001
Mean dot deviation	1	0.004436	0.051	0.9591
Sum of dot deviations	1	-0.003546	-0.790	0.4298
Trial block	1	0.000417	6.350	0.0001

$R^2 = 0.2184$

Accuracy

An analysis of variance, using response accuracy as the dependent measure, was performed and is summarized in Table 11. Response accuracy was defined as the mean number of correct responses in each condition. That is, the sector of the 3 x 3 numbered grid in which subjects located the target character was checked, and whether they correctly identified the target was recorded for each trial. The target character's distance from the center of rotation was the only significant effect ($p < 0.001$), and the Student-Newman-Keuls test of the distance variable (see Table 12) showed that the response was most accurate at distance zone 1, followed by zones 4 and 3, which were not significantly different from each other. The least accurate response was found at zone 2.

Most subjects also mentioned that they sometimes identified the target close to the lines in the identification grid and thus were uncertain in which sector the target was located. Most of the "errors" were of this type from the experimenter's observations during the sessions, rather than because subjects identified a wrong character. The design of this experiment did not allow a way to identify which character the subjects mistook in case of such errors.

The effect of the angle of rotation was close to significance at $p = 0.0661$, and the mean response accuracy ranged from 0.9082 at $40°$ to 0.9609 at $70°$ (the second most accurate responses, 0.9570, were found at $0°$, $15°$, $90°$, and $180°$). Subjects' responses were highly accurate, indicating that subjects carefully searched for and closely examined the target character before responding (subjects were told that speed and accuracy were equally important).

Table 11

Analysis of Variance Summary on Mean Response Accuracy

Source	df	MS	F	p
Subjects (S)	15	0.45357		
Direction (D)	1	0.0063872	0.41	0.5296
S x D	15	0.015424		
Angle (A)	36	0.019437	1.40	0.0661
S x A	540	0.013929		
Distance (L)	3	1.12552	36.16	0.0001
S x L	45	0.031130		
D x A	36	0.018459	1.30	0.1182
S x D x A	540	0.014215		
D x L	3	0.0054371	0.44	0.7240
S x D x L	45	0.012297		
A x L	108	0.010520	0.84	0.8744
S x A x L	1620	0.012486		
D x A x L	108	0.012228	0.95	0.6169
S x D x A x L	1620	0.012828		
Total	4735			

Note. Greenhouse and Geisser ε for L and S x L is 0.7623.

Table 12

Student-Newman-Keuls Results for the Effect of Distance (Means sharing the
vertical bar are not significantly different from one another [$p < .05$].)

Distance zone	Mean response accuracy (%)
1	0.9821
| 4	0.9440
| 3	0.9329
2	0.9079

CONCLUSIONS AND RECOMMENDATIONS

The performance of this random search task, as measured by response
time, is influenced by three categories of variables. The first variable that
affects response time through the distortion of dot-matrix patterns of
characters is the angle of rotation. The mean response times varied from
5.870 seconds at 0° to 8.172 seconds at 115° (39% difference). The extent of
distortion, in terms of the sum of dot deviations from the ideal positions, is
not a monotonic function of the angle; rather, it varies nonsystematically.

The second variable category that influences response time is the target
character's distance from the center of rotation. The (radial) distance from
where the subjects' eyes were fixated at the stimulus onset, which was the
center of rotation in this experiment, is the main factor in determining the
time to search for the target character. The x and y coordinates of the
target character relative to the center of rotation also determine the extent
of dot-matrix pattern distortion. The results of this experiment indicated
that the combined effects of these components are stronger than the effect of
the angle of rotation (the mean response times varied by more than 60%).

The third variable category is the dot-matrix characters themselves that
are the determining factor in distortion by their interactions with the other
factors affecting the extent of distortion. The mean response times varied
from 4.866 seconds for character C to 10.679 seconds for numeral 2 (more than
a two-fold difference).

As stated earlier, these factors interact to determine the extent of
dot-matrix distortion. The simulation of the dot-matrix pattern distortion
clearly demonstrates that the angle of rotation and the x and y coordinates of
the dot-matrix pattern relative to the center of rotation determine the extent
of distortion of a particular character and that their effects are not
orthogonal. The lack of orthogonality among these factors provides the best
explanation of the seemingly random ordering of the mean response times at
different angles, the nonmonotonic effect of the target's distance from the
center of rotation, and the three-way interaction including the direction of
rotation. It seems appropriate to conclude that the extent of character
distortion for each trial was not adequately predicted by the levels of the
independent variables and their combinations.

Mechanism of Random Search

A possible mechanism for this random search task is based on an improved understanding of the pertinent variables and the subjects' comments about their task strategy. Some subjects spoke of their task strategy as one in which, after they were shown the next target character, they mentally rotated the image of the character and, when they signaled for the stimulus, looked for the rotated image in the random search pattern. This task strategy agrees with the experimenter's observations that (a) the first trial of each block resulted in longer response times, (b) the standardization trial distracted subjects and often resulted in longer response times, and (c) the condition trial immediately following the standardization trial also took longer. The fact that the subjects needed to know the angle of rotation before the stimulus was presented to create an internal image of the rotated target character can explain the longer response times in these instances.

How the subjects determined the angle of rotation remains to be answered. One possible strategy is to search initially those characters with "linear" characteristics, that is, such characters composed of vertical and horizontal lines as E, F, H, I, L, T, and 1, and estimate the angle of rotation from these lines' orientation. Another possibility is to rotate the internal image until the match is found. The amount of time spent in determining the angle of rotation varied among trials, as subjects thought increasingly certain of the angle of rotation over the trials in the block. The magnitude of the resulting intra-block variance is not known. If such mental rotation of the target character image took place, once the angle of rotation was known, the response time was not affected by the time required for mental rotation. The task allowed the subjects to inspect the next target character as long as they desired, and only when they were ready for the next trial did they press the mouse button for the stimulus.

Mental Compensation for Distortion

Since the target character was also distorted, the internal image of a character simply rotated, as reported in the studies of mental rotation using stroke characters, would not be sufficient to perform this random search task. The major component in a possible mechanism for this task involves what might be most appropriately termed mental compensation for the distorted dot-matrix patterns. This component, along with the search strategy, is probably most responsible for determining the task performance.

The mechanism of mental compensation proposes the smoothing of a dot-matrix pattern on the stimulus field, in an attempt to match the undistorted internal image of the target character. Since the distortion of dot-matrix patterns is unpredictable, the smoothing of an actual image is undoubtedly easier to perform than rotating and distorting the upright pattern. The distortion of dot-matrix patterns is such that most features that make the particular character distinct are lost. The distortion even creates an extraneous feature, for example, a gap or a protrusion, which makes the pattern more confusing. The compensation for distortion is undoubtedly an essential step in the identification of dot-matrix characters.

Another step that most of the subjects appeared to have taken in performing this random search task was to check their selection by inspecting the rest of stimulus screen, after the initial identification of the target. As stated earlier, the target character was presented only once, while the other characters were presented twice in the stimulus field. Therefore, if a

dot-matrix pattern that was similarly distorted were found, the pattern that was identified as the target would not be the correct target. Because the two dot-matrix patterns of a character were necessarily positioned at different sets of coordinates, the distorted dot-matrix patterns would not be identical unless one set of coordinates was the horizontal and/or vertical mirror image of the other. This step also slowed the response.

This research has thus far focused on how the dot-matrix patterns of characters (i.e., their external features) were distorted in rotation and how the distortion affected recognition from the feature detection theory point of view. How might this problem be approached in terms of a spatial frequency analysis model? Maddox (1979, 1980) investigated the confusions among dot-matrix characters by correlating the empirical probabilities of confusions between two characters and two physical measures of their "similarity." One similarity measure was derived from the correlation between the Fourier coefficients of the two-dimensional luminance scans of the two dot-matrix characters on the CRT display. The other measure was a phi (ϕ) coefficient calculated from the two characters' dot-matrix patterns. The results were disappointing in that no strong correlations were found between the probability of confusion and the Fourier coefficient measure; the phi (ϕ) coefficient measure fared better.

A similar study using stroke characters and pictures was reported by Harvey, Roberts, and Gervais (1983). Three models of internal representations, one of which was the spatial frequency analysis model, were compared by correlating the probability of confusion between two characters (a different set from Maddox [1979, 1980]) with the "inter-letter distance" (their measure of the difference in internal representations of the two characters) calculated during each model. They reported that the model based on the two-dimensional Fourier transforms of (stroke) characters, adjusted for the human contrast sensitivity, provided the best fit (R^2 of 0.70).

This spatial frequency approach can be applied to the present study, although substantial efforts would be required. Fourier coefficients of dot-matrix characters during different conditions are derived from their two-dimensional luminance profiles. The difference between the Fourier coefficients of the undistorted and distorted patterns might be used as a measure of distortion, while comparisons of character patterns distorted during the same condition would reveal which character is likely to suffer more from the distortion. This concept is exciting, since it offers a means of quantifying the level of distortion and thus help design dot-matrix characters less susceptible to distortion. Considering the modest success achieved by Maddox (1979, 1980) and Harvey, Roberts, and Gervais (1983), however, the necessary efforts may not be justified.

Direction for Future Research

This investigation of the effect of dot-matrix distortion because of rotation in a random search task setting provided valuable information to understand the processes involved and identified the issues that warrant further research. The strength of the three categories of variables investigated in this study clearly demonstrated that the effect of dot-matrix distortion on the legibility of characters is substantial. Factors that reflect the dot-matrix characters' geometry and thus influence their sensitivity to distortion were discussed, and a measure of quantifying the extent of dot pattern distortion was introduced.

An experiment to follow and extend the scope of this study should consider the following:

1. The distorting effects of the angle of rotation and of the x and y coordinates of the target character relative to the center of rotation should be separated. While the only effect of the angle of rotation revealed in this study is through the distortion of dot-matrix patterns, the target's x and y coordinates and radial distance from the center of rotation evidently affect the response time through distortion and search strategy. Hence, by rotating dot-matrix patterns of all characters at a common center of rotation and thus keeping the x and y coordinates constant, the distorting effect of the distance variable could be completely eliminated. The position of a target character would then only influence response time through search strategy, and the distortion of dot-matrix patterns would be a function solely of the angle of rotation and not of distance. Maintaining the effects of variables orthogonally to each other is essential to an increased understanding.

2. The way(s) in which the angle of rotation influences the task performance should be verified. In this study, the distortion of dot-matrix patterns was the only effect identified, and the possibility of any angle-dependent mechanism was eliminated. This issue can be further clarified by eliminating the distortion caused by the angle of rotation (e.g., by physically rotating the display with an undistorted upright stimulus field) and repeating this study. As with the distance variable, identifying any other pertinent issues is crucial.

3. An effective means of quantifying the extent of dot-matrix distortion is needed to understand how it is determined by such factors as the angle of rotation and coordinates and how it, in turn, affects the recognition of dot-matrix characters. Exhaustive research employing more characters of different size and font would provide readily applicable results and provide the empirical data base against which to test the effectiveness of various objective measures of visual characteristics.

The development of an effective model would not only help design fonts less susceptible to distortion but would also advance the understanding of the underlying cognitive mechanism. Ultimately, a means of predicting human performance with dot-matrix characters can be developed and expanded to a more generalized theory for digitized discrete element images.

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APPENDIX

ANALYSIS OF VARIANCE SUMMARIES FOR EACH CHARACTER

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These analyses (see Tables 1 through 4) use the pooled between-subjects terms as the error term to test all main effects and interactions. This approach allowed evaluation of certain main effects and interactions that could not otherwise be tested simultaneously; the tests were consequently more conservative.

Table 1

Summary of Analysis of Variance, Character B

Source	df	MS	F	p
Direction (D)	1	11.165	0.13	0.7224
Angle (A)	36	85.768	0.97	0.5201
Distance (L)	3	2446.343	27.67	0.0001
D x A	36	97.785	1.11	0.3062
D x L	3	51.152	0.58	0.6291
A x L	108	92.271	1.04	0.3634
D x A x L	108	90.688	1.03	0.4113
Pooled Error	2072	88.416		
TOTAL	23678			

Table 2

Summary of Analysis of Variance, Character C

Source	df	MS	F	p
Direction (D)	1	33.857	1.38	0.2406
Angle (A)	36	34.836	1.42	0.0516
Distance (L)	3	1029.477	41.90	0.0001
D x A	36	43.707	1.78	0.0031
D x L	3	108.845	4.43	0.0041
A x L	108	25.674	1.04	0.3600
D x A x L	108	30.067	1.22	0.0627
Pooled Error	2072	24.570		
TOTAL	2367			

Table 3

Summary of Analysis of Variance, Character I

Source	df	MS	F	p
Direction (D)	1	9.078	0.19	0.6622
Angle (A)	36	66.372	1.40	0.0598
Distance (L)	3	746.991	15.71	0.0001
D x A	36	60.360	1.27	0.1317
D x L	3	54.990	1.16	0.3250
A x L	108	42.707	0.90	0.7626
D x A x L	108	38.501	0.81	0.9225
Pooled Error	2072	47.547		
TOTAL	2367			

Table 4

Summary of Analysis of Variance, Character K

Source	df	MS	F	p
Direction (D)	1	0.0000517	0.00	0.9990
Angle (A)	36	32.009	0.97	0.5162
Distance (L)	3	1793.621	54.48	0.0001
D x A	36	30.668	0.93	0.5861
D x L	3	16.549	0.50	0.6823
A x L	108	32.780	1.00	0.4954
D x A x L	108	29.133	0.88	0.7931
Pooled Error	2072	32.920		
TOTAL	2367			

Table 5

Summary of Analysis of Variance, Character V

Source	df	MS	F	p
Direction (D)	1	132.385	2.14	0.1432
Angle (A)	36	99.061	1.60	0.0130
Distance (L)	3	2270.330	36.78	0.0001
D x A	36	49.364	0.80	0.7965
D x L	3	39.110	0.63	0.5933
A x L	108	66.261	1.07	0.2895
D x A x L	108	57.283	0.93	0.6869
Pooled Error	<u>2072</u>	61.728		
TOTAL	2367			

Table 6

Summary of Analysis of Variance, Character 0

Source	df	MS	F	p
Direction (D)	1	162.965	1.89	0.1698
Angle (A)	36	129.775	1.50	0.0285
Distance (L)	3	906.592	10.49	0.0001
D x A	36	114.122	1.32	0.0968
D x L	3	32.726	0.38	0.7683
A x L	108	86.472	1.00	0.4809
D x A x L	108	79.947	0.93	0.6940
Pooled Error	<u>2072</u>	86.399		
TOTAL	2367			

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Table 7

Summary of Analysis of Variance, Character 2

Source	df	MS	F	p
Direction (D)	1	527.556	4.86	0.0275
Angle (A)	36	104.558	0.96	0.5306
Distance (L)	3	1140.196	10.51	0.0001
D x A	36	203.484	1.88	0.0013
D x L	3	35.426	0.33	0.8062
A x L	108	114.657	1.06	0.3292
D x A x L	108	117.311	1.08	0.2712
Pooled Error	2072	88.416		
TOTAL	2367			

Table 8

Summary of Analysis of Variance, Character 7

Source	df	MS	F	p
Direction (D)	1	0.122	0.00	0.9441
Angle (A)	36	24.775	1.00	0.4679
Distance (L)	3	1412.344	57.06	0.0001
D x A	36	25.473	1.03	0.4217
D x L	3	72.833	2.94	0.0319
A x L	108	21.375	0.86	0.8379
D x A x L	108	23.283	0.94	0.6526
Pooled Error	2072	24.753		
TOTAL	2367			