The Effect of Rotation on Legibility of Dot-Matrix Characters

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(ABSTRACT)

When dot-matrix characters are rotated, as might be the case 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 the direction (clockwise or counterclockwise) and the angle of stimulus image rotation, and the target character's distance from the center of screen, which was also the center of rotation; the dependent variables were response time and response correctness.

Significant effects were found in the angle of rotation, the target character's distance from the center, and the target character. The results indicate that (1) no angle-dependent mechanism is involved in performing this task and the angle of rotation influences recognition mainly through the distortion of dot-matrix patterns, (2) the target character's (radial) distance from the center of screen is the determining factor for search time, while the x and y coordinates of the target contributed to dot-matrix pattern distortion, and (3) 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 were discussed and the direction for future research is offered.

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Table of Contents

List of Illustrations

List of Tables

INTRODUCTION

Recent developments in digital electronics have made possible numerous applications which had previously been products of the designers' wildest imaginations. Traditional media of communication, for instance, are fast being changed or replaced by various offspring of digital technologies. Digital storage media, such as magnetic disks/tapes and laser 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 even been considered before.

A moving map display is one such application that is enjoying newly found interest and has a potential for widespread use. Normally, an image of a conventional map, printed on paper, is digitized and stored in a digital form. This approach will allow not only re-creation of the whole map through another medium, e.g., a visual display, a printer, a plotter, etc., but also selective re-creation of the map in any way one desires. One can thus design a digital map display system that will 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 found in aircraft, both military and commercial, and in automobiles, to provide the operators with pertinent vehicle 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 an integrated picture of the situation. The main factor that is currently keeping moving map displays from wider use 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, there arises a problem of resolution: the larger the number of elements used to describe the continuum, the finer the resolution, and thus the more accurate the description of the entity. There are always trade-offs that must 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 nontrivial. The finer resolution one desires, the more bits its storage will require. This issue of resolution is rather complex, as it exists in both spatial and temporal domains. The problem begins with the resolution of alphanumeric characters.

Characters in typeface are drawn in strokes; however, when they are digitized, they are represented by a collection of dots positioned to simulate the strokes best. As digital technologies developed, dot matrices were developed to simulate various typefaces. In these 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 its spatial resolution), and 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 upright, as their dot-matrix patterns were created for that particular orientation. Unfortunately, when their dot-matrix patterns are rotated, as they are likely to be in a moving map display, relative positions of dots are altered and thus the character pattern is distorted. The performance of human operators using such displays would then be affected by the degradation of the dot-matrix patterns.

One way to counteract the distortion of dot-matrix patterns is offered by Crow (1978). He discusses algorithms which provide gray scale for rotated dot-matrix characters. By controlling the grayscale and thus the luminance of each dot, this approach simulates a spatial bell-shaped curve of which luminance peaks 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 to correct the distortion might involve the use of spatial and 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 to compensate 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 as to 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 has been very little research which has investigated 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 rotation of digitized characters on human performance are identified and understood, corrective means can be developed and tested.

BACKGROUND

There are two issues that must be considered in investigating the effect of rotated dot-matrix characters on human performance. The first question deals with how human performance is influenced by rotation in tasks requiring recognition of (non-dot-matrix, stroke) characters. The second question 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/patterns, both two-dimensional and three-dimensional, and characters. Issues involved with pattern recognition are many and complex; however, an issue central and most critical in the case of rotated patterns is the process through which identification and discrimination are carried out.

In 1971, Shepard and Metzler reported a study in which the idea of mental rotation was introduced. Their task involved inspections 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 time was a linear function of the angular difference between the shapes, and this result was interpreted to suggest the existence of a mental rotation process in which one mentally rotated an image of one shape and compared it with the other.

Shepard and Klun (as reported by Cooper and Shepard, 1973) performed two experiments in which they investigated mental rotation with alphanumeric characters. Subjects were presented with one of 12 characters --- F, G, J, R, e, j, k, m, 2, 4, 5, and 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, which might be performed on some orientation-free features of the character and without mental rotation. Shepard and Klun found that (1) reaction time was a monotonically (although not linearly) increasing function of angular deviation from the upright, (2) the normal orientation resulted in faster response than the mirror image, and (3) if both the identity and orientation of the upcoming character were provided, the reaction time function became flat, while either pieces 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 thesis. The task was to discriminate between normal and mirror images of six characters --- G, J, R, 2, 5, and 7 --- rotated multiples of 60 degrees. There were eight levels of advance information, regarding the identity and the orientation of the stimulus, which influenced the subjects' reaction time (Figure 1).

The results were in agreement with the earlier Shepard and Klun study in that (1) the reaction time with no advance information increased monotonically but not linearly with the angular deviation from the upright, (2) with either identity or orientation information alone, the 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, (3) 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 the constant reaction time irrespective of rotation, and (4) there appeared to be two types of mental rotation: pre-stimulus and post-stimulus.

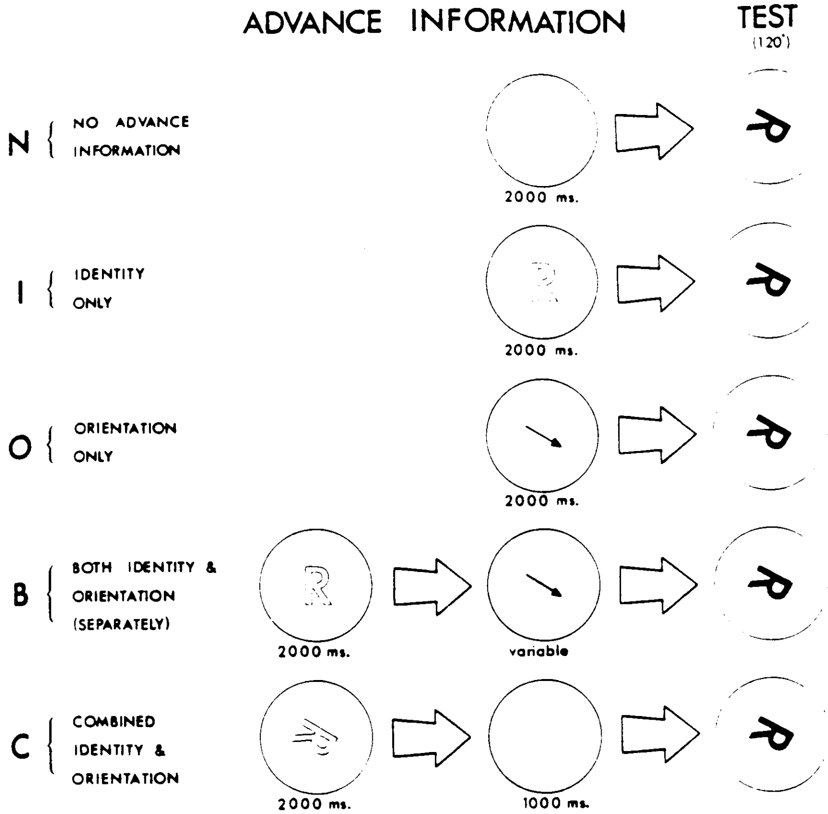


Figure 1. Schematic illustration of the advance information conditions: (In Condition B, there were four levels of orientation cue duration --- 100, 400, 700, and 1000 ms.) From Cooper and Shepard (1973).

When the subjects were given enough time to integrate the advance information with regard to 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. In the second experiment, it was found that when the mentally rotated image did not match the stimulus, the 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 carry out 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 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 under this strategy, response time depends on the angular deviation from the upright. Under the frame rotation strategy, on the other hand, "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, e.g., an internal image and the stimulus image. In their second experiment, Cooper and Shepard utilized 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 their study). Their 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 degrees was repeated for their first experiment. They found that for the mirror image characters, the response time increased linearly with the angular deviation from the upright, whereas the 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, i.e., the functions for both the normal and the mirror image started out to be linear. These results suggest that the 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 the stimulus characters --- G, J, R, 2, 5, or 7 --- presented normally or backward (mirror image) for one second in orientation multiples of 60 degrees. Although this task was not expected to require mental rotation, the results showed that the reaction time did depend on angular deviation from the upright. 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 did not require information about its orientation and was likely to take place prior to determination of orientation. The results of these experiments were somewhat contradictory and did not clarify whether identification of a character did not require mental rotation and was thus completely independent of orientation; they appear, at least, to 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 degrees, but each four-second presentation of the character was preceded by target information. Under 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. Their 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 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 vs. 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 the reaction time was not sensitive enough to measure the effect of orientation on identification and thus it had appeared that identification was independent of orientation.

In Jolicoeur and Landau's 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 degrees. In this study, the identification error rate was measured instead of the 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 measured, they estimated that approximately 15 milliseconds would be sufficient to compensate for a 180-degree rotation (or a rate of 12 degrees 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 indeed require mental rotation, as 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 in order to identify them (Corballis, 1988; Corballis and 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, e.g., searching for the target character.

Distortion of Dot-Matrix Characters

The research on recognition of rotated characters, summarized in the preceding section, utilized stroke characters which were tachistoscopically presented to subjects. Most other research that deals with 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, in particular, the resultant distortion of dot-matrix patterns thus need to be examined separately.

Research on dot-matrix characters has focused on such characteristics as their matrix and physical sizes; element shape, size, and spacing; and font (Decker, Pigion, and Snyder, 1987). The American National Standard (Human Factors Society, 1988) has been 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 and Snyder (1984) 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 found to be not significant. One type of dot-pattern degradation was represented in this study, i.e., 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/symbol orientation, and "motion parameters," each of which had two levels. (Character/symbols used were I, N, Q, U, V, 1, 3, 8, □, and △.) The task was to identify a character/symbol, and the 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 degrees). The results showed that neither had a significant effect, but that the interaction between matrix size and orientation was significant (15 degree rotated 8 x 11 font produced the shorter reaction time; however, the 5 x 7 font did better upright). Apart from noting that the effect of rotation on dot-matrix characters was considered, this study did not offer useful information. Its shortcoming lies in that only two levels of each variable were examined and that the experimental design confounded 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 made up of discrete dots which approximate the strokes, as closely as the "resolution" of the matrix allows. For instance, consider a line the length of which is five units (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, to represent the five unit long line makes little difference in this case (Figure 2a).

When a circle of some radius is to be drawn, the difference between the stroke and dot-matrix representations becomes more obvious. In order 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 held constant), and the matrix would allow a closer approximation to the actual curvature (Figure 2b). The point to be emphasized is that dot-matrix patterns are approximations of the actual patterns, except for the horizontal, vertical, and 45-degree 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 located where the actual stroke drawing would be when rotated, but rather is an approxi-

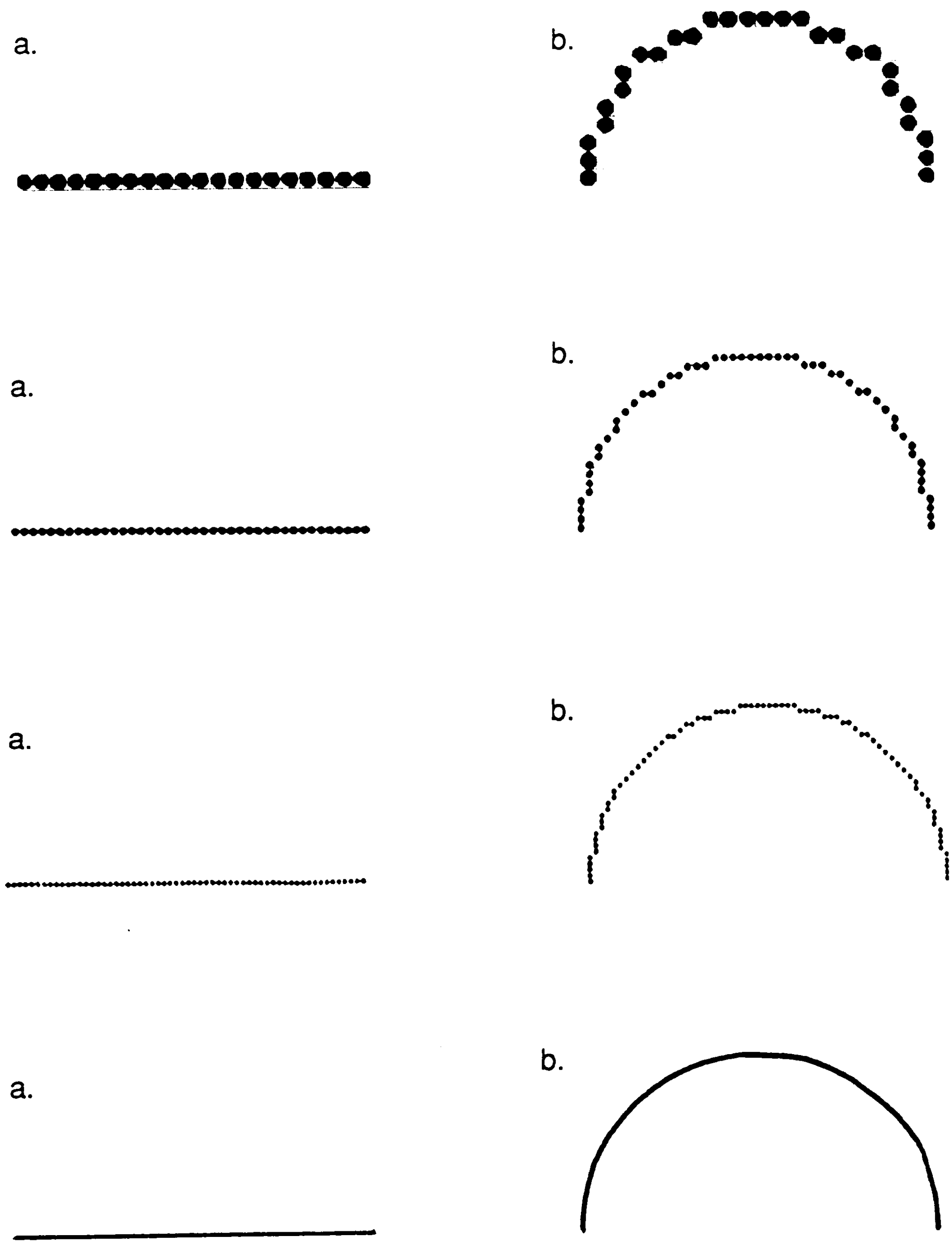


Figure 2. Dot-matrix representations of a line and an arc under various resolutions (i.e., dots per area).

mation of the original dot position which was itself an approximation of the stroke drawing. The resulting dot-matrix patterns can thus be quite distorted, as the relative positions of dots can be exaggerated through the series of transformations.

Research Objective

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

Recognition of 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) and 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 was intended to observe and measure these factors' effects on human performance in the generic task environment and to gain better understanding of the problems.

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 utilized for this study (Figure 3). Three parameters --- angle of image rotation, direction of image rotation (clockwise and counterclockwise), and target character distance from the center of rotation --- were varied (Figure 4).

Experimental subjects were screened for their 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 participants, and all of them 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 "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 cd/m^2 and the "off" pixels at 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 uppercase 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

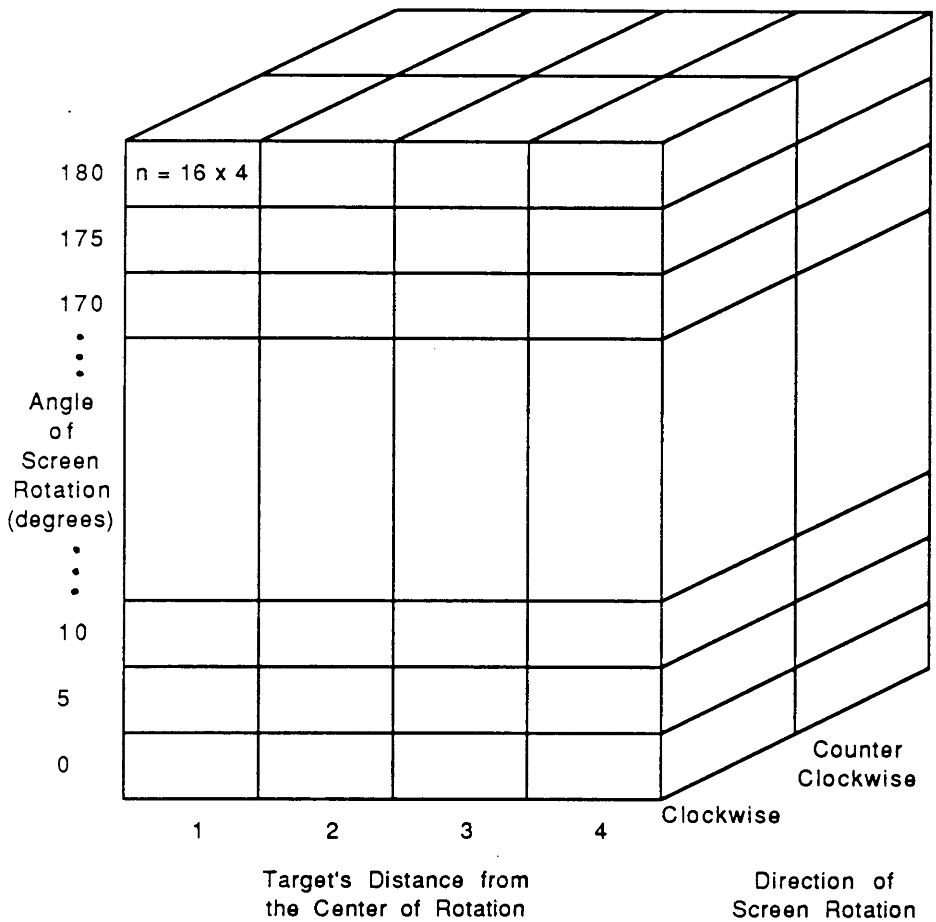


Figure 3. Experimental design.

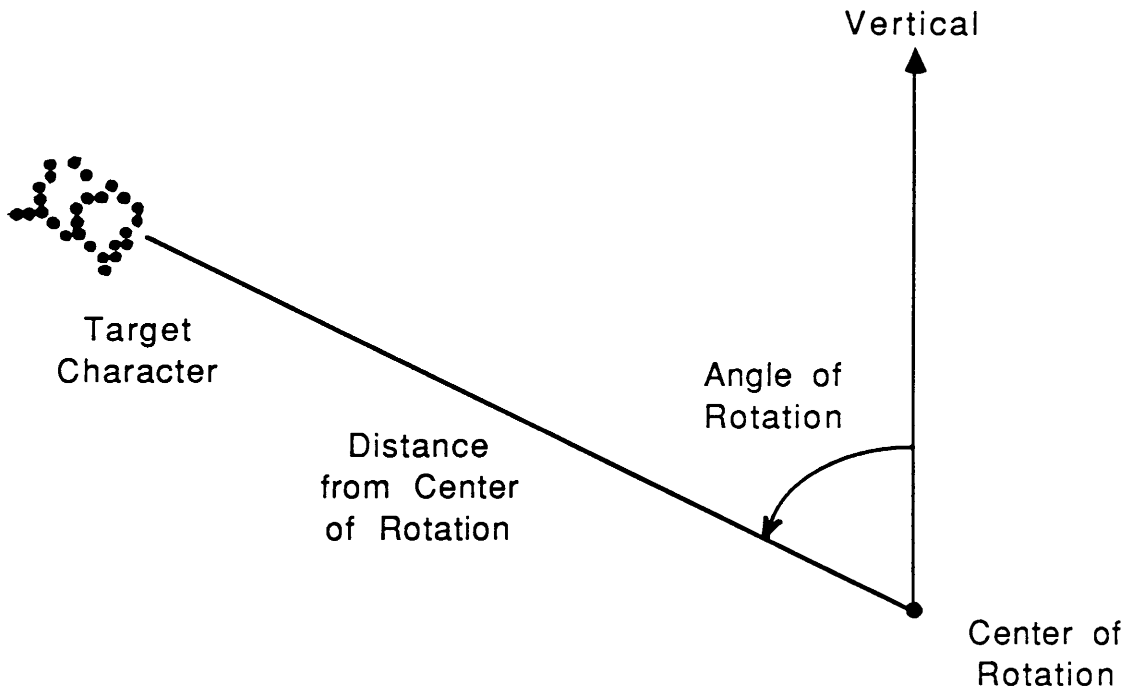


Figure 4. Independent variables.

graphics processor interfaced with a microcomputer (Figure 5). Experimental sessions were controlled by the microcomputer, with interactive links to the experimenter 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 away from the display such that the vertical angular subtense of a displayed character was 20 arcminutes at the subject's eye. In order 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 the mainframe computer, where all statistical analyses were performed using the Statistical Analysis System (SAS Institute, 1982).

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 where 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 information was presented at the center of the screen in the upright orientation, and it also served to guide the subjects' eyes to be fixated at the center of the screen prior to the onset of the stimulus. As the subject pressed the right button on the mouse input device, a stimulus

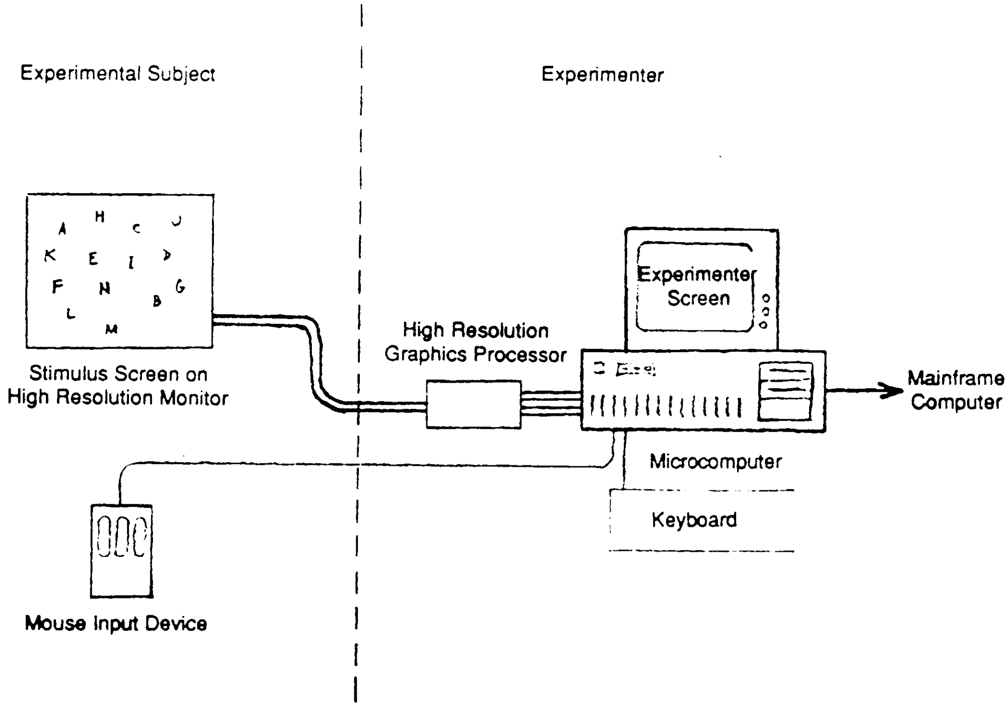


Figure 5. Experimental apparatus.

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

Each subject participated in three experimental sessions scheduled over three consecutive days at about the same time of day. During the first session, subjects familiarized themselves with the task during 20 practice trials, and 480 recorded trials followed. During the second and third sessions, subjects completed 500 trials. 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. Breaks, about five minutes in duration, were given after every 125 trials, or at the subject's request. The sessions typically lasted from 2-1/2 to 3 hours, and subjects were paid by the hour for the average total of 7-1/2 hours.

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, e.g., 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, which was used for this study, is to rotate a whole screen image around some common point of rotation, e.g., the center of screen. As each character rotates around some reference point, which is now unlikely to be within its dot-matrix, all dots in the pattern must receive new coordinates to perform the rotation. Each dot's coordinates are 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 is determined only by the angle of rotation. So long as the rotation reference point remains constant, the distorted pattern is identical regardless of its position in the random character pattern. In the latter approach, the resulting dot-matrix pattern is 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 moving map displays, for example, an original image (e.g., a map, including alphanumeric characters in its legends) is digitized upright, and in their 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, 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 five degrees between 0 and 180 degrees were investigated in this study, for a total of 37 levels. When combined with the direction of screen rotation variable, all angles in five degree increment around 360 degrees were covered. Two important assumptions were made with regard to the nature of this independent variable. As summarized earlier, research concerning non-dot-matrix characters concluded that mental rotation was not involved in recognition of 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, which 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 degrees from the vertical. At 45 and 135 degrees from the vertical, some distortions would be encountered. While vertical, horizontal, and 45-degree diagonal lines in the original upright pattern would remain straight, other dots in the pattern would be displaced from the optimal positions. At angles between (vertical, horizontal, and 45-degree diagonal), all dots would be 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 degrees, local minima at 45 and 135 degrees, and peaks between these minima (Figure 6).

Assuming that the response time would be influenced only by the distortion of dot-matrix characters, images rotated between 0 and 90 degrees (right side up) and between 90 and 180 degrees (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 was monotonically increasing toward a peak at 180 degrees, that would suggest the involvement of mental rotation or some other process which was dependent on the angular departure from the upright.

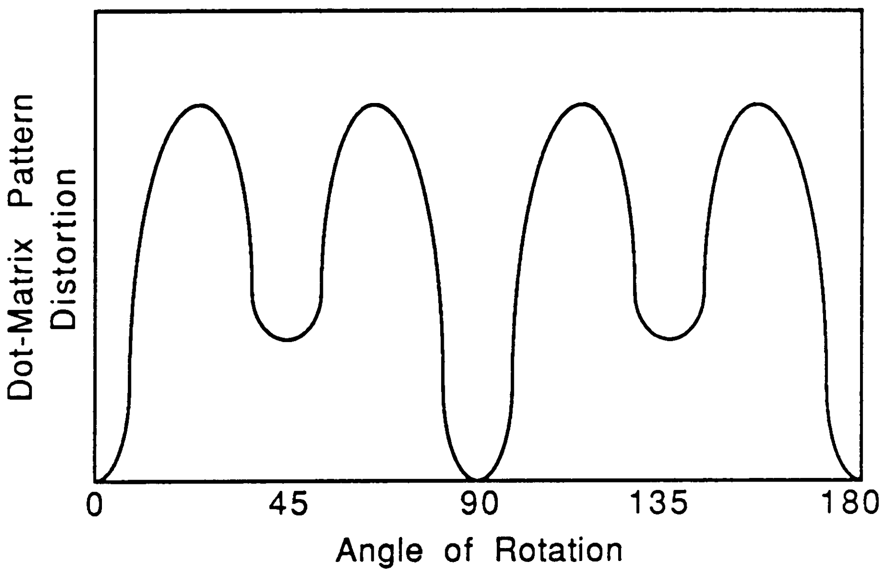


Figure 6. Expected distortion as a function of angle of rotation.

Direction of Image Rotation

This variable compared a clockwise rotation from a counterclockwise one. There has been no report in the literature that a clockwise rotation resulted in either superior or inferior performance. There remained a question concerning the symmetry of characters. Based on their symmetry, characters in the 7 x 9 element Lincoln/MITRE font can be categorized as follows:

1. Symmetrical along the vertical axis (8) --- A, M, T, U, V, W, Y, and 8.
2. Symmetrical along the horizontal axis (5) --- B, C, D, E, and K.
3. Symmetrical along both vertical and horizontal (5) --- H, I, O, X, and 1.
4. Rotatable (5) --- N, Z, 0, 6, and 9.
5. Asymmetrical (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.

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 such 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 would allow the data to be reanalyzed including the target character as another independent variable, and it would provide insights to how dot-matrix distortion affected individual characters.

Distance from Center of Rotation

As stated earlier, all coordinates for the characters in random 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 the 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 located 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 were to start from the center and to gradually move outward, the time to find the target might depend on its distance from the center. If, on the other hand, the search strategy were to scan across the screen from the top to the bottom, for example, the response time would then be independent of this variable.

Issues involving search strategies are many and beyond the scope of this thesis. Hence, two issues potentially critical to this experiment were considered.

1. 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.

2. Intraindividual 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" 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

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

and

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

where 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 parenthesis to the nearest integer.

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

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 the response time. Each variable was expected to have a significant effect; their interaction, however, 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 attempts 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 on character size and viewing distance (Decker et al., 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 more unique and 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 higher performance (Decker et al., 1987).

Target Character

Only upper case alphabet characters and numerals 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, i.e., the ways in which they are made up of lines and arcs, are extremely complex. There exists no means to quantify their characteristics systematically.

Geyer and DeWald (1973) reviewed three sets of "feature lists" of uppercase (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 feature lists (Table 1), for example, characters are represented based on the presence or absence of 12 common features. In Geyer's lists, on the other hand, characters are described by the number of 16 features present (Table 2). Based on their results, such lists provide some insights as to how one 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, with the exception of vertical, horizontal and 45-degree 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 in order 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 which represent the others in certain characteristics (e.g., their symmetricity, curvilinearity, the number of dots in their patterns) was selected. While the

Table 1. Gibson Feature Set and Lists (Gibson, 1969)

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					+	+						+								+						+

Table 2. Geyer Feature Set and Lists (Geyer and DeWald, 1973)

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		2	1	1	1	1	2	2		1		1		1	2					
3. Slant (/)	1																					1	1		1	
4. Slant (\)	1																					1	1		1	
5. Context Segment		2	3	2			3			1					4	1	4	1	2		1					
Open																										
6. Horizontal			1				1													2						
7. Vertical										1											1					
8. Wedged, horizontal		1									1							1						2	1	2
9. Wedged, vertical										2		1	2				1				1	1	2	1		
10. Internal Protrusion												1										1				
11. Intersection, internal	2	1			1	1		2			1							1								
12. Bar, horizontal	1				1	1	1	1																		
13. Bar, slant crossing																1										
14. Symmetry, vertical	1								1				1		1					1	1	1	1	1		
15. Symmetry, horizontal		1	1	1	1			1	1		1				1									1		

experiment was kept at a manageable size, it was hoped that meaningful generalizations would be made with regard to 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 (Figure 7), 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 on subjects' response errors and it shows, for instance, that 1 was most likely to be confused with another character, or that numeral 2 was often mistaken for the character Z. By selection of characters likely to be confused with another, it was hoped that subjects would be forced to examine the character carefully before responding and also to identify dot-matrix patterns which might be so distorted to be undistinguishable 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 degrees 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. As stated earlier, the use of such confusing characters would likely require mental rotation in identification, which was to be avoided as it would confound the effect of dot-matrix pattern distortion. Other character pairs which were similar to a lesser degree were also ruled out on this basis.

Based on these criteria, eight characters were used as the target characters in this study (Figure 8). Each of the eight characters had at least one other character with which it was likely to be confused. These eight characters were intended to be representative samples of the 7 x 9 Lincoln/MITRE font "population."

S\R	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	0	1	2	3	4	5	6	7	8	9	Σ
A																								2										1			3
B																																					0
C						1	6															1															8
D					1																																1
E																																					0
F					2		1																														3
G						1		1							2		3																				7
H																																					0
I				1	1			1												3					2			1		1		1	2	1			14
J			1																1		1				1						1	2		1			8
K		1																																			1
L					2									1											1				1			1		1			7
M						1								1																							2
N		1											1																								2
O																											3										3
P		1																3																			4
Q															1			6											1								8
R					1															1																	2
S																																					0
T																			1						4		1										6
U				1																		1		1													3
V																		1			1		3	2	18	1		1						2			29
W																			1												1						2
X																									1												1
Y		1		1																						1											3
Z																													5					1			6
0																1	1									1						1	3	11		2	20
1	1					1	1	3	6	2		1						1	4	4	1	2			7	1	1		1	1	5		3	3		1	[illegible]
2											2					1		1								29		1						3		2	39
3																																					0
4		1																			1											1					3
5																		1	1														1		1		4
6																				1																	1
7																									2	7			1						1		11
8																																	1	2		1	4
9																1													1								2
Σ	1	5	1	3	7	4	8	5	6	2	2	1	1	2	3	3	4	13	8	9	4	4	3	5	36	40	5	3	10	2	7	6	10	26	2	6	257

FONT: LINCOLN/MITRE 7x9

Figure 7. **Confusion matrix for 7 x 9 Lincoln/MITRE font** (Maddox, 1979; Snyder and Maddox, 1978).

Table 3. Summary of Target Character Selection.

Distinct Characters, i.e., no identification error according to the confusion matrix (Snyder and Maddox, 1978).

B, E, H, S, and 3

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

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

Character Pairs 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

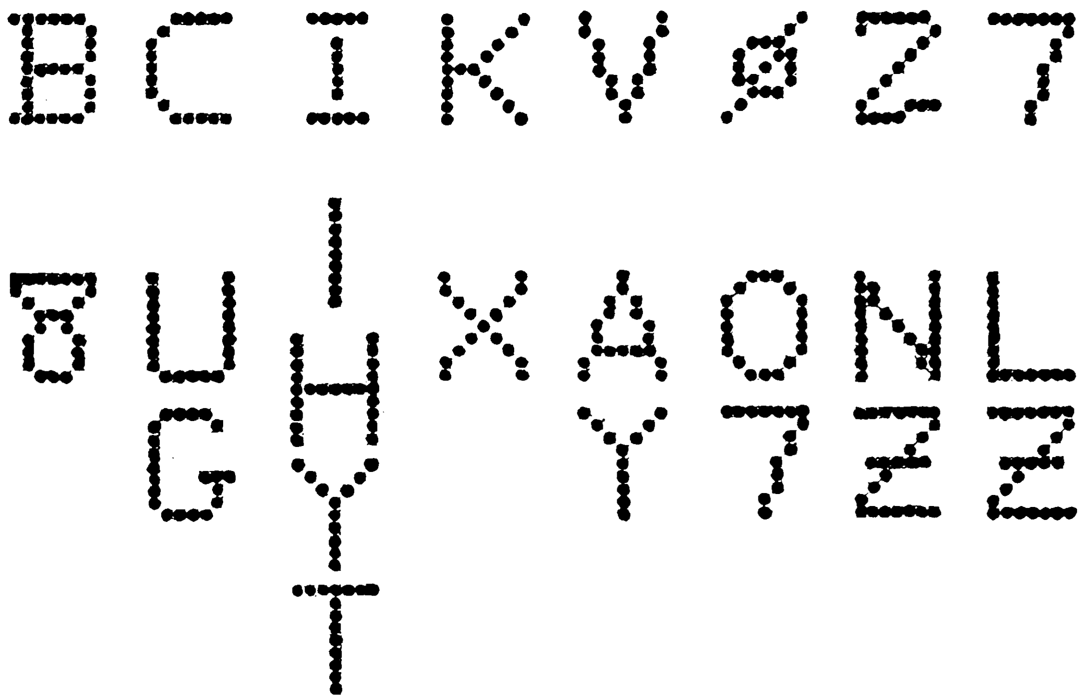


Figure 8. Target characters (a) and corresponding distractors (b).

Standardization Trials

As this study was to require a substantial amount of data collection from each experimental subject (average running time of 7-1/2 hours), the 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 breaks at various intervals, some effect of fatigue was considered inevitable. Also, as the experiment was to be conducted over three 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 the performance.

This experiment was organized to minimize the practice effect in two ways: (1) practice trials were given on the first day, familiarizing subjects with the task, before the actual data were collected, and (2) the four observations in the same condition were not administered consecutively, i.e., 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 subjects' "base" performance, and as a way to address these issues in the event that there existed a significant difference both intra- and inter-individual, 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 performance throughout the sessions. Regression of these data by trial would indicate any change in 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 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 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 effect 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 measure design analysis of variance using the mean response times was performed using SAS and its results are summarized in Table 4. Significant main effects in the angle of rotation and in 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 target character's distortion, was found to be not significant, while the three-way interaction among the direction and angle of rotation and the distance variable was unexpectedly found significant.

The effect of the direction of rotation and the interactions involving this variable were expected to be nonsignificant, and the prediction was proven correct except in the three-way interaction. As can be seen in Table 4, the main effect and the two-way interactions are nonsignificant. 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 in response time for the random search task.

Angle of Rotation

The angle of rotation was assumed to affect the extent of dot-matrix pattern distortion and thus the response time. It was also hypothesized that the extent of distortion, in terms of dot deviations from the optimal, formed a regular function (Figure 6 on page 23), zero at 0, 90, and 180 degrees; local minima at 45 and 135 degrees and peaks between these angles; and that the 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 9, shows that the hypothesis was incorrect. Although the minimum mean response time was recorded at 0 degrees, the response times at 90 and 180 degrees were not quite as short as at 0 degrees, 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.

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	0.4220
S x D	15	21.994		
Angle (A)	36	28.476	1.77	0.0046
S x A	540	16.123		
Distance (L)	3	2512.591	47.36	0.0001
S x L	45	53.058		
D x A	36	24.811	1.08	0.3537
S x D x A	540	23.054		
D x L	3	10.949	0.96	0.4197
S x D x L	45	11.401		
A x L	108	15.671	1.13	0.1693
S x A x L	1620	13.810		
D x A x L	108	17.653	1.26	0.0431
S x D x A x L	1620	14.058		
TOTAL	4735			

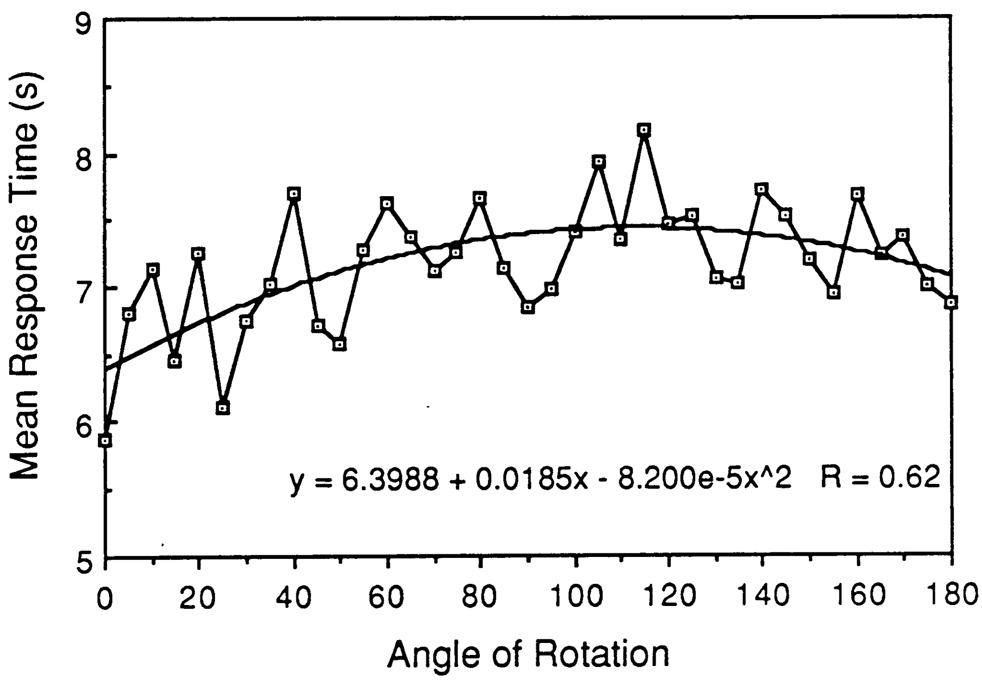


Figure 9. Mean response time as a function of angle of rotation.

The irregular shape of this function, at least, 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 it hardly increased as the angle moved toward 180 degrees 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 degrees, however).

The irregular shape of the mean response time curve suggests several points: (1) If the response time is solely affected 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). (2) There might be other factors, not necessarily through distortion, influencing the task performance. The mean response times at 90 and 180 degrees, where there was no distortion of dot-matrix patterns, were not close to the response time minimum at 0 degrees.

The Student-Neuman-Keuls test of the mean response times at each angle (Table 5) indicates that there is no apparent pattern or grouping of angles. No significant difference in mean response time, which set certain angles apart from the rest, was found. For instance, the mean response times at 90 and 180 degrees were almost one second longer than the minimum at 0 degrees. If the difference were shown significant, it would raise a serious concern about the factors affecting the task performance. Also, the fact that the difference between 90 and 180 degrees is quite small further supports the absence of some angle dependent mechanism. The reasons for this particular ordering of angles, however, are not clear.

Distance from 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, and the mean response time at each distance zone is shown in Figure 10 and Table 6. The target

Table 5. Student-Neuman-Keuls Results across Angles of Rotation ($p \leq 0.05$).

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

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 poor prior understanding of this distance variable is thus responsible for the false prediction concerning the extent of distortion.

In the view 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 search 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). In order to test this hypothesis, regressions using the actual (continuous) radial distances from the center were performed and are discussed later.

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 thus the task performance. It was, however, found to be nonsignificant, whereas a significant three-way interaction among these two variables and the direction of rotation was found.

Intuitively, it is easier to explain the three-way interaction than the two-way interaction. As discussed earlier, some of the target characters were symmetrical while the others were not, and dot

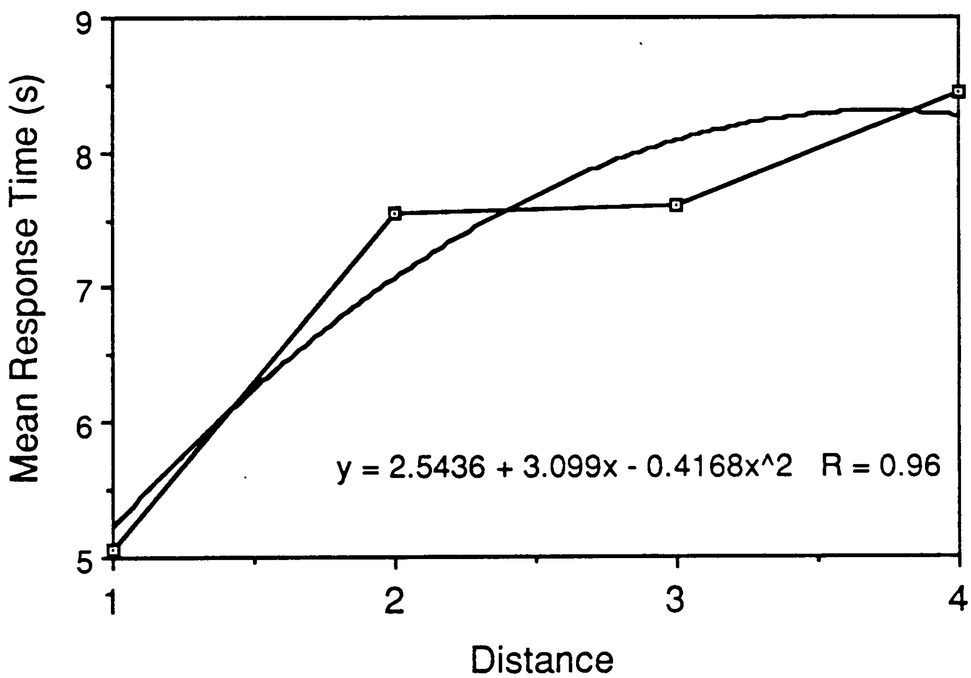


Figure 10. Mean response time as a function of distance zone.

Table 6. Student-Neuman-Keuls Results across Distance Zones ($p \leq 0.05$).

Distance Zone	Mean Response Times (s)
4	8.432
3	7.604
2	7.559
1	5.064

deviations in an asymmetrical dot-matrix pattern are different depending on the direction of rotation. It therefore seems plausible that in some conditions the interactions among the three variables exerted a strong enough effect to bring it into significance.

Analyses of variance at each direction (Table 7) and each angle of rotation (Appendix C) were then performed in order to clarify the three-way interaction. At the clockwise rotation, the angle by distance interaction was found to be marginally significant ($p = 0.0346$), while at counterclockwise rotation, it did not approach significance. The mean response times at each angle and distance combination at the clockwise rotation (Figure 11) were then tested using the Student-Neuman-Keuls test, and the combinations at which the response times were significantly different from the rest were identified. Six angle/distance combinations with the longest mean response times were noted: in decreasing order, 100 degrees at distance zone 3, 20 degrees at zone 4, 80 degrees at zone 4, 105 degrees at zone 4, 85 degrees at zone 2 and 155 degrees at zone 4. The angle and distance combinations which resulted in the 24 shortest response times were all located in distance zone 1, and the 10 shortest combinations were, in increasing order, at 150, 95, 180, 35, 25, 70, 0, 170, 5, and 65 degrees. It is clear that most of the angle by distance combinations which resulted in the shortest and longest mean response times were located at distance zones 1 and 4, respectively, as the test of the distance effect indicated.

Analyses of variance at each angle of rotation (Appendix C) revealed that significant interactions between the direction of rotation and the target character's distance from the center of rotation were found at 85 ($p = 0.0131$) and 160 ($p = 0.0324$) degrees (Figure 12), while there were no significant interactions at other angles. At 85 degrees, significant differences in the mean response times were noted at distance zones 2 through 4, but the reason is not immediately clear.

Based on these tests, significantly different mean response times were recorded at certain direction/angle/distance combinations, which resulted in the significant three-way interaction. These combinations were, however, not grouped in such a way to show significance in the lower

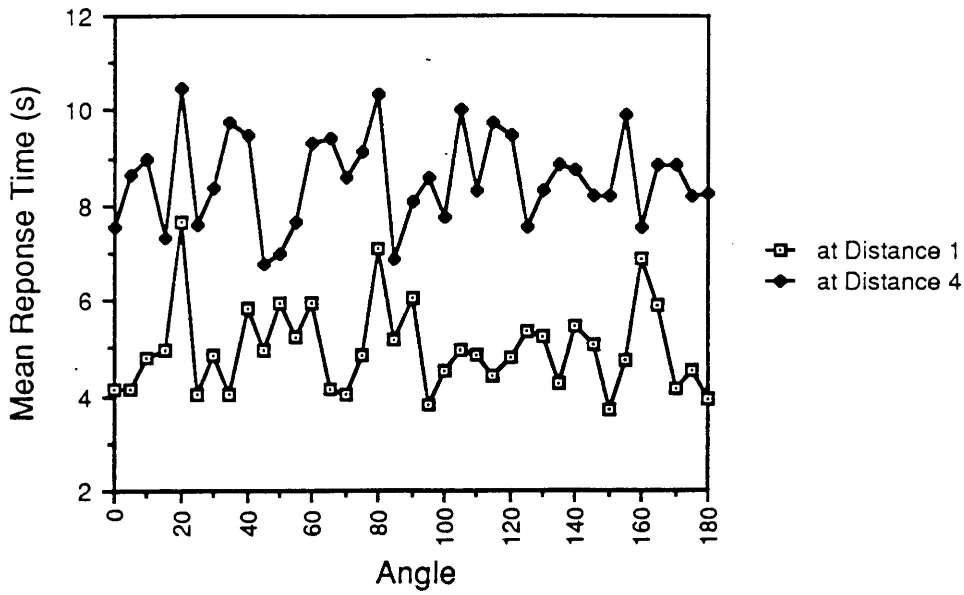
Table 7. Summary of Analysis of Variance for Each Direction of Rotation.

At Clockwise Rotation

Source	df	MS	F	p
Subject (S)	15	173.071		
Angle (A)	36	18.999	0.99	0.4823
S x A	540	19.124		
Distance (L)	3	1425.780	43.28	0.0001
S x L	45	32.941		
A x L	108	17.402	1.27	0.0358
S x A x L	1620	13.702		
TOTAL	2367			

At Counterclockwise Rotation

Source	df	MS	F	p
Subject (S)	15	102.466		
Angle (A)	36	34.728	1.73	0.0060
S x A	540	20.068		
Distance (L)	3	1102.090	34.84	0.0001
S x L	45	31.635		
A x L	108	15.982	1.12	0.1885
S x A x L	1620	14.224		
TOTAL	2367			



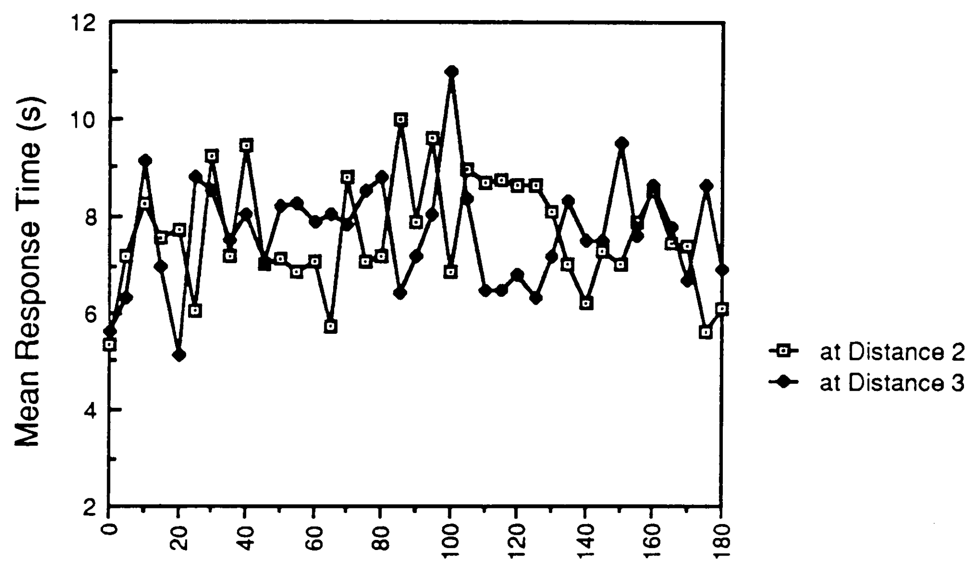
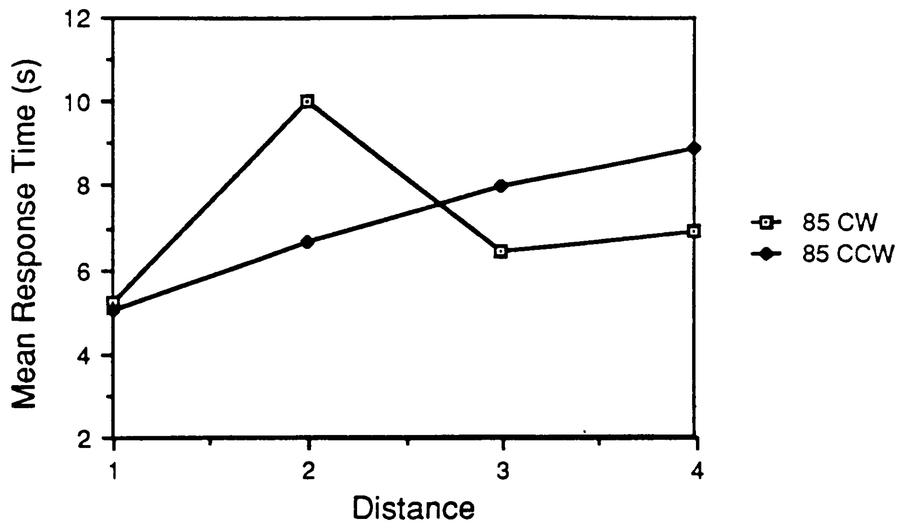


Figure 11. Angle by distance interaction at clockwise rotation.



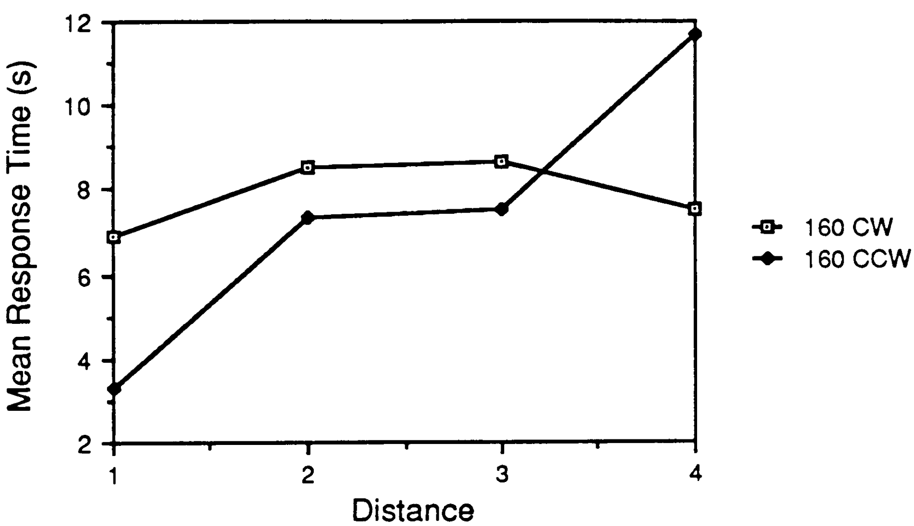


Figure 12. Interaction between direction of rotation and distance zone.

order effects and interactions. That is, these observations did not appear in an orderly, predictable manner.

Effect of Target Character

As the effect of the direction of rotation was found to be nonsignificant as expected, the data were collapsed across the direction of rotation and reanalyzed (Table 8). 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 allowed the effect of target characters and its interactions with the angle and distance variables to be examined. 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 earlier, the eight target characters were selected on basis of their greater likelihood to be confused with other characters (the dot-matrix patterns of the target characters and their "distractors" are shown in Figure 8 on page 34), and mental rotation should not be required for their identification as 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.

The Student-Neuman-Keuls test of characters reveals the differences among the eight target characters on basis of their mean response times. Numeral 2 differed significantly from the rest, with

Table 8. Summary of Analysis of Variance across the Direction of Rotation.

Source	df	MS	F	p
Subject (S)	15	1014.926		
Angle (A)	36	113.905	1.77	0.0046
S x A	540	64.494		
Distance (L)	3	10050.365	47.36	0.0001
S x L	45	212.231		
Character (C)	7	8985.851	48.80	0.0001
S x C	105	184.136		
A x L	108	62.684	1.13	0.1693
S x A x L	1620	55.238		
A x C	252	66.179	1.07	0.2319
S x A x C	3780	62.054		
L x C	21	242.190	3.97	0.0001
S x L x C	315	60.984		
A x L x C	756	59.930	1.07	0.1041
S x A x L x C	11340	56.135		
TOTAL	18943			

the longest mean response time (Table 9). 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 felt 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 under the identical condition, their distortion and the subject's ability to recognize them are likely different.

Another factor which might influence the distortion of dot-matrix patterns was reflected in subjects' apparent dislike of numeral 0. Although the height of its pattern was 9 dots, as the other characters were, the dots in numeral 0 were concentrated in the center of the dot matrix (Figure 8 on page 34). The close proximity of dots probably made the central circular feature, which distinguishes numeral 0, to 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 out over the dot matrix. This difference in the arrangement of dots must be one of the factors that is responsible for the shorter response time for character K.

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, turned out to be the only significant interaction.

Table 9. Student-Neuman-Keuls Results for Characters ($p \leq 0.05$).

Character	Mean Response Times (s)
2	10.679
B	8.888
0	8.134
V	6.885
I	6.469
K	5.981
7	5.416
C	4.866

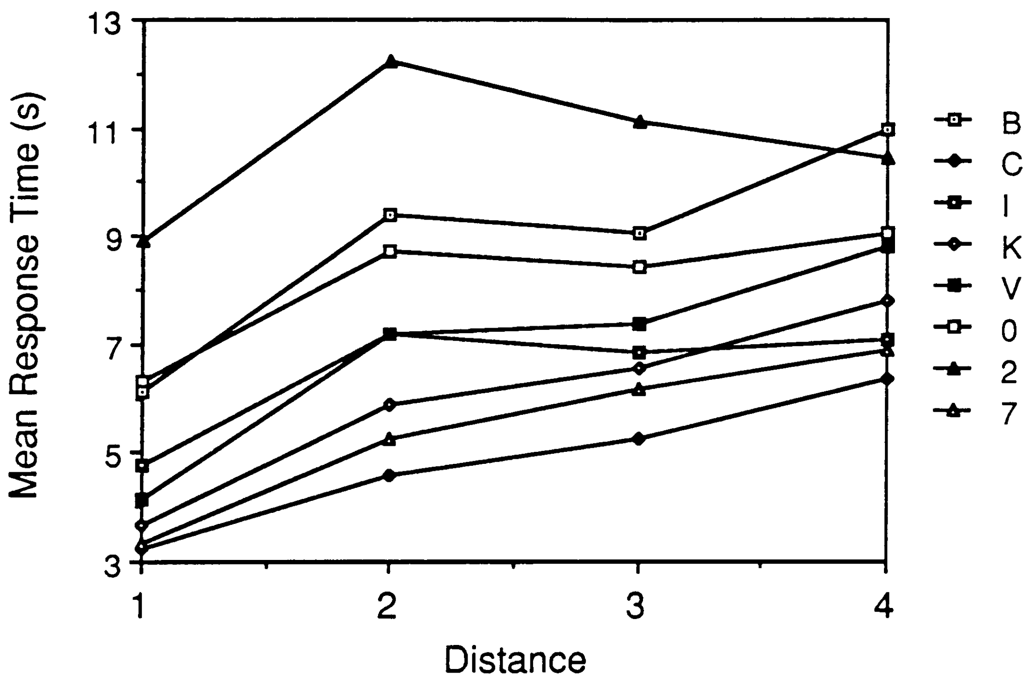


Figure 13. Distance by character interaction.

An analysis of variance for each target character (Appendix B) 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 (Figure 13). 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 an irregular manner for character V (Figure 14), while character K showed more moderate fluctuation.

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 effect might indicate that the target character's distance from the center influences the task performance in additional ways, other than through distortion of dot-matrix patterns, e.g., search strategy, and that the combined effects may have contributed to the more pronounced change in performance. The angle of rotation, on the other hand, affected the response time (only) 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, the target character, and distance from the center of rotation influence the 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 there were also other factors involved in determining the outcome.

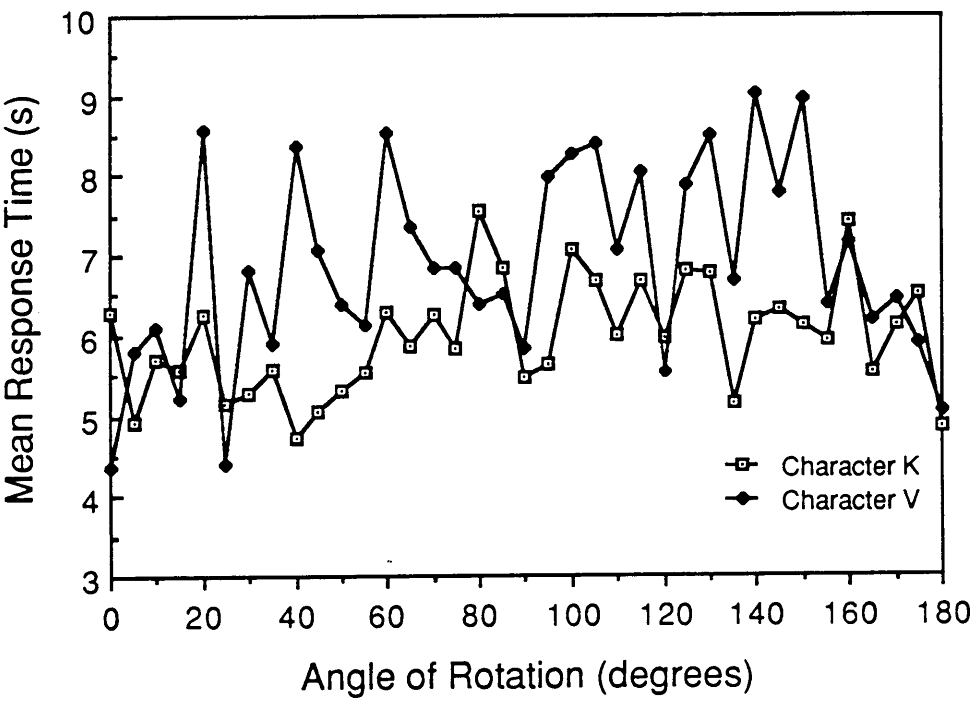


Figure 14. Angle by character interaction.

Standardization Trials

The concept of standardization trials, although its rationale appeared sound, turned out to be 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 were apparently distracted by the standardization trials which were presented randomly in any part of a trial block. The response times for the standardization trial and the condition trial immediately following it tended to be longer than the others, as subjects were forced to search in different orientations from the preceding trials in the same block. Neither did the standardization trials 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 continuous variables, the trial block number and the (radial) distance from the center of the screen. The trial block number varied from 1 to 296: 1 to 96 from the first session (day), 97 to 196 from the second, and 197 to 296 form 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 to 400. The response speed, the reciprocal of response time, was regressed against these variables.

The trial block number variable was to reflect the 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 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, and the results were that neither variable was significant and the fit was very poor for all subjects (R-square for the best fitting subject was 0.0383). There were evidently no systematic shifts in the subject's performance over time in the 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 the R-square (0.1846, Table 10) 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 nonsignificant ($p = 0.1052$), while the effect of radial distance was found to be significant ($p < 0.0001$).

In standardization trials, the stimulus patterns were always presented upright, and thus there was never any distortion to the characters' matrix patterns. The data from these trials reflect the subjects' "base" 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 a little change in subjects' performance over time, and thus such external factors as fatigue and learning had negligible effects on the performance. Hence, the results of the standardization trials were useful, at least, in showing the consistency of subjects' performance over time.

Simulation of Dot-Matrix Pattern Distortion

In order to understand the issue of dot-matrix pattern distortion better, specifically how the angle of rotation, the target character, and its distance from the center of rotation influenced the level of distortion, a simulation of dot-matrix patterns under various conditions and attempts to quantify the dot-matrix patterns of characters were made, 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 degrees from 5 to 85 degrees around the lower left corner of its dot matrix (Figure 15a). 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 (Figure 16a). 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

Table 10. Regression Analysis Summary for Standardization Trials.

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

R-square = 0.1846

plot clearly demonstrated that in terms of the sum of dot deviations the effect of angle of rotation did not vary systematically. (Its similarity with the expected distortion function (Figure 6 on page 23) is limited to the points at 0 and 90 degrees.)

A simulation was repeated for the effect of the character's distance from the center of rotation. Shown in Figure 15b, the x coordinate of the lower left corner of character B's dot-matrix was varied from 0 to 16, while keeping the y coordinate at 0, and the dot-matrix pattern was then rotated 45 degrees. The sum of dot deviations was also calculated and plotted for each distance (Figure 16b). Once again, the patterns did not appear to change systematically.

Several points need to be noted about these simulations. In order 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 was not the case during the experiment, where 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 rotated the same number of degrees were compared, they would likely be distorted differently, as their distances from the center might be different. The patterns which were presented to the subjects under the same combinations of variables were most probably different, and thus their task performance would necessarily vary. The effect of 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

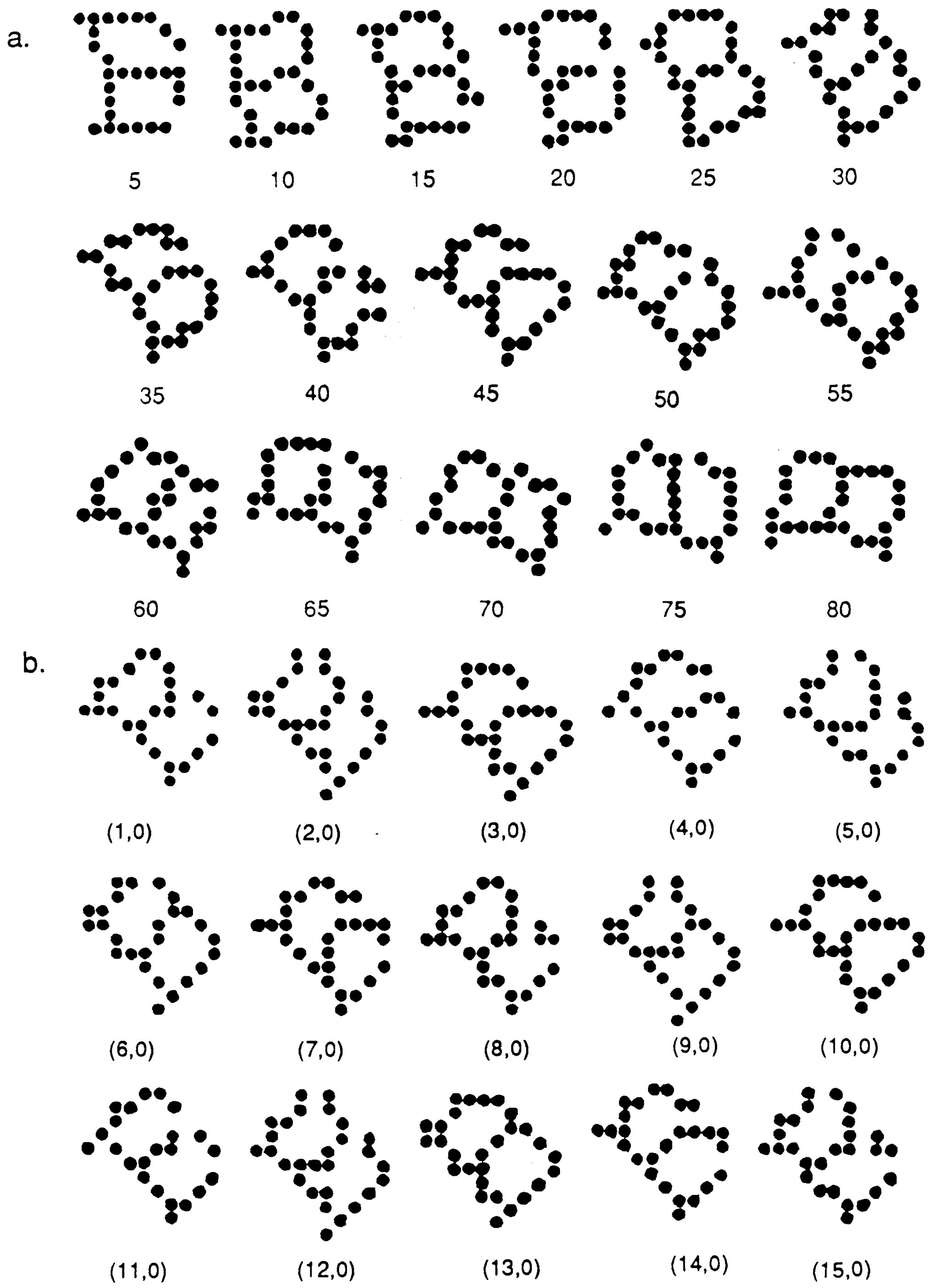


Figure 15. Character pattern distortion: (a) Character B rotated different angles at (0,0). (b) Character B rotated 45 degrees at different x coordinates.

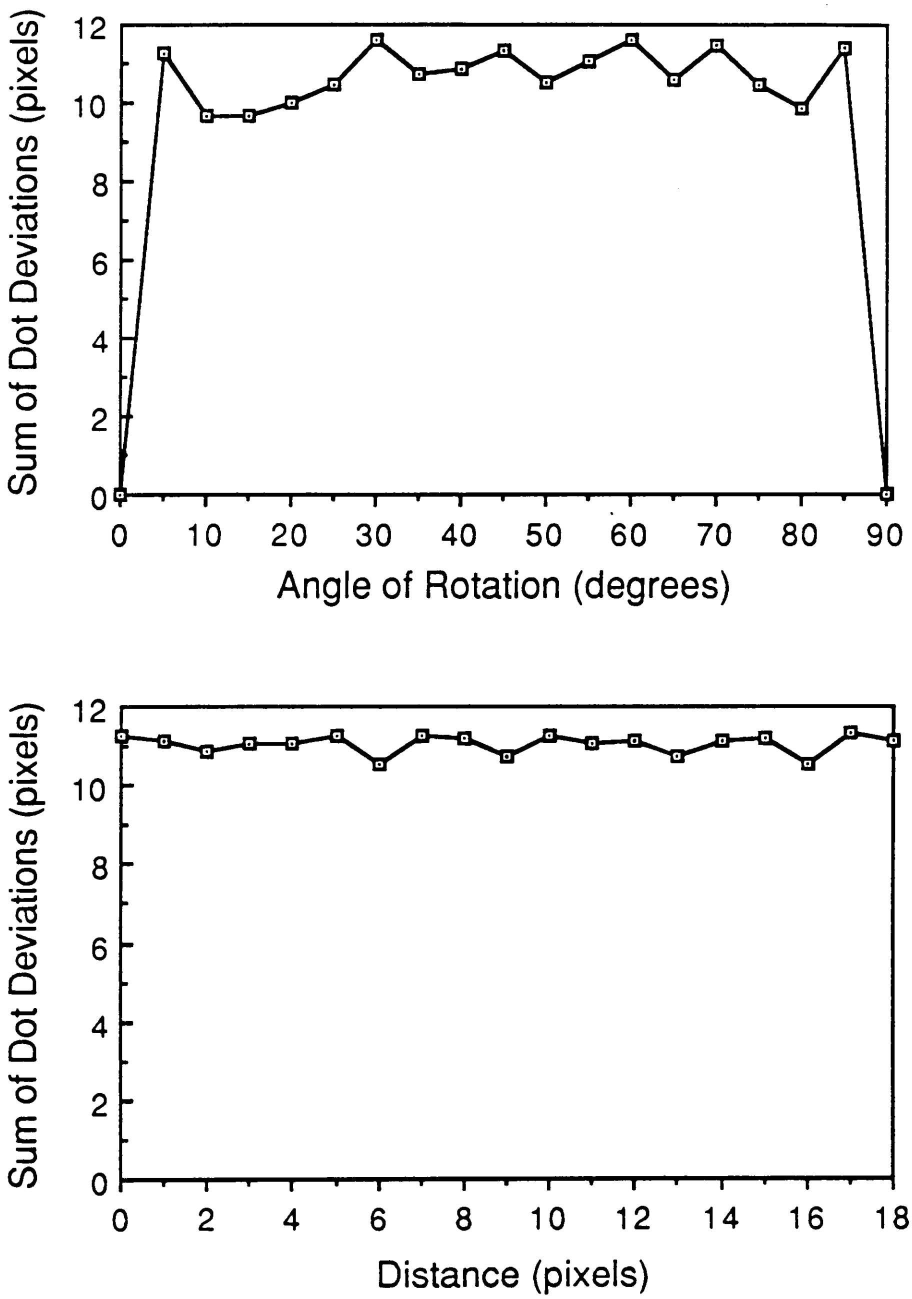


Figure 16. Sum of dot deviations in character B: (a) by angle of rotation and (b) by the x coordinate.

the same angle of rotation, different combinations of the x and y coordinate components result in different dot-matrix pattern distortions, and 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; the x and y coordinates do.

Lastly, these distorting effects of angle and coordinate components act differently on characters, as characters are composed of different numbers of dots, to be moved about, and different curvilinear characteristics. Figure 17 shows all eight target characters rotated 25 degrees at distance 0. Apparently, some characters are more readily recognizable than others. Curvilinear characteristics of dot-matrix patterns of characters are difficult to quantify, as demonstrated in the earlier discussion of the effect of target character.

In a comparison of the two figures on simulated distortion (Figure 16), the size of changes in the dot deviation appear to be greater under the varying angles of rotation, even if the points at 0 and 90 degrees are excluded, than under the varying x coordinate. This 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.

Regressions of Response Speed Data

A revised list of factors that might have influenced the task performance was considered. The angle of rotation was still considered to affect the character pattern distortion. The x and y coordinates of the target character are now understood 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 actual dot deviation was calculated for each target character pattern used in this experiment (the x and y coordinates of

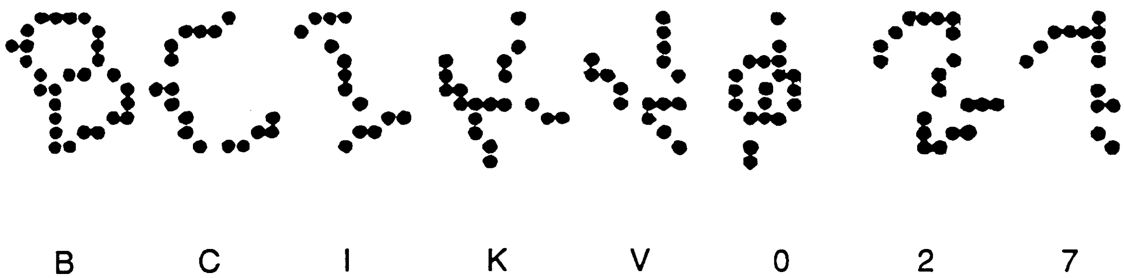


Figure 17. Target characters rotated 25 degrees at (0,0).

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 using various combinations of regressors were performed. The best fit (R-square of 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 (Table 11). A comparable fit (R-square of 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 there are other measures, yet to prevail upon this author, that more accurately quantify the character's geometry and the extent of its distortion, and that the mechanism of random search must be better understood.

Regression analyses were then repeated for each character separately, as having failed to quantify the character's pattern adequately it now seemed more appropriate to treat character as a fixed effect variable. The results were disappointing: the R-square values varied among characters, with even the best fitting character failing to provide a significantly better R-square value. Evidently, the issues involved in the search and recognition of rotated dot-matrix characters are extremely complex.

<u>Accuracy</u>

An analysis of variance was repeated using the response accuracy as the dependent measure, instead of response time (Table 12). The 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 or not 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 ($p < 0.0001$), and the Student-Neuman-Keuls test of the distance variable (Table 13)

Table 11. 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 Deviation	1	-0.009554	-11.715	0.0001
Trial Block	1	0.000420	6.385	0.0001

R-square = 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 Deviation	1	-0.003546	-0.790	0.4298
Trial Block	1	0.000417	6.350	0.0001

R-square = 0.2184

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, and the least accurate response was found at zone 2. The effect of angle of rotation was close to significance at $p = 0.0661$, and the mean response accuracy ranged from 0.9082 at 40 degrees to 0.9609 at 70 degrees (the second most accurate responses, 0.9570, were found at 0, 15, 90, and 180 degrees). Subjects' responses were highly accurate, indicating that subjects carefully searched for and made a close examination of the target character before responding (subjects were told that speed and accuracy were equally important).

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 experimenters' observations during the sessions, rather than due to subjects identifying a wrong character. The design of this experiment did not allow a way to identify what character the subjects mistook in case of such errors.

Table 12. Analysis of Variance Summary on Mean Response Accuracy.

Source	df	MS	F	p
Subject (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			

Table 13. Student-Neuman-Keuls Results for the Effect of Distance.

Distance Zone	Mean Response Accuracy (%)
1	0.9821
4	0.9440
3	0.9329
2	0.9079

CONCLUSIONS

The performance of this random search task, as measured by response time, is influenced by three categories of variables. The first variable which affects the 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 degrees to 8.172 seconds at 115 degrees (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 unsystematically.

The second variable category is the target character's distance from the center of rotation. The (radial) distance from where 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 and thus affects the response time. 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 over 60%).

The third variable category is the dot-matrix characters themselves which 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 in numeral 2 (more than 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 demonstrated that the angle of rotation and the x and y coordinates of the dot-matrix pattern relative to the center of rotation determined 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 to 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 accurately represented by the levels of independent variables.

Mechanism of random search

A possible mechanism for this random search task was considered based on the 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, they looked for the rotated image in the random search pattern. This task strategy is in agreement with the experimenters' observations that the first trial of each block resulted in longer response times, that the standardization trial distracted subjects and often resulted in longer response times, and that the condition trial immediately following the standardization trial also took longer. That the subjects needed to know the angle of rotation before the stimulus was presented, in order 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 characters with "linear" characteristics, i.e., 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 was found. The amount of time spent in figuring out the angle of rotation varied among trials, as subjects felt increasingly certain of the angle of rotation over the trials in the block. The magnitude of the resulting intra-block variance is not known. In the event that 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 felt ready for the next trial did they press the mouse button for the stimulus.

Mental Compensation for Distortion

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, as the target character was also distorted. 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. As 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. As can be seen in Figure 17 on page 63, the distortion of dot-matrix patterns is such that most features which makes the particular character distinct are lost and even creates an extraneous feature, e.g., 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 took 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 which was identified as the target would not be the correct target. As 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 thesis 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 the 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 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 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 under 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-square 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 under 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 under the same condition would reveal which character is likely to suffer more from the distortion. This is indeed an exciting concept, as it offers a means to quantify the level of distortion and thus to help design dot-matrix characters less susceptible to distortion. Considering the modest success achieved by Maddox (1979, 1980) and Harvey et al. (1983), however, the necessary efforts may not be justified.

Direction for Future Research

This investigation of the effect of dot-matrix distortion, due to 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 which reflect the dot-matrix characters' geometry and thus influence their sensitivity to distortion were discussed, and a measure to quantify 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 the 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 the distance. Maintaining the effects of variables orthogonal 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 a possibility of any angle dependent mechanism was ruled out. 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 to quantify 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 bank 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 also advance the understanding of the underlying cognitive mechanism. Ultimately, a means to predict 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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Table A-1.

Summary of Analysis of Variance, Distance Zone 1.

Source	df	MS	F	p
Direction (D)	1	23.517	0.47	0.4940
Angle (A)	36	69.565	1.38	0.0637
Character (C)	7	2270.452	45.16	0.0001
D x A	36	82.386	1.64	0.0095
D x C	7	46.135	0.92	0.4913
A x C	252	50.834	1.00	0.4794
D x A x C	252	51.725	1.03	0.3672
Pooled Error	4144	50.270		
TOTAL	4735			

NOTE: For these analyses of variance, the between-subject terms were pooled and used as the error term to test all main effects and interactions. This allowed evaluation of certain main effects and interactions which could otherwise not be tested simultaneously; the tests were consequently more conservative.

Table A-2.

Summary of Analysis of Variance, Distance Zone 2.

Source	df	MS	F	p
Direction (D)	1	14.246	0.21	0.6461
Angle (A)	36	106.094	1.57	0.0165
Character (C)	7	3698.565	54.75	0.0001
D x A	36	83.411	1.23	0.1591
D x C	7	42.027	0.62	0.7381
A x C	252	72.683	1.08	0.2027
D x A x C	252	72.639	1.08	0.2046
Pooled Error	4144	67.560		
TOTAL	4735			

Table A-3.

Summary of Analysis of Variance, Distance Zone 3.

Source	df	MS	F	p
Direction (D)	1	29.322	0.58	0.4464
Angle (A)	36	65.026	1.29	0.1181
Character (C)	7	2066.496	40.87	0.0001
D x A	36	88.433	1.75	0.0038
D x C	7	109.813	2.17	0.0337
A x C	252	55.572	1.10	0.1419
D x A x C	252	49.888	0.99	0.5470
Pooled Error	4144	50.558		
TOTAL	4735			

Table A-4.

Summary of Analysis of Variance, Distance Zone 4.

Source	df	MS	F	p
Direction (D)	1	124.265	1.80	0.1797
Angle (A)	36	61.274	0.89	0.6608
Character (C)	7	1676.908	24.30	0.0001
D x A	36	56.849	0.82	0.7627
D x C	7	76.368	1.11	0.3558
A x C	252	67.330	0.98	0.5954
D x A x C	252	70.394	1.02	0.4040
Pooled Error	4144	69.017		
TOTAL	4735			

Table B-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	2367			

NOTE: For these analyses of variance, the between-subject terms were pooled and used as the error term to test all main effects and interactions. This allowed evaluation of certain main effects and interactions which could otherwise not be tested simultaneously; the tests were consequently more conservative.

Table B-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 B-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 B-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 B-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	2072	61.728		
TOTAL	2367			

Table B-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	2072	86.399		
TOTAL	2367			

Table B-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 B-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			

Table C-1.

Summary of Analysis of Variance, Angle 0.

Source	df	MS	F	p
Direction (D)	1	19.559	0.46	0.4976
Distance (L)	3	229.692	5.41	0.0012
Character (C)	7	164.695	3.88	0.0004
D x L	3	10.521	0.25	0.8629
D x C	7	42.076	0.99	0.4368
L x C	21	46.209	1.09	0.3565
D x L x C	21	58.707	1.38	0.1205
Pooled Error	448	42.446		
TOTAL	511			

NOTE: For these analyses of variance, the between-subject terms were pooled and used as the error term to test all main effects and interactions. This allowed evaluation of certain main effects and interactions which could otherwise not be tested simultaneously; the tests were consequently more conservative.

Table C-2.

Summary of Analysis of Variance, Angle 5.

Source	df	MS	F	p
Direction (D)	1	29.659	0.66	0.4155
Distance (L)	3	273.856	6.13	0.0004
Character (C)	7	343.565	7.70	0.0001
D x L	3	61.491	1.38	0.2940
D x C	7	18.709	0.42	0.8905
L x C	21	22.809	0.51	0.9661
D x L x C	21	47.887	1.07	0.3746
Pooled Error	448	44.645		
TOTAL	511			

Table C-3.

Summary of Analysis of Variance, Angle 10

Source	df	MS	F	p
Direction (D)	1	228.031	3.85	0.0503
Distance (L)	3	301.217	5.09	0.0018
Character (C)	7	283.242	4.79	0.0001
D x L	3	66.582	1.13	0.3385
D x C	7	111.756	1.89	0.0697
L x C	21	53.269	0.90	0.5911
D x L x C	21	50.559	0.85	0.6513
Pooled Error	448	59.172		
TOTAL	511			

Table C-4.

Summary of Analysis of Variance, Angle 15.

Source	df	MS	F	p
Direction (D)	1	35.638	0.86	0.3554
Distance (L)	3	74.797	1.80	0.1470
Character (C)	7	280.304	6.73	0.0001
D x L	3	44.259	1.06	0.3645
D x C	7	60.164	1.45	0.1853
L x C	21	48.658	1.17	0.2743
D x L x C	21	14.370	0.35	0.9974
Pooled Error	448	41.634		
TOTAL	511			

Table C-5.

Summary of Analysis of Variance, Angle 20.

Source	df	MS	F	p
Direction (D)	1	126.654	1.58	0.2100
Distance (L)	3	284.388	3.54	0.0147
Character (C)	7	421.439	5.24	0.0001
D x L	3	188.839	2.35	0.0718
D x C	7	44.052	0.55	0.7978
L x C	21	52.862	0.66	0.8742
D x L x C	21	44.725	0.56	0.9453
Pooled Error	448	80.359		
TOTAL	511			

Table C-6.

Summary of Analysis of Variance, Angle 25.

Source	df	MS	F	p
Direction (D)	1	140.826	3.67	0.0561
Distance (L)	3	491.912	12.81	0.0001
Character (C)	7	205.094	5.34	0.0001
D x L	3	42.840	1.12	0.3423
D x C	7	38.618	1.01	0.4263
L x C	21	18.857	0.49	0.9731
D x L x C	21	47.524	1.24	0.2143
Pooled Error	448	38.396		
TOTAL	511			

Table C-7.

Summary of Analysis of Variance, Angle 30.

Source	df	MS	F	p
Direction (D)	1	552.889	10.62	0.0012
Distance (L)	3	377.836	7.53	0.0001
Character (C)	7	279.324	5.57	0.0001
D x L	3	19.945	0.40	0.7548
D x C	7	156.237	3.11	0.0032
L x C	21	25.751	0.51	0.9651
D x L x C	21	39.872	0.79	0.7272
Pooled Error	448	50.168		
TOTAL	511			

Table C-8.

Summary of Analysis of Variance, Angle 35.

Source	df	MS	F	p
Direction (D)	1	4.594	0.09	0.7700
Distance (L)	3	616.358	11.49	0.0001
Character (C)	7	296.127	5.52	0.0001
D x L	3	35.150	0.66	0.5801
D x C	7	72.374	1.35	0.2255
L x C	21	44.892	0.84	0.6744
D x L x C	21	96.249	1.79	0.0172
Pooled Error	448	53.657		
TOTAL	511			

Table C-9.

Summary of Analysis of Variance, Angle 40.

Source	df	MS	F	p
Direction (D)	1	136.631	2.37	0.1247
Distance (L)	3	126.576	2.19	0.0883
Character (C)	7	508.347	8.80	0.0001
D x L	3	81.531	1.41	0.2386
D x C	7	171.058	2.96	0.0048
L x C	21	107.081	1.85	0.0125
D x L x C	21	71.598	1.24	0.2126
Pooled Error	448	57.749		
TOTAL	511			

Table C-10.

Summary of Analysis of Variance, Angle 45.

Source	df	MS	F	p
Direction (D)	1	33.892	0.79	0.3744
Distance (L)	3	254.600	5.94	0.0006
Character (C)	7	224.304	5.23	0.0001
D x L	3	81.887	1.91	0.1271
D x C	7	55.207	1.29	0.2544
L x C	21	37.795	0.88	0.6155
D x L x C	21	43.267	1.01	0.4500
Pooled Error	448	42.865		
TOTAL	511			

Table C-11.

Summary of Analysis of Variance, Angle 50.

Source	df	MS	F	p
Direction (D)	1	130.482	3.42	0.0650
Distance (L)	3	126.192	3.31	0.0201
Character (C)	7	150.445	3.95	0.0003
D x L	3	7.659	0.20	0.8958
D x C	7	46.255	1.21	0.2939
L x C	21	30.532	0.80	0.7200
D x L x C	21	52.709	1.38	0.1210
Pooled Error	448	38.134		
TOTAL	511			

Table C-12.

Summary of Analysis of Variance, Angle 55.

Source	df	MS	F	p
Direction (D)	1	32.633	0.62	0.4314
Distance (L)	3	198.408	3.77	0.0108
Character (C)	7	430.504	8.18	0.0001
D x L	3	77.026	1.46	0.2238
D x C	7	22.771	0.43	0.8817
L x C	21	41.035	0.78	0.7455
D x L x C	21	33.553	0.64	0.8912
Pooled Error	448	52.624		
TOTAL	511			

Table C-13.

Summary of Analysis of Variance, Angle 60.

Source	df	MS	F	p
Direction (D)	1	2.761	0.04	0.8334
Distance (L)	3	299.529	4.80	0.0026
Character (C)	7	363.425	5.83	0.0001
D x L	3	133.672	2.14	0.0940
D x C	7	126.590	2.03	0.0500
L x C	21	75.281	1.21	0.2395
D x L x C	21	34.715	0.56	0.9453
Pooled Error	448	62.359		
TOTAL	511			

Table C-14.

Summary of Analysis of Variance, Angle 65

Source	df	MS	F	p
Direction (D)	1	140.585	2.63	0.1054
Distance (L)	3	200.777	3.76	0.0109
Character (C)	7	327.399	6.13	0.0001
D x L	3	180.172	3.37	0.0184
D x C	7	20.216	0.38	0.9148
L x C	21	63.458	1.19	0.2562
D x L x C	21	47.155	0.88	0.6138
Pooled Error	448	53.402		
TOTAL	511			

Table C-15.

Summary of Analysis of Variance, Angle 70.

Source	df	MS	F	p
Direction (D)	1	19.637	0.37	0.5430
Distance (L)	3	483.983	9.13	0.0001
Character (C)	7	104.694	1.98	0.0568
D x L	3	26.024	0.49	0.6886
D x C	7	90.738	1.71	0.1041
L x C	21	46.137	0.87	0.6301
D x L x C	21	58.038	1.10	0.3492
Pooled Error	448	52.989		
TOTAL	511			

Table C-16.

Summary of Analysis of Variance, Angle 75.

Source	df	MS	F	p
Direction (D)	1	9.738	0.17	0.6800
Distance (L)	3	390.441	6.83	0.0002
Character (C)	7	327.946	5.74	0.0001
D x L	3	47.172	0.83	0.4805
D x C	7	44.297	0.77	0.6087
L x C	21	74.998	1.31	0.1612
D x L x C	21	40.134	0.70	0.8323
Pooled Error	448	57.166		
TOTAL	511			

Table C-17.

Summary of Analysis of Variance, Angle 80.

Source	df	MS	F	p
Direction (D)	1	250.866	3.63	0.0575
Distance (L)	3	209.345	3.03	0.0294
Character (C)	7	396.369	5.73	0.0001
D x L	3	46.174	0.67	0.5725
D x C	7	106.055	1.53	0.1541
L x C	21	38.298	0.55	0.9470
D x L x C	21	60.590	0.88	0.6236
Pooled Error	448	69.199		
TOTAL	511			

Table C-18.

Summary of Analysis of Variance, Angle 85.

Source	df	MS	F	p
Direction (D)	1	0.00661	0.00	0.9910
Distance (L)	3	261.017	5.08	0.0018
Character (C)	7	403.873	7.86	0.0001
D x L	3	186.324	3.63	0.0131
D x C	7	91.879	1.79	0.0877
L x C	21	37.063	0.72	0.8120
D x L x C	21	38.998	0.76	0.7699
Pooled Error	448	51.370		
TOTAL	511			

Table C-19.

Summary of Analysis of Variance, Angle 90.

Source	df	MS	F	p
Direction (D)	1	120.396	2.51	0.1136
Distance (L)	3	238.716	4.98	0.0021
Character (C)	7	296.157	6.18	0.0001
D x L	3	41.013	0.86	0.4638
D x C	7	97.697	2.04	0.0489
L x C	21	45.357	0.95	0.5298
D x L x C	21	91.288	1.91	0.0095
Pooled Error	448	47.903		
TOTAL	511			

Table C-20.

Summary of Analysis of Variance, Angle 95.

Source	df	MS	F	p
Direction (D)	1	146.954	2.69	0.1014
Distance (L)	3	562.991	10.32	0.0001
Character (C)	7	252.352	4.63	0.0001
D x L	3	28.103	0.52	0.6719
D x C	7	91.345	1.67	0.1131
L x C	21	58.398	1.07	0.3767
D x L x C	21	45.357	0.83	0.6808
Pooled Error	448	54.536		
TOTAL	511			

Table C-21.

Summary of Analysis of Variance, Angle 100.

Source	df	MS	F	p
Direction (D)	1	7.005	0.09	0.7619
Distance (L)	3	448.867	5.89	0.0006
Character (C)	7	364.070	4.78	0.0001
D x L	3	169.849	2.23	0.0842
D x C	7	31.003	0.41	0.8982
L x C	21	49.733	0.65	0.8788
D x L x C	21	97.053	1.27	0.1873
Pooled Error	448	76.216		
TOTAL	511			

Table C-22.

Summary of Analysis of Variance, Angle 105.

Source	df	MS	F	p
Direction (D)	1	11.604	0.17	0.6761
Distance (L)	3	381.332	5.74	0.0007
Character (C)	7	458.781	6.91	0.0001
D x L	3	35.859	0.54	0.6551
D x C	7	60.744	0.91	0.4946
L x C	21	91.501	1.38	0.1231
D x L x C	21	52.326	0.79	0.7355
Pooled Error	448	66.401		
TOTAL	511			

Table C-23.

Summary of Analysis of Variance, Angle 110.

Source	df	MS	F	p
Direction (D)	1	31.940	0.54	0.4634
Distance (L)	3	402.657	6.79	0.0002
Character (C)	7	247.665	4.18	0.0002
D x L	3	26.982	0.45	0.7139
D x C	7	67.946	1.15	0.3333
L x C	21	120.568	2.03	0.0047
D x L x C	21	37.133	0.63	0.9003
Pooled Error	448	59.311		
TOTAL	511			

Table C-24.

Summary of Analysis of Variance, Angle 115.

Source	df	MS	F	p
Direction (D)	1	338.585	3.89	0.0493
Distance (L)	3	436.927	5.01	0.0020
Character (C)	7	179.256	2.06	0.0469
D x L	3	65.941	0.76	0.5189
D x C	7	109.899	1.26	0.2680
L x C	21	138.532	1.59	0.0476
D x L x C	21	24.980	0.29	0.9993
Pooled Error	448	87.144		
TOTAL	511			

Table C-25.

Summary of Analysis of Variance, Angle 120.

Source	df	MS	F	p
Direction (D)	1	0.836	0.01	0.9135
Distance (L)	3	725.282	10.26	0.0001
Character (C)	7	485.989	6.87	0.0001
D x L	3	81.893	1.16	0.3254
D x C	7	51.817	0.73	0.6443
L x C	21	97.759	1.38	0.1209
D x L x C	21	88.500	1.25	0.2036
Pooled Error	448	70.716		
TOTAL	511			

Table C-26.

Summary of Analysis of Variance, Angle 125.

Source	df	MS	F	p
Direction (D)	1	163.014	1.68	0.1962
Distance (L)	3	84.288	0.87	0.4584
Character (C)	7	347.306	3.57	0.0009
D x L	3	55.748	0.57	0.6330
D x C	7	233.645	2.40	0.0202
L x C	21	176.865	1.82	0.0151
D x L x C	21	138.352	1.42	0.1021
Pooled Error	448	97.283		
TOTAL	511			

Table C-27.

Summary of Analysis of Variance, Angle 130.

Source	df	MS	F	p
Direction (D)	1	9.979	0.24	0.6277
Distance (L)	3	340.971	8.05	0.0001
Character (C)	7	303.539	7.16	0.0001
D x L	3	52.697	1.24	0.2934
D x C	7	102.980	2.43	0.0188
L x C	21	48.201	1.14	0.3047
D x L x C	21	34.546	0.82	0.7017
Pooled Error	448	42.375		
TOTAL	511			

Table C-28.

Summary of Analysis of Variance, Angle 135.

Source	df	MS	F	p
Direction (D)	1	6.521	0.16	0.6934
Distance (L)	3	458.988	10.95	0.0001
Character (C)	7	239.286	5.71	0.0001
D x L	3	10.200	0.24	0.8660
D x C	7	4.453	0.11	0.9979
L x C	21	30.404	0.73	0.8076
D x L x C	21	36.715	0.88	0.6229
Pooled Error	448	41.904		
TOTAL	511			

Table C-29.

Summary of Analysis of Variance, Angle 140.

Source	df	MS	F	p
Direction	1	266.170	2.73	0.0990
Distance (L)	3	260.627	2.68	0.0468
Character (C)	7	327.426	3.36	0.0017
D x L	3	64.548	0.66	0.5754
D x C	7	84.476	0.87	0.5234
L x C	21	105.676	1.08	0.3608
D x L x C	21	64.559	0.66	0.8698
Pooled Error	448	97.411		
TOTAL	511			

Table C-30.

Summary of Analysis of Variance, Angle 145.

Source	df	MS	F	p
Direction (D)	1	28.336	0.47	0.4952
Distance (L)	3	353.952	5.82	0.0007
Character (C)	7	167.252	2.75	0.0083
D x L	3	1.845	0.03	0.9929
D x C	7	111.388	1.83	0.0795
L x C	21	95.035	1.56	0.0541
D x L x C	21	70.242	1.16	0.2874
Pooled Error	448	97.411		
TOTAL	511			

Table C-31.

Summary of Analysis of Variance, Angle 150.

Source	df	MS	F	p
Direction (D)	1	3.528	0.07	0.7919
Distance (L)	3	387.022	7.64	0.0001
Character (C)	7	482.006	9.52	0.0001
D x L	3	102.028	2.02	0.1110
D x C	7	43.988	0.87	0.5310
L x C	21	55.907	1.10	0.3394
D x L x C	21	53.134	1.05	0.4013
Pooled Error	448	50.624		
TOTAL	511			

Table C-32.

Summary of Analysis of Variance, Angle 155.

Source	df	MS	F	p
Direction (D)	1	188.144	3.26	0.0716
Distance (L)	3	398.805	6.91	0.0001
Character (C)	7	122.751	2.13	0.0395
D x L	3	16.531	0.29	0.8351
D x C	7	56.296	0.98	0.4480
L x C	21	44.316	0.77	0.7591
D x L x C	21	42.242	0.73	0.8002
Pooled Error	448	57.676		
TOTAL	511			

Table C-33.

Summary of Analysis of Variance, Angle 160.

Source	df	MS	F	p
Direction (D)	1	22.714	0.19	0.6597
Distance (L)	3	458.067	3.91	0.0080
Character (C)	7	345.507	2.95	0.0049
D x L	3	345.314	2.95	0.0324
D x C	7	189.419	1.62	0.1280
L x C	21	98.940	0.85	0.6630
D x L x C	21	104.869	0.90	0.5966
Pooled Error	448	117.029		
TOTAL	511			

Table C-34.

Summary of Analysis of Variance, Angle 165.

Source	df	MS	F	p
Direction (D)	1	36.969	0.72	0.3957
Distance (L)	3	206.535	4.04	0.0075
Character (C)	7	290.603	5.68	0.0001
D x L	3	3.411	0.07	0.9776
D x C	7	28.307	0.55	0.7937
L x C	21	55.597	1.09	0.3587
D x L x C	21	55.161	1.08	0.3683
Pooled Error	448	51.161		
TOTAL	511			

Table C-35.

Summary of Analysis of Variance, Angle 170.

Source	df	MS	F	p
Direction (D)	1	179.741	2.92	0.0883
Distance (L)	3	395.566	6.42	0.0003
Character (C)	7	276.861	4.50	0.0001
D x L	3	50.610	0.82	0.4823
D x C	7	59.041	0.96	0.4609
L x C	21	75.349	1.22	0.2258
D x L x C	21	71.912	1.17	0.2752
Pooled Error	448	61.583		
TOTAL	511			

Table C-36.

Summary of Analysis of Variance, Angle 175.

Source	df	MS	F	p
Direction (D)	1	35.180	0.81	0.3693
Distance (L)	3	233.980	5.37	0.0012
Character (C)	7	246.506	5.66	0.0001
D x L	3	72.039	1.65	0.1762
D x C	7	27.438	0.63	0.7312
L x C	21	63.626	1.44	0.0954
D x L x C	21	30.590	0.70	0.8320
Pooled Error	448	43.555		
TOTAL	511			

Table C-37.

Summary of Analysis of Variance, Angle 180.

Source	df	MS	F	p
Direction (D)	1	160.048	2.50	0.1145
Distance (L)	3	330.511	5.16	0.0016
Character (C)	7	423.873	6.62	0.0001
D x L	3	23.940	0.37	0.7718
D x C	7	49.503	0.77	0.6100
L x C	21	83.926	1.31	0.1618
D x L x C	21	67.445	1.05	0.3966
Pooled Error	448	64.015		
TOTAL	511			

APPENDIX D. SUBJECT INSTRUCTION

Random Search Task Instruction

In this experiment, you will be asked to search for an alphanumeric character (letter or number) from among other alphanumeric characters on the screen. The placement of your target character will be at random. At the beginning of each trial you will see the words, "Ready, the target character is ___." This will be your target character for that trial. It will appear in only one position on the screen.

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

The screen will then be erased so that you can initiate a new trial. During the experiment, we want you to respond **as quickly and as accurately as possible** --- both are important. Please keep your head in a straight and upright position while searching, as it would move your eyes from the intended position. We will begin the session on the first day with 20 practice trials. If you have any questions, please ask. If you are comfortable with the procedure, we will begin the experiment. Each session will last approximately two and half hours. You will be offered the opportunity to take short breaks at various intervals during each session. If your eyes are tired, please take advantage of the breaks so that our data will be as accurate as possible.

You will participate in three experimental sessions. As you know, you will be receive $37.50 upon completion of the three sessions. We require that each of your sessions be scheduled at approximately the same time of day on three consecutive days.

Do you have any questions?

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