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Is There a Threshold For Mental Rotation?

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IS THERE A THRESHOLD FOR MENTAL ROTATION?

BY

JOSEPH STEPHEN ROSSI

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF ARTS

IN

PSYCHOLOGY

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ABSTRACT

In the mental rotation paradigm, observers are shown two stimulus patterns which differ from each other in angular orientation. It has been found that the time required to recognize that two such patterns are the same is a linear function of the angular disparity in the portrayed orientations of the two patterns. Although it has not been claimed that the internal process is strictly continuous, it nevertheless appears to be an analog of the corresponding physical process. Observers were shown pairs of perspective line drawings of three-dimensional block figures which differed in orientation from a standard by either 0, 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 60, 90, 120, 150, or 180°. Since no previous studies have included orientation disparities of less than 20°, such disparities were included in the present study to obtain a more refined idea of the nature of the mental rotation process. Regression analyses revealed that the time required to decide that comparison stimuli were the same as standard stimuli was not a linear but rather a constant function for angular disparities from zero to 18°. Data points above 18° fit a linear function similar in slope and intercept to that originally found by Shepard and Metzler (1971). The finding of a threshold for mental rotation suggests that the template matching mechanism which performs "same-different" comparisons is to some extent flexible. Thus, standard and comparison objects with subthreshold angular disparities are not rotated at

all, but are immediately accommodated by the flexible template system. However, the converse proposition, that objects with supra-threshold angular disparities need be rotated only into the threshold region for a comparison to occur, was not supported. Although in general males seem to outperform females in cognitive tasks requiring spatial ability, no significant sex differences were found, either in the rate of mental rotation or in the size of the threshold for mental rotation. A second experiment was conducted to insure that the threshold for mental rotation was not simply a sensory threshold. Five observers were shown pairs of sequentially presented stimulus figures and asked to rate their impression of the total orientation of each pair, in accordance with Anderson's (1974) functional measurement paradigm. Analyses of variance showed that a simple additive model for the summation of the angles fit the obtained data well. Furthermore, the psychophysical function relating perceived orientation to physical orientation was flat between zero and 6° for four of five subjects, and roughly linear over the rest of the range. These results indicate that while angular disparities of 6° or less between objects are not apparent to observers, there is no evidence for a sensory threshold in the neighborhood of the mental rotation threshold. These results confirm as a psychological effect the threshold for mental rotation. Furthermore, these results may have important implications concerning the perception of complex forms by the human visual system.

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PREFACE

The research described in Part I of this report is the culmination of a long interest in mental imagery, extending back to my undergraduate work. Before beginning this thesis I had conducted several studies on mental imagery using self-report questionnaires. Although I was a bit dissatisfied with an essentially subjective methodology, there seemed to be no alternative. Dr. Collyer then suggested that if I were really interested in the study of mental imagery I should become acquainted with Roger Shepard's work on mental rotation. Upon becoming so "acquainted", my immediate thought was to use the mental rotation paradigm to validate the self-report questionnaires, which are still widely used. A proposal was written to that effect as part of a graduate seminar in perception. That proposal contained a supplementary proposal to investigate the mental rotation reaction time function at small angles, a range not previously investigated. In short, as perhaps often happens, that original proposal was never carried out, but the "supplement" has become the basis for this thesis. Experiment II was conceived towards the conclusion of Experiment I, at a time when the results of that latter experiment seemed fairly well established. In fact, Experiment II was completely designed, implemented, conducted, and analysed while a few observers remained to be tested in Experiment I. Experiment I has now been accepted

for presentation at the Third American Conference on the Fantasy and Imaging Process in New York (November, 1979), and submitted for presentation at the 51st Annual Meeting of the Eastern Psychological Association in Hartford (April, 1980).

September, 1979

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PART I

IS THERE A THRESHOLD FOR MENTAL ROTATION?

CHAPTER 1

Introduction

The subject matter of cognitive psychology has been broadly characterized as solutions to the questions, What do we know? and, How do we acquire and use what we know (Pylyshyn, 1973)? The research reported here is related to a general area of study concerned primarily with the first question. More specifically, the question of interest deals with cognitive representation: How is what we know represented in the brain? What is the nature of internal cognitive representations?

For many years psychologists have oriented their approaches to such questions by emphasizing patterns of verbal responses (e.g., Skinner, 1957). This emphasis has largely been the result of behaviorist strictures on what constitutes the legitimate domain of psychological research. Thoughts embodied in words and propositions are, if not overt, at least liable to overt expression, and hence subject to direct measurement.

Internal, nonverbal representations--mental images--have not been investigated nearly as extensively as have the verbal processes. While the study of mental imagery does have a long history (e.g., James, 1890), the notion of the mental image has been periodically banished from western psychology (Holt, 1964). Behaviorists criticized the study of "mentalistic" topics: the process of imaging was covert

and therefore not subject to reliable or valid measurement. Since images could not be measured, they could not be studied scientifically (Watson, 1913). However, mental images have a subjective reality that many otherwise objective observers find hard to deny. Furthermore, there are several kinds of problem-solving tasks that are difficult to account for without recourse to a theory of mental images (Adams, 1974). Indeed, Anderson (1978), a critic often not kind to the study of mental images, has agreed that the question of interest is not whether mental images exist, but whether such images are functionally significant. The investigation of the phenomenon has therefore undergone something of a resurrection over the last 15 years.

Many contemporary studies of mental imagery use self-report questionnaires to assess individual differences in the ability to form or control imagery. However, ten years of research with and on imagery questionnaires have left researchers in an embarrassing position; we still don't know what these instruments measure (Hiscock, 1978). These questionnaires are unable to provide information about the nature of the visual image, the function of such images, and the relationship between images and perceptual experience.

To adequately assess the nature and function of mental images, more objective methods will be required than are offered by the self-report approach. Such a method is available in the "mental rotation" technique introduced by

Shepard and Metzler (1971). It has long been known that subjects are able to recognize as the same two two-dimensional representations of objects presented in different orientations (e.g., Mach, 1959, originally published in 1886). Shepard and Metzler (1971) showed subjects pairs of computer-generated perspective line drawings of three-dimensional block shapes. Pairs consisted of standard and comparison figures presented simultaneously. Subjects' task was to decide as quickly and as accurately as possible whether or not each pair represented the same or represented different shapes. Standard and comparison stimuli differed for "same" pairs only in that the comparison figure was a rotated version of the standard. Angle of rotation was varied from zero to 180 degrees in 20 degree increments and was either a flat rotation (i.e., a rotation in the picture plane) or a rotation in depth. Standard and comparison stimuli differed for "different" pairs in that the comparison figure was a reflected (mirror-image) version of the standard. It was found that reaction time for correct "same" decisions was a linear function of angle of rotation for both types of rotation, with no difference in reaction time as a function of type of rotation. These findings are consistent with subjects' introspective reports of what they do to arrive at a decision of "same" or "different." Subjects claimed to imagine a rotation of the comparison figure into the same orientation as the standard before a decision was made.

Such "mental rotations" could be accomplished in either two or three dimensions with equal facility, and at a rate of approximately 60 degrees per second.

The basic results of the Shepard and Metzler (1971) study have been replicated using a number of different stimulus patterns, including letters (Carpenter & Eisenberg, 1978; Cooper & Shepard, 1973a, 1973b; Corballis, Zbrodoff, Shetzer & Butler, 1978; Jacewicz & Hartley, 1979), digits (Corballis, et al., 1978), random, two-dimensional shapes (Attneave figures: Attneave & Arnoult, 1956) varied in complexity (Cooper, 1975, 1976a; Cooper & Podgorny, 1976), left and right human hands (Ashton, McFarland, Walsh & White, 1978; Cooper & Shepard, 1975), schematic city maps (Hochberg & Gellman, 1977), simple two-dimensional line figures (Petrusic, Varro & Jamieson, 1978), small greek letters (Jacewicz & Hartley, 1979), dot patterns (Corballis, Zbrodoff & Roldan, 1976), and teddy bears and ice cream cones (Marmor, 1975, 1977)! These results have, furthermore, been repeated using older college students (Jacewicz & Hartley, 1979), elderly males (Gaylord & Marsh, 1975), young children (Marmor, 1975, 1977), and even with blind subjects using the haptic sense to rotate objects (Carpenter & Eisenberg, 1978; Marmor & Zabeck, 1976). Moreover, the linear nature of the reaction time function continues as the angle of rotation is increased beyond 180 degrees up to 360 degrees when subjects are instructed to rotate in a particular direction (Cooper, 1975; Cooper &

Podgorny, 1976; Metzler & Shepard, 1974). These findings strongly suggest that reaction time is determined by the extent of the mental trajectory through which the subject must rotate the comparison figure.

In performing mental rotation tasks observers claim that they are able to form mental images of the stimuli and perform transformational operations on these images. Shepard and Feng (unpublished, reported in Shepard, 1975) reported that subjects were apparently able to perform pre-specified rotations on a particular letter, which was only named and not presented visually. For example, the letter "M" becomes the letter "W" when rotated 180 degrees to the left, but remains the letter "M" when reflected about its vertical axis. One particularly interesting result of their study was that, for all seven letters used in the study, rotation 180 degrees to the left was significantly faster than reflection of the letter about both its vertical and horizontal axes, even though in all cases identical images resulted from the required transformations. This result would be expected, however, if subjects were actually carrying out the required manipulations. The results of this study, then, support subjects' claims that they are able to rotate as well as form mental images.

If subjects are able to form images and subsequently manipulate these images, then simultaneous presentation of standard and comparison figures should not be necessary for the performance of mental rotation tasks. Using successive

presentation of standard and comparison figures in a series of studies, Cooper and Shepard have found that subjects are able to "hold" an image of the standard figure and perform required transformations before the presentation of the comparison figure (Cooper, 1975, 1976a; Cooper & Podgorny, 1976; Cooper & Shepard, 1973a, 1973b, 1975, 1978). Using letters as stimuli, Cooper and Shepard (1973a, 1973b) followed standard figure presentation with an arrow indicating the orientation of the upcoming test figure. This orientation information was presented at one of four durations ranging from 100 to 1000 msec. Immediately upon the offset of the orientation cue, the rotated test figure was presented in the indicated orientation. Subjects were then required to determine as quickly as possible whether the test figure was a normal or reflected (backward) character. At short orientation cue durations, reaction times increased in a positively accelerated fashion as the angle of rotation increased, indicating sufficient time to prepare for the smaller angles but not for the larger ones. At the 1000 msec duration there was sufficient time for subjects to perform all required transformations, and reaction time was rapid and constant for all orientations.

In a subsequent study, Cooper (1975) allowed subjects to control the duration of the orientation cue. Subjects were instructed to rotate a random two-dimensional polygon (Attneave figure) in a specified direction and through a specified angle. Subjects indicated the completion of the

process of preparation by pressing a button, which initiated the presentation of the test figure in the previously specified orientation. Subjects were then required to determine whether the test figure was a standard or reflected version of the original figure. Cooper found that the time to prepare was a linear function of the specified angle of rotation. Furthermore, discriminative reaction time was not affected by the orientation of the test figure, that is, was a constant function of angle of orientation, thus indicating that subjects were indeed prepared for the presentation of the test stimulus when they so indicated.

The results of these studies, and similar other studies (Cooper, 1976a; Cooper & Podgorny, 1976; Cooper & Shepard, 1975), support the introspective claims of subjects that they are able to form and manipulate mental images. Furthermore, these studies extend what we can know about mental images from questionnaire studies by providing information about the rate at which mental transformations are carried out, the time it takes to prepare such operations, and the discriminative reaction time for comparing such images.

Mental rotation studies have also been able to demonstrate that there is a relationship between internal representation of mental transformation and actual perceptual experience. In the Cooper (1975) study reported above, it was found that the slope of preparation time function was very similar to the slope of the reaction time

function for a task in which advance information about subsequent test figure orientation was not given. This similarity in slope suggests that similar processes of mental rotation underlie the preparing for a rotated object that is not yet present and the responding to a rotated object that has already been presented. The similarity between these mental processes and perceptual experience has been made more explicit in studies which have investigated the time it takes to respond to an object while imagining the object in rotation (Cooper, 1976a; Cooper & Shepard, 1973a; Metzler & Shepard, 1974) and in studies of the illusion of apparent rotational movement (Robins & Shepard, 1977; Shepard & Judd, 1976). The investigation of this similarity has recently been extended beyond the mental rotation paradigm (Podgorny & Shepard, 1978; Shepard, 1978; Shepard & Podgorny, 1978).

Perhaps the principal claim that Shepard and his colleagues have made on the basis of their mental rotation studies is that, in the course of comparing the shapes of two similar objects differing in orientation, an observer necessarily passes through a series of internal states that bear a one-to-one relation to the physical states that the object would pass through if it were physically rotated from one orientation to the other (Cooper & Shepard, 1973a, 1978; Shepard, 1975; Shepard & Podgorny, 1978). Their primary evidence for this view has been presented above. Thus, in rotating mentally an object from Orientation A to

Orientation C the internal representation of the object passes through a number of intermediate Orientations $B(1)$, $B(2)$, ..., $B(n)$ as if an actual object were rotating from Point A to Point C. Although it has not been claimed that the internal process is strictly continuous, it nevertheless appears to be an analog of the corresponding physical process.

Previous studies have not been able to shed any light on the question of the continuity of the internal process of mental rotation, although Shepard and Judd (1976) have produced the illusion of continuous rotation by presenting rapidly alternating end states. However, the actual physical speed of rotation required to produce this illusion for the three-dimensional line drawings used in the Shepard and Judd study was in excess of 1000 degrees per second, a rate far greater than the internal psychological rate of rotation obtained from subjects who are required to mentally manipulate similar figures [the rate obtained in the original Shepard and Metzler (1971) study was approximately 60 degrees per second]. Although the perceptual experience of continuous rotation is reported by observers engaged in a Shepard and Judd task, the phenomenon is probably more closely related to the phi effect (specifically, alpha movement; see Murch, 1973) than to the internal process of mental rotation reported by subjects engaged in the Shepard and Metzler task.

No previous studies have examined successive angles of

rotation of less than 20 degrees, and in most experiments the angular increment is either 45 or 60 degrees. In Experiment I angular increments of 3 degrees from zero to 30 degrees, as well as additional increments of 30 degrees up to 180 degrees, are used in a Shepard and Metzler (1971) task to obtain a more refined idea of the nature of the process of mental rotation. Such a procedure allows an examination of the claim that rotation from Orientation A directly to Orientation C is not possible. Thus, it may be that at small angular departures from zero degrees, mental rotation is not necessary to make discriminative judgements concerning the similarity of standard and comparison figures. Previous studies do not force the conclusion that the rotation of a rotated comparison figure must proceed all the way to the zero degree orientation of the standard. It seems likely that such rotation need proceed only to a point near the physical zero point, whereupon a template matching type of mechanism might signal the occurrence of a match or mismatch. It is the purpose of Experiment I to determine the extent to which this possibility is correct.

At the present time, based on previous research, all that can be predicted is that a threshold for mental rotation, if it exists, must be less than 20 degrees of physical rotation. Since no studies have used angles less than 20 degrees, nothing at all is known about the nature of the reaction time function for "same" decisions between zero and 20 degrees rotation. All investigators have assumed

that the function remains strictly linear in this range. However, it is possible that the linearity of the function breaks down in this range. This is simply a mathematical way of describing the existence of a threshold. If the notion of a threshold for mental rotation is correct, then it must be at some point in the zero to 20 degree range that the statistical linearity of the reaction time function breaks down. Perhaps the most interesting result would be the occurrence of a step function in this range. This would indicate not only the magnitude of the threshold but would also suggest that mental rotation is a noncontinuous process, at least at small angular orientations. Figure 1 shows the reaction time function as obtained by Shepard and Metzler (1971) for "same" figures in flat rotation as well as an idealized reaction time function depicting a threshold of approximately 15 degrees.

Experiment I also examines potential sex differences in the mental rotation task. In general, males seem to outperform females in cognitive tasks requiring spatial ability (e.g., Bouchard & McGee, 1978; Buffery & Gray, 1972; Maccoby & Jacklin, 1974). But evidence for sex differences in the mental rotation task has not been clear. Vandenberg (1975; Vandenberg & Kuse, 1978) has recently developed the Mental Rotations Test, a paper and pencil version of the Shepard and Metzler (1971) task, on which males consistently outscore females (DeFries, Ashton, Johnson, Kuse, McClearn, Mi, Rashad, Vandenberg & Wilson, 1976; DeFries, Vandenberg,

Figure 1. Idealized Threshold for Mental Rotation.

An idealized threshold of 15° extent is depicted superimposed on the reaction time function for "same" figures in "flat" rotation obtained by Shepard and Metzler (1971).

McClearn, Kuse, Wilson, Ashton & Johnson, 1974; Vandenberg & Kuse, 1978; Wilson, DeFries, McClearn, Vandenberg, Johnson & Rashad, 1975; Yen, 1975). Using the same test, however, McGee (1978b) found only partial support for sex differences. Evidence from actual mental rotation tasks has also been inconclusive. Using simple line figure, Petrusic, et al. (1978) found that males rotated at a faster rate than females, while Corballis, Nagourney, Shetzer and Stafanatos (1978), using a rather more complex line drawing, found no such parametric differences between males and females.

The reaction time function which describes the mental rotation task yields two parameters on which males and females may be compared: slope and intercept. These parameters are characteristic of all linear functions and may be estimated separately for males and females. The reciprocal of the slope, when it is expressed in seconds per degree, gives the rate of the rotation of the manipulated (comparison) figure in degrees per second. The intercept of the function gives the basic comparison time of the standard and comparison figures after rotation. These parameters may be estimated via a least squares regression analysis.

Spatial ability is not simple to define, but is usually considered to mean the ability to see relationships between shapes or objects or to visualize what a shape would look like if its orientation were changed (Maccoby & Jacklin, 1974; Williams, 1977). In this sense, slope, that is, the rate of mental rotation, is a more direct measure of spatial

ability than is intercept, which merely reflects the time to decide "same" or "different" after the rotation has been completed. Thus, if males and females differ in spatial ability, the parameter most likely to be affected is the slope of the reaction time function. It is also possible, though, that sex differences in the magnitude of the threshold for mental rotation may exist. If males have greater spatial abilities than females, then the template matching system which performs "same-different" comparisons may be more flexible for males than for females. Greater spatial ability may permit this mechanism to be more accommodating for disparities in angular orientations for male subjects.

In summary, then, Experiment I is designed to examine two hypotheses. First, it is expected that a threshold exists for mental rotation. Since no previous studies have used comparison figures with angular orientations of less than 20 degrees, the threshold, if it exists, must be smaller than 20 degrees. Since angles as great as 180 degrees will be used in the study, the threshold should be revealed as a small but significant second-order trend in the reaction time function. The second hypothesis to be tested in Experiment I concerns sex differences in spatial ability. The mental rotation task has not often been used for this purpose, although it appears to be an excellent means of assessing potential sex differences in cognitive spatial abilities, since the task seems not to be affected

by verbal abilities. If sex differences are exhibited in the mental rotation paradigm, the parameters most likely to be affected are the slope and threshold of the reaction time function. The literature on sex differences in cognitive spatial abilities suggests that males should be able to rotate figures at a faster rate than females, and also possibly exhibit a larger threshold for mental rotation than females.

CHAPTER 2

Method

Subjects

Subjects were seven male and nine female graduate students in psychology, and two male and two female upper division undergraduate psychology majors at the University of Rhode Island. Thus, 20 subjects were used in Experiment I, nine males and 11 females. Subjects ranged in age from 20 to 37 years old, with a mean age of 26.6 years (S.D. = 4.2) and a median age of 26.0 years. All subjects were right-handed except for one left-handed undergraduate male, one ambidextrous graduate male and one ambidextrous graduate female. In addition, five subjects were discarded for error rates in excess of 15% (range: 19-31%). These subjects were two graduate male, one graduate female, and two undergraduate female psychology students, all right-handed, with a mean age of 26.0 years (S.D. = 4.8). (One discarded subject admitted to a childhood diagnosis of dyslexia after about half of the experimental trials had been completed.) All subjects had normal, or corrected to normal vision. Complete subject data appear in Appendix A.

Materials

Stimulus materials were perspective line drawings of three-dimensional block figures similar to those used by Shepard and Metzler (1971) (see Figure 2). Figures were constructed using three-dimensional graph paper, oriented at angles of 0, 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 60, 90,

Figure 2. Stimulus Figures. Stimulus figures used in Experiment I are shown in Figure 2: (A) test figure of Orientation A; (B) test figure of Orientation B; (C) figure used in practice session (also used in isomeric orientations).

A

B

C

120, 150, and 180 degrees by using a protractor, and then affixed to a piece of heavy typing paper. Stimulus figures were then photographed and slides constructed by the Audio-Visual Department of the University of Rhode Island. A mini-experiment was run using the slides as "subjects" to determine the variation of the physical angle of orientation of each slide from the nominal value of the angular orientation. The results of this exercise are given in Appendix B. Slides for which the physical angle deviated from the nominal value by more than one degree for angles less than or equal to 30 degrees, or by more than three degrees for angles greater than 30 degrees, were reconstructed by the author.

Apparatus

Apparatus used in Experiment I were a Kodak Ektagraphic RA-960 Random Access slide projector with remote control unit, a GAF ESP 2000AV slide projector with Randax 20 random access remote control unit, a Lafayette Clock/Counter, Model #54417, with digital millisecond (msec) readout, a Standard Instrument Corporation Photo Head photocell, Model No. PC-503A-2, and a ERS Foringer Power Supply, Model No. PS-024.

Design

Design of the experiment was a $2 \times 2 \times 2 \times 16$ (sex $\times$ orientation $\times$ type of judgement $\times$ angle) factorial. All factors fit the fixed-effects (Winer, 1971) analysis of variance model and were within-groups factors except for

Sex, which was a between-groups factor. A complete specification of the experimental design is given in Table 1. Figures 3 and 4 show the possible combinations of the

Table 1

Design Specification for Experiment I

Sex	Type of Judgement	Orientation	Angular Orientation of Comparison Figure
Female	Same	A	0, 3, 6, 9, 12, 15, 18, 21, 24 27, 30, 60, 90, 120, 150, 180°
		B	"
	Different	A	"
		B	"
Male	Same	A	"
		B	"
	Different	A	"
		B	"

standard figure with the comparison figure (the zero degree orientation of the comparison figure is used for the purpose of illustration, although the comparison figure could take on any of 16 different angular orientations). Figure 3 shows the two combinations for which the subject response "same" was correct while Figure 4 shows the combinations for which the the response "different" was correct. Both standard and comparison figures could be presented with either a left-hand (Orientation A) or a right-hand

Figure 3. . "Same" Stimulus Figure Configurations. .

Shown are the two possible stimulus pairings for which the response "same" was correct.

STANDARD

COMPARISON

Figure 4. "Different" Stimulus Figure Configurations.

Shown are the two possible stimulus pairings for which the response "different" was correct.

STANDARD

COMPARISON

(Orientation B) orientation. Both standard figure orientations were paired with both orientations of the comparison figure for each of the 16 possible angular rotations of the comparison figure for a total of 64 trials.

Procedure

Subjects were recruited on a volunteer basis, except for three undergraduate subjects who were offered credit in an experimental psychology course, for an experiment in "pattern perception and pattern comparison". Although the use of volunteer subjects can sometimes produce bias in a psychological experiment, usually with respect to demand characteristics (Orne, 1962), such is probably not a problem in the present experiment. Reaction time experiments frequently depend on rapid responses from subjects, and volunteers are likely to be highly motivated in this respect.

After appearing for the experimental session, subjects were seated and shown a standard figure and a comparison figure of zero degree rotation. The experimenter explained that the subject's task was to decide whether standard and comparison figures represented the same or different shapes. It was emphasized that a "same" decision should be made when the comparison figure was a rotated version of the standard and that a "different" decision should be made when the comparison figure was a reflected (mirror-image) version of the standard figure. Examples of rotated and reflected pairs were given concurrently with these instructions. The

experimenter then explained that the simultaneous presentation of the standard and comparison figures would trigger a photocell which would initiate a reaction timer and that the subject should signal a decision by pressing a switch, located on the right-hand arm of the chair, forward for a "same" decision and backward for a "different" decision. An "S" and a "D" marked these positions on the arm of the chair. Switch closure stopped the reaction timer and lit a display light visible only to the experimenter signalling the type of decision made. The experimenter emphasized that the speed of the subject's discriminative judgement was being measured and that a decision should be made as quickly as possible without guessing. At this point the experimenter resolved any questions that remained and a series of 16 practice trials, using the stimulus figure in Figure 2C were run. Practice trials consisted of eight "same" and eight "different" stimulus pairs. Angular orientations of the comparison figure were 0, 15, 30, 60, 90, 120, 150, and 180 degrees. Angles 0, 30, 90, and 150 degrees were shown in Orientation A, while the remaining angles were shown in Orientation B. If a discriminative error was made during a practice trial, the experimenter left the figures projected on the wall, explained that there had been a mistake, and asked the subject to satisfy him- or herself as to the correct decision. Once the subject was satisfied the practice session was continued. After completion of the practice session the experimenter again

asked for questions. Experimenter then explained that a longer set of stimulus presentations was about to follow, and that the figure would be slightly different but of the same general nature as the practice stimulus (see Figures 2A and 2B). Furthermore, it was pointed out that feedback on discriminative judgements would no longer be given. Fast but accurate judgements were again emphasized, and the experimental session was begun. The experimental session consisted of 64 trials: on 32 trials the comparison figure was a rotated version of the standard, while on the remaining 32 trials the comparison figure was a reflected version of the standard figure. Each subject was run through the set of 64 trials once in order to minimize fatigue and keep the subject's total participation time in the experiment at less than 60 minutes. Order of presentation of both standard and comparison figures was randomized with the restrictions that 1) each of the 64 possible combinations of standard and comparison figure pairings occurred only once, and 2) that comparison figures of the same Orientation separated by nine degrees or less not appear on successive trials. Stimulus figures were projected on a blank white wall in a darkened room, with the standard figure always appearing to the left of the comparison figure. Subjects were seated 193 cm from the projection plane, and the total projected stimulus array subtended a visual angle of approximately 30 degrees. Presentation of the stimuli was controlled by the

experimenter. No warning or "Ready" signal was used as the advance of the slide carousels provided sufficient indication of the imminent onset of a trial. Stimulus presentation was initiated by the experimenter by removing an opaque black curtain from in front of the slide projectors. A pin hole made in all standard slides provided a small beam of illumination which triggered a photocell assembly. The photocell circuit initiated a reaction timer which could be stopped by the switch mounted on the arm of the subject's chair. Subject's response also caused one of two lights on the experimenter's control board to be lit, depending on which decision was made. After switch closure the experimenter replaced the curtain in front of the slide projectors, recorded the type of decision made and the reaction time, reset the timer, advanced the slide carousels for the next trial, and again removed the curtain, initiating the next trial. Intertrial interval was approximately 30 seconds. Trials on which subjects responded incorrectly were rerun at the end of the test session. Because of the speeded nature of the dependent variable, it was decided that reaction times in excess of 10,000 msec would also be counted as errors. Previous studies have indicated that the mean error rate for all subjects should be in the vicinity of 5 to 10%. It was therefore decided that data from individual subjects whose error rate exceeded 15% would be discarded from the analysis (see Subject paragraph).

CHAPTER 3

Results

Because of the necessity for speed of decision in a reaction time task, and because subjects were instructed to make their decisions as rapidly as possible without guessing, latencies for "same" responses which exceeded three standard deviations of the mean for any particular angle, based on the standard deviation for that angle, were omitted from the analysis. This resulted in the omission of 16 of 640 data points, with an average z score of 3.66. No subject had more than two of their 32 data points omitted and this never occurred at the same angle for any subject. Also, no more than two of the 40 data points at any particular angular orientation of the comparison figure were lost. Five data points were omitted for males and 11 for females. A complete specification of the data points omitted is given in Appendix C. Data points for "different" scores were not omitted because these scores do not enter into any meaningful analyses of the experimental hypotheses.

Mean reaction time for "same" judgements was 1723 msec (S.D. = 322) and for "different" judgements was 2554 msec (S.D. = 651). A $2 \times 2 \times 2 \times 16$ analysis of variance (ANOVA) was performed using the Bicmedical Statistical Package program BMDP2V (Dixon, 1977). The four-factor ANOVA results are given in Table 2. The difference in reaction time (831 msec) for Type of Judgement was statistically significant ($F = 37.15$, $df = 1, 18$, $p < .001$) but was not an impressively

large effect ($w^2 = .076$). Main effect for Orientation (A or B) was not significant ($F = 0.71$, $df = 1, 18$, $p > .05$). Main effect for Sex was also not significant ($F = 0.18$, $df = 1, 18$, $p > .05$). Main effect for Angle was significant, but is discussed in detail below.

Table 2

ANOVA Summary Table for Experiment I

Source	SS	df	MS	F	w^2
Sex (S)	2337360	1	2337360	0.18	--
Error	236735648	18	13151980		
Type of Judgement (T)	188240144	1	188240144	37.15**	.076
TS	779824	1	779824	0.15	--
Error	91202544	18	5066808		
Angle (A)	693436160	15	46229072	37.40**	.280
AS	12723200	15	848213	0.69	--
Error	333714432	270	1235979		
TA	31015168	15	2067677	2.00*	.013
TAS	13136128	15	875742	0.85	--
Error	279621376	270	1035635		
Orientation (O)	935104	1	935104	0.71	--
OS	6090320	1	6090320	4.61*	.002
Error	23777232	18	1320957		
TO	96668	1	96668	0.12	--
TOS	1148388	1	1148388	1.44	--
Error	14376404	18	798689		
AO	14152448	15	943496	0.93	--
AOS	9022976	15	601532	0.59	--
Error	273858816	270	1014292		
TAO	14416448	15	961096	1.12	--
TAOS	4146592	15	276439	0.32	--
Error	232041136	270	859412		

* $p < .05$ ** $p < .001$

The interaction of Type of Judgement and Angle was significant ($F = 2.00$, $df = 15, 270$, $p < .02$, $w^2 = .013$) but unimportant, reflecting only the difference in shape of the reaction time function for "same" and "different" figures. This result will only be mentioned here for, as pointed out above, only data from "same" decisions are relevant to the hypotheses of interest in Experiment I.

A significant ($F = 4.61$, $df = 1, 18$, $p < .05$) interaction for Sex by Orientation was obtained, reflecting a tendency for female, but not male, subjects to have shorter latencies for figures of Orientation B than for figures of Orientation A. The effect is not readily interpretable and, at any rate, was very small ($w^2 = .002$), probably representing a chance deviation. The remaining first order interactions, the second order interactions, and the third order interaction were all not significant.

Since the main effect for Orientation was not significant, subjects' latencies for "same" scores at each angle for Orientations A and B were averaged. If one of these data points had been eliminated for being out of range, then the remaining data point was used as the estimate of the subject's reaction time. Because the main effect for Sex was not significant, means and standard deviations for the "same" reaction times were calculated based on the data for all 20 subjects. These results appear in Table 3 and are plotted in Figure 5. A one-way repeated measures analysis of variance was computed using the

Figure 5. "Same" Reaction Time as a Function of Angular Orientation. Mean reaction time for "same" stimulus figures are depicted as a function of angular orientation. Means, in msec, are surrounded by standard error bars. The sloped regression line is based on non-threshold orientations-- 0° , 21° - 180° --and was fit by a least-squares procedure. The slope of this regression line is 13.76 msec deg^{-1} and the intercept is 1116 msec. The zero-slope regression line was fit by a least-squares procedure to threshold orientations-- 0° - 18° inclusive--and has an intercept of 1109 msec.

"canned" statistical program BMDP2V (Dixon, 1977). The main effect for Angle was significant ($F = 54.11$, $df = 15, 285$, $p < .001$) and large, accounting for 74% of the variance in the reaction time scores ($w^2 = .740$). Results for the one-way ANOVA on Angle appear in Table 4.

Table 3

Means, Standard Deviations (SD), and Standard Errors of the Mean (SEM) for "Same" Reaction Times (msec)

Angle	Mean	SD	SEM
0°	1029	297	66
3°	1139	320	72
6°	1102	250	56
9°	1043	293	66
12°	1133	360	80
15°	1117	347	78
18°	1201	512	114
21°	1248	402	90
24°	1399	500	112
27°	1376	406	91
30°	1712	675	151
60°	2173	595	153
90°	2440	746	167
120°	2845	973	218
150°	3086	969	217
180°	3519	917	205

Table 4

ANCOVA Summary Table for Angle

Source	SS	df	MS	F	w^2
Angle	203325216	15	13555014	54.11*	.740
Error	71398368	285	250521		

* $p < .001$

A Tukey test for post hoc means comparisons was

performed as a follow-up test for the significant main effect of Angle. The following results, which are summarized in Table 5, were obtained: zero to 15 degree angles significantly faster than 30 to 180 degree angles; zero to 27 degree angles significantly faster than 60 to 180 degree angles; zero to 30 degree angles significantly faster than 90 to 180 degree angles; zero to 60 degree angles significantly faster than 120 to 180 degree angles; zero to 90 degree angles significantly faster than the 150 and 180 degree angles; and zero to 120 degree angles significantly faster than the 180 degree angle (all differences significant at the .05 level). Thus, the following ranges or pairs of angles were not significantly different: zero to 27 degrees; 18 to 30 degrees; 30 and 60 degrees; 60 and 90 degrees; 90 and 120 degrees; 120 and 150 degrees; and 150 and 180 degrees. It is a little surprising that pairs of

Table 5

Tukey Test Results¹

0° 3 6 9 12 15 18 21 24 27 30 60 90 120 150 180°

¹Underlined ranges of angles do not differ significantly in reaction time ($p > .05$).

angles in the upper range (e.g., 60 and 90 degrees) were not significantly different from each other. This may be due to the nature of the Tukey test, which preserves a specified alpha-level error rate for the entire set of pairwise means comparisons. Thus, with 16 means, and 120 possible pairwise mean comparisons, the actual alpha level of any particular comparison is considerably less than .05.

Threshold Estimation

Unfortunately, there is no single statistical test that answers the questions, Is there a threshold? and, What is the magnitude of the threshold? While the plot of the data in Figure 5 appears compelling with respect to the notion of a threshold, statistical confirmation of the effect would be even more compelling. Moreover, while the existence of a threshold seems rather obvious from the graph, the estimation of the magnitude of the threshold by "eyeballing" might be rather arbitrary. Therefore, a series of statistical tests were conducted in order to obtain, by the consensus of converging results, evidence confirming the existence and estimating the magnitude of the threshold for mental rotation.

Is there a threshold for mental rotation? If a threshold exists, the data must exhibit significant, nonlinear trend. A trend analysis was therefore conducted using the BMDP2V computer program. Both the linear ($F = 792.60$, $df = 1, 285$, $p < .001$) and the quadratic (second order) ($F = 6.93$, $df = 1, 285$, $p < .01$) trend components

were significant. The linear trend accounted for 97.6% of the variation in reaction time for Angle, while the quadratic trend accounted for 0.9% of such variation (Winer, 1971). The linear correlation between angle and reaction time was 0.850; this correlation increased to 0.854 with the addition of the quadratic component. The proportion of total variance accounted for by the linear and quadratic trend components was 0.723 and 0.006, respectively. Higher order trend components were not significant ($F = 0.93$, $df = 13, 285$, $p > .05$). Trend analysis results are summarized in Table 6.

Table 6

Trend Analysis Results					
Source	SS	df	MS	F	η^2
Linear	198547216	1	198547216	792.60**	.723
Quadratic	1735228	1	1735228	6.93*	.006
Higher Orders	3042800	13	234100	0.93	--
Error	71398368	285	250521		
* $p < .01$ ** $p < .001$					

Estimation of threshold magnitude. Since all points which do not exceed threshold should lie on a line with zero slope, a series of linear regression analyses, using BMDP1R, were conducted in order to determine the magnitude of the threshold for mental rotation. A preliminary analysis using all data points from all subjects resulted in a best-fitting line with intercept at 1032 msec (S.E. = 698), and a slope

(regression coefficient) of 14.40 msec/degree (S.E. = 0.51), which was significantly different from zero ($t = 28.052$, $df = 622$, $p < .001$). Correlation of the data points to this line was 0.747, accounting for 55.8% of the variance in reaction time scores ($r^2 = .558$).

The initial regression analysis on suspected threshold angles was begun on the range of angles from zero to nine degrees. Data from successively larger angles were added to the analysis until the regression slope became significantly different from zero. A summary of these regression analyses appears in Table 7.

Table 7

Regression Summary for Group Data

Range of Angles	Intercept ¹	SE	Slope ²	SE	t	df	r
0-9°	1077	333	-0.45	7.95	-0.057	154	.004
0-12°	1068	342	2.60	5.82	0.448	192	.032
0-15°	1063	347	3.77	4.46	0.846	231	.055
0-18°	1050	395	6.33	3.99	1.586	271	.095
0-21°	1039	401	8.16	3.29	2.477*	311	.139
0, 21-180°	1116	823	13.76	0.72	19.242**	387	.699
0-180°	1032	698	14.40	0.51	28.052**	622	.747

Notes:

¹Intercept and its standard error are expressed in msec.

²Slope and its standard error are expressed in msec/degree.

* $p < .01$

** $p < .001$

The last analysis resulting in nonsignificant slope included angles from 0 to 18 degrees, and yielded an intercept of 1050 msec (S.E. = 395) and a slope of 6.33 msec deg⁻¹ (S.E. = 3.99). While this slope is not statistically

significant, it is nevertheless not exactly equal to zero. It is useful to fit a zero-slope line to the range of subthreshold angles in order to estimate the reaction time for these angles. For this purpose an iterative minimum sum of squares procedure was conducted on the angles from 0 to 18 degrees. The result was a reaction time value of 1109 msec for subthreshold angles. This value is depicted as the zero-slope reaction time function in Figure 5.

A final regression analysis was conducted on data points outside the threshold in order to estimate slope and intercept for rotated angles. Since the estimate of the magnitude of the threshold seems to indicate that it may extend to 18 degrees, this last regression analysis was conducted after elimination of data points from 3 to 18 degrees, inclusive. Intercept was estimated as 1116 msec (S.E. = 823), and slope as 13.76 msec/degree (S.E. = 0.72), which was significantly different from zero slope ($t = 19.242$, $df = 387$, $p < .001$). The slope indicated that the rate of rotation for "same" figures was 72.7 degrees per second. The correlation between reaction time and angle was 0.699, accounting for 48.9% of the total variance. The best-fitting (least squares) regression line described by this analysis is the line fit to the data in Figure 5. The correlation of the average reaction time for all subjects at each of the ten non-threshold angles fit by this regression line was 0.988 ($df = 8$, $p < .001$), which accounted for 97.6% of the total variance in mean reaction time scores.

Sex Differences

Mean reaction time for "same" scores was 1732 msec for females (S.D. = 366) and 1710 msec for males (S.D. = 306). Males were also faster for "different" responses, with an average latency of 2479 msec (S.D. = 809) compared to 2615 msec for females (S.D. = 522). As previously reported, however, neither the main effect for Sex nor the Sex X Angle interaction was statistically significant.

A series of regression analyses were conducted separately on male and female data in order to estimate the magnitude of the threshold for mental rotation for each sex. The procedure used was the same as that employed in estimating the threshold for the group data described above. Successively larger angles were added to the analysis until the obtained regression slope became significantly greater than zero. Results are shown in Tables 8 (Females) and 9 (Males) and indicate a threshold of 18 degrees for females and 21 degrees for males.

Separate regression analyses, which are also summarized in Tables 8 and 9, were then conducted for non-threshold angles on males (0, 24 to 180°) and females (0, 21 to 180°). For females, intercept was 1083 msec (S.E. = 825) and slope was 14.66 msec/degree (S.E. = 1.02), which was significantly different from zero ($t = 14.333$, $df = 206$, $p < .001$). Correlation between angle and reaction time was 0.707, which accounted for 49.9% of the variance. For males, intercept was 1201 msec (S.E. = 853) while slope was 12.53 msec/degree

(S.E. = 1.09), which was significantly greater than zero slope ($t = 11.546$, $df = 161$, $p < .001$). Correlation between angle and reaction time for males was 0.673, accounting for 45.3% of the variance.

Table 8

Regression Summary for Females

Range of Angles	Intercept ¹	SE	Slope ²	SE	t	df	r
0-9°	1108	359	-9.01	11.69	-0.771	82	-.08
0-12°	1086	356	-1.77	8.34	-0.212	102	-.02
0-15°	1081	358	-0.77	6.30	-0.122	123	-.01
0-18°	1051	426	5.25	5.86	0.896	145	.074
0-21°	1026	435	9.33	4.87	1.917*	167	.147
0, 21-180°	1083	825	14.66	1.02	14.333**	206	.707

Notes:

¹Intercept and its standard error are expressed in msec.

²Slope and its standard error are expressed in msec/degree.

* $p < .05$

** $p < .001$

Slope estimates indicated a rotation rate of 68.2 degrees per second for females and 79.8 degrees per second for males. An analysis of covariance (ANCOVA) revealed that the difference in slopes was not significant ($F = 2.05$, $df = 1, 367$, $p > .05$) (Biomedical Computer Program BMDX82; Dixon, 1971). ANCOVA analysis also showed that the 118 msec advantage in intercept for females was not significant ($F = 0.19$, $df = 1, 368$, $p > .05$).

The correlation between reaction time and angle was also calculated separately for males and females based on latencies for all angles, including threshold angles. The

correlation for females was 0.750 ($df = 335$, $p < .001$) and for males was 0.747 ($df = 289$, $p < .001$).

Table 9

Regression Summary for Males

Range of Angles	Intercept ¹	SE	Slope ²	SE	t	df	r
0-9°	1041	301	9.62	10.58	0.909	70	.108
0-12°	1048	326	7.55	8.10	0.932	88	.099
0-15°	1042	334	8.97	6.27	1.430	106	.138
0-18°	1049	359	7.61	5.33	1.427	124	.127
0-21°	1054	359	6.79	4.35	1.560	142	.130
0-24°	1025	381	10.94	3.86	2.833*	160	.218
0, 24-180°	1201	853	12.53	1.09	11.546**	161	.673

Notes:

¹Intercept and its standard error are expressed in msec.

²Slope and its standard error are expressed in msec/degree.

* $p < .01$

** $p < .001$

Individual Data

Since only two data points were obtained from each subject at each angle, results based on individual data are subject to cautious interpretation due to the unreliable nature of the estimates. Particularly unreliable would be estimates of individual thresholds. More than two data points per angle would be necessary to provide stable estimates of the regression coefficients.

Average reaction time at each angle for each subject's "same" scores appears in Appendix D. Summary statistics for individuals appear in Tables 10 (Females) and 11 (Males). Included are means and standard deviations for "same" and "different" responses, as well as a brief summary of basic

regression parameters for each subject. Intercept and slope estimates were based on average reaction time for angles 0, 30, 60, 90, 120, 150, and 180°. These angles were chosen so as to maximize the chances of excluding an individual's threshold angles so that a reasonable estimate of the rate of mental rotation might be obtained for each subject.

Table 10

Individual Data Summary

Females

Subject	Reaction Time ¹				Intercept ²	Rate ³ of Rotation	r ⁴	Total Error Rate ⁵
	Same Mean	Same SD	Different Mean	Different SD				
1	1646	854	3198	1255	1129	78.5	.843*	.047
2	1675	1043	2388	907	1047	65.2	.813*	.047
3	1713	1220	2066	833	993	54.8	.864*	.094
7	1255	1045	1981	892	760	68.9	.808*	.031
8	2224	639	2872	861	2026	126.2	.859*	.000
10	1282	371	2886	615	913	155.1	.963***	.016
11	1941	1098	3011	1489	1388	64.2	.928**	.094
12	2454	1355	2725	1253	1612	47.8	.940**	.047
14	1807	1231	3418	1319	1026	52.1	.940**	.031
16	1483	614	1819	654	891	92.7	.910**	.047
20	1576	767	2401	950	1528	135.2	.595	.047

Notes:

¹Means and standard deviations for "same" and "different" reaction times are expressed in msec.

²Intercept is in msec.

³Rate is in degrees per second.

⁴The correlation r is between angle and average latency for the 0, 30, 60, 90, 120, 150, and 180° angles. With df = 5, the significance levels are:

* p < .05

** p < .01

*** p < .001.

⁵Total error rate is the combined error rate for both "same" and "different" figures and for both types of errors (see Appendix F).

Once estimates of the rate of rotation and the intercept for each subject had been obtained, the correlation of these two parameters was calculated. For all subjects combined this correlation was 0.276 ($df = 18$, $p > .05$), while for males it was 0.340 ($df = 7$, $p > .05$) and for females 0.221 ($df = 9$, $p > .05$), a difference which was not significant ($z = 0.239$, $p > .05$).

Table 11¹

Individual Data Summary

Males

Subject	Reaction Time				Intercept	Rate of Rotation	r	Total Error Rate
	Same Mean	SD	Different Mean	SD				
4	1421	1036	2153	831	469	57.0	.845*	.047
5	2088	1406	2663	1800	1481	53.4	.796*	.062
6	1397	807	2024	1192	1293	130.6	.537	.016
9	1871	1054	4140	2079	1478	70.8	.876**	.062
13	1708	657	1792	427	1633	159.4	.652	.031
15	1204	630	1450	464	987	116.5	.954***	.141
17	1751	689	2144	940	1252	92.1	.896**	.031
18	1995	1032	2978	888	1279	61.7	.878**	.047
19	1958	814	2970	1260	1488	98.1	.648	.047

Notes:

¹See Notes for Table 10.

Also included in Tables 10 and 11 is the correlation between "same" response latency and the 7 angles included in the regression analysis. The extent of the unreliability in the individual data can be seen by noting that this correlation failed to reach the .05 level of statistical significance for four of the 20 subjects (Subject #'s 6, 13,

19, and 20).

"Different" Response Data

Because data from "different" responses do not have any bearing on the hypotheses of Experiment I, the analysis of these data is not presented here. However, a complete analysis of "different" data may be found in Appendix E.

Error Analysis

Overall error rate for all subjects for both "same" and "different" responses was 0.049, very similar to the error rate of 0.032 obtained by Shepard and Metzler (1971). Error rate for "same" figures was 0.055 and for "different" figures was 0.044. Error rate for females was 0.046, while for males it was 0.054. These results are summarized in Table 12. Error rates for individual subjects, which ranged

Table 12

Error Rate Summary

"Same" Figures	.055
"Different" Figures	.044
Male Subjects	.054
Female Subjects	.046
Overall Error Rate	.049

from zero to 14.1%, appear in Tables 10 and 11. Appendix F contains a complete error summary for Experiment I.

CHAPTER 4

Discussion

Replication of Previous Results

With respect to the larger angles of rotation, Experiment I has essentially replicated the results of previous studies. The effect of the Angle manipulation for "same" responses was large, accounting for 74% of the variance in the reaction time scores, while the correlation between angle and the obtained average reaction time at each angle was extremely high ($r = 0.988$). While Shepard and Metzler (1971) do not report these statistics for their data, it seems from the plot of the means and standard errors of their data (Shepard & Metzler, 1971, Figure 2) that roughly similar estimates of w^2 and r would have been obtained had they been calculated. (My own calculation, based on their Figure 2, gives a correlation of 0.999 for the Shepard and Metzler mean reaction time data; unfortunately, it is not possible to estimate w^2 based on limited graphical information.)

Very similar estimates of intercept, the time taken to make a decision after rotation has been completed, were obtained in the two studies. Regression analysis on the larger angles of rotation in Experiment I revealed an intercept of 1116 msec, while an estimate derived from Shepard and Metzler's Figure 2 yielded an intercept estimate of 1167 msec. Furthermore, the obtained intercept is consistent with those obtained by other investigators using

similar stimulus figures (Gaylord & Marsh, 1975; Just & Carpenter, 1976).

Differing somewhat for the two studies were the obtained rates of mental rotation. Shepard and Metzler (1971) reported a rate of "approximately 60 degrees per second" (although their Figure 2 actually seems to indicate a rate of about 50 degrees per second), while Experiment I indicated a rate of about 73 degrees per second. It is not clear if this difference is significant. Unfortunately, most other mental rotation studies have used letters as stimuli, and only a few studies have used the three-dimensional figures used in both the present study and in the Shepard and Metzler study. Without a number of studies to refer to, it is hard to judge the significance of the obtained differences in rotation rate. Gaylord and Marsh (1975) obtained rotation rates of about 100 degrees per second for younger college students (ages 18-24) and about 60 degrees per second for older college students (ages 65-72). Metzler and Shepard (1974) reported a rate of approximately 50 degrees per second when distinctive "landmark" features were added to the ends of the stimulus figures, presumably as an aid to the comparison of standard and comparison figures. Just and Carpenter (1976) obtained rotation rates of about 35 degrees per second, although their subjects wore eye movement recording devices, which might account for the much slower rate found in their study.

The rate obtained in the present study seems to fall

within the range reported by other investigators using similar stimulus figures. Subjects in Experiment I received far less practice than did subjects in the Shepard and Metzler (1971) study and yet displayed faster rates of rotation. No systematic studies of the effect of practice on the parameters of the mental rotation task have been undertaken. In fact, Cooper has suggested that practice probably does not affect the rate of mental rotation at all (Cooper & Podgorny, 1976). Nevertheless, it might be worthwhile to conduct such a study, as some investigators have informally reported practice effects which tend to reduce slope and intercept while not changing the linear nature of the function (Cooper, 1975; Petrusic, et al., 1978), while others have observed no practice effects at all (Cooper & Shepard, 1973a).

Perhaps more important than considerations of practice is the fact that only two different stimulus figures were used in the present study, as compared to five used by Shepard and Metzler. It is plausible that the slower rate of rotation obtained by Shepard and Metzler might be due to some uncertainty as to which figure was about to be presented on any particular trial. This component of reaction time would be pre-rotational and therefore not distinguishable from the rate of rotation when analysed simply by a least squares procedure. By monitoring eye movements during a mental rotation task, Just and Carpenter (1976) were able to separate the transformational and

pre-rotational components of reaction time. The resulting transformational component indicated a rate of rotation of about 65 degrees per second. While Just and Carpenter used only three subjects, other aspects of their study render it very similar to the present one: they used only three stimulus figures, and their subjects received only minimal pre-test practice. It is important to note, however, that systematic studies of the effects of mental rotation of number of stimulus figures have also not been conducted. It is, therefore, only possible to speculate that fewer stimulus figures lead to faster estimates of rotation rate by minimizing pre-rotational processes, such as search for the salient aspects of a figure, or its distinctive end features.

In any event, the speed of rotation obtained in Experiment I is certainly more consistent with the rates cited above than with the rates found by investigators who used stimulus figures different from those used in the present study. Petrusic, et al., (1978) found a rotation rate of approximately 270 degrees per second using a simple, right-angled line drawing, while Hochberg and Gellman (1977), using a very similar figure, found a rate of about 300 degrees per second. Use of letters as stimuli produce even faster rates of mental rotation and, in general, it seems that more familiar stimuli can be rotated at greater speeds than less familiar ones. For example, Carpenter and Eisenberg (1978) found a rate of 450 degrees per second for

letter stimuli, while for similar stimuli Cooper and Shepard (1973a, 1976) reported rates in excess of 600 degrees per second.

A Threshold for Mental Rotation

The results of Experiment I have also extended the findings of previous studies. All previous studies have found significant linear increases in reaction time as a function of angle of rotation, generally with no significant second-order (quadratic) trends. However, no previous studies have examined angles of rotation of less than 20 degrees. The inclusion of these angles in Experiment I has produced a significant, though small, second-order trend in the reaction time data.

It is apparent, of course, that the linear component of the trend accounts for a very large proportion of the variance in these data, as a glance at Figure 5 readily shows. In fact, the linear trend accounts for 97.6% of the variation in reaction time due to the Angle manipulation and to 72.3% of the total variance in the reaction time scores. The second-order trend, on the other hand, while statistically significant, is quite a small effect, accounting for 0.9% of the variation in reaction time due to Angle, and only 0.6% of the total variance in reaction time scores.

It is important to emphasize, however, that the size of the second-order trend found in Experiment I should not mitigate its importance. Although it is true that small

effects can be made statistically significant simply by the inclusion of a sufficiently large number of observations (e.g., Nunnally, 1960), it is also the case that the judgement of the importance of an effect should be made by considering its practical significance. This is an issue that has been widely debated in the psychological literature, and in its extreme form has led to the complete eschewing of statistical analyses. [This point of view is most frequently found in the clinical and functional analysis of behavior literatures, where it is argued that statistical analysis would lead to the discovery of weak and unstable variables which might confound, complicate, and otherwise delay the development of the field (Baer, 1977).]

The smallness of the second-order trend is, of course, primarily due to the fact that the magnitude of the threshold itself is rather small. However, the result is also partly artifactual. The reason for this is that the reaction time function being analysed includes angles which extend far beyond the threshold itself. In fact, the range of angles examined in Experiment I is approximately one order of magnitude larger than the threshold. Under these circumstances the threshold could not possibly account for a very large proportion of the variance. If the range of angles examined in the present study had been restricted, for example, to 45 degrees instead of 180 degrees, the proportion of variance accounted for by the second-order trend would have undoubtedly been much more impressive.

Although the effect is small, there are both practical and theoretical reasons why the second-order trend should not be dismissed as a mere statistical artifact. In spite of the fact that the linear component of the trend accounts for an impressively large proportion of the reaction time variation, the regression line fit to the data actually does quite poorly as a predictor of reaction time for small angles. Figure 5 clearly shows that the predicted values of the angles from zero to 21 degrees are systematically greater than the observed values. The bias is for some angles quite substantial; for example, at 15 degrees the predicted reaction time is 1322 msec, 215 msec greater than the obtained value and an overestimation of nearly 20%.

More important than the predictive capability of the linear trend component are the theoretical considerations with which the second-order trend is associated. The second-order trend found in Experiment I is directly interpretable as a threshold for mental rotation, and although small, has important theoretical implications. Previous research suggests that mental rotation is an analog process wherein the internal representation of an object is rotated into standard form before a "same-different" discriminative judgement can be made. In the course of comparing the shapes of two similar objects differing in orientation, an observer passes through a series of internal states which bear a one-to-one relation to the corresponding physical states that the object would pass through in order

to achieve congruence.

The finding of a threshold for mental rotation suggests that the template matching mechanism which performs "same-different" comparisons is to some degree flexible. Thus, objects with subthreshold angular disparities are not rotated at all, but are immediately accommodated by the flexible template system. However, the converse proposition, that objects with supra-threshold angular disparities need be rotated only into the psychological zero region for a comparison to occur, is not supported by the data. The regression line for supra-threshold angular disparities indicates, as Figure 5 shows, that the rotation of the comparison figure continues all the way to zero degrees. The supra-threshold regression line does not intersect the subthreshold regression line near the 18 degree point, as would be expected if mental rotation were discontinued as soon as a rotated figure attained subthreshold disparity with respect to a standard figure; in fact, the intercepts of the supra-threshold (1116 msec) and the zero-slope subthreshold (1109 msec) regression lines are nearly identical, differing by only 7 msec.

Why should supra-threshold angles be rotated entirely back to the zero degree orientation of the standard? Such a strategy appears to be an inefficient use of processing capacity, especially for angular disparities which exceed threshold by only a few degrees. Yet this strategy was adopted by all but two subjects (and possibly for one other

subject as well, although the individual data for this subject was not unambiguous in this respect). The answer may lie in the limited amount of practice received by the subjects in this experiment. In performing the relatively novel task presented in the mental rotation paradigm, subjects may have adopted a cautious strategy. Thus, subjects may have rotated to zero degrees in order to maintain a high degree of accuracy in an unfamiliar task. Alteration of the speed-accuracy trade-off by instructing subjects to emphasize speed of response at the expense of accuracy should, by this reasoning, push the point of intersection of the regression lines for sub- and supra-threshold angles up to 18 degrees. The same effect should also be achieved by greatly increasing the number of practice trials. Recent work by Schneider and Shiffrin (1977; Shiffrin & Schneider, 1975, 1977) on controlled and automatic search processes seems to support these ideas. Nevertheless, research needs to be conducted to determine whether there may be another, more theoretically important reason for continuing to standard orientation rotation of comparison figures with supra-threshold angular orientations.

Magnitude of the Threshold

An "eyeball" analysis of Figure 5 suggests that the threshold for mental rotation for the stimuli used in Experiment I is at least 15 degrees. Above this point, data points begin to drift systematically towards the main

regression line. Inclusion of points beyond 15 degrees in the threshold therefore becomes a statistical question. A series of regression analyses were therefore conducted in order to determine when the slope of the regression line became significantly greater than zero. These analyses, which are summarized in Table 7, suggest a statistical threshold of 18 degrees.

With the inclusion of the data from the 21 degree angle, the slope of the regression line becomes significantly greater than zero. Even before this point, however, as an examination of both Figure 5 and Table 7 shows, an appreciable slope is exhibited by the regression line, albeit not a statistically significant slope. If the slope associated with the sub-threshold angles were no different from the slope exhibited by the supra-threshold angles, it might be legitimate to conclude that the non-significant slope of the smaller angles was due to unreliability in the dependent variable and not to the existence of a threshold. But the rate of rotation indicated by the slope for the angles from zero to 18 degrees is approximately 160 degrees per second, more than twice the rate of rotation obtained for the supra-threshold angles. In fact, this rate is greater than that obtained in any study using similar stimulus figures. Only two individual subjects exhibited similar rates of rotation (see Tables 10 and 11), and for one of these subjects (Subject #13) the slope, even at 180 degrees, was not statistically significant. The logic of

the regression approach to the estimation of threshold magnitude suggests that this subject's threshold is in excess of 180 degrees. Of course, such a large threshold is extremely unlikely for figures as complex as those used in this experiment. The RT's for this subject clearly increase from zero to 180 degrees (see Appendix D for individual reaction time data at each angle), but in such an erratic fashion that the standard error of the slope is greater than the slope itself. For this subject, then, data is unreliable to the extent that an estimate of the threshold for mental rotation would be misleading.

The case of Subject #13 illustrates the problem of the regression approach to the estimation of threshold magnitude: unreliable data may be confused with random variation about a regression line with zero slope. While this is a problem with respect to the interpretation of the individual data summarized in Tables 10 and 11, and therefore this data should be interpreted cautiously, it is probably not a problem with respect to the grouped data. There are several reasons for this point of view, the most important of which is that the threshold was predicted to occur in the vicinity of the point at which it was found.

Secondly, there is no particular reason why unreliable data should exhibit near-zero slope. In fact, unreliable data might exhibit any degree of slope; it is the standard error of the slope which indicates if the slope is significantly different from zero. If the standard error is

large enough, then even appreciable slope may not attain statistical significance. Table 7 lists the slopes and standard errors of several ranges of angles in the region of the threshold. While the standard errors are large in comparison to that obtained for the non-threshold angles, it is important to note that the slopes masked by these standard errors indicate rates of rotation much greater than obtained by other investigators using similar figures. If instead these slopes indicated a rate of rotation more similar to the rate found for supra-threshold angles then, as mentioned above, it would be legitimate to conclude that the data were merely unreliable, and not indicative of a threshold.

A third reason is that there is only a small increase in reaction time over the range of angles included in the threshold, and not the extreme variation that would be characteristic of unreliable data. Finally, the standard errors of the reaction times (see Table 3) for threshold angles are not consistent with an interpretation of unreliable data. In fact, these standard errors are only about one-half to one-third the value of the standard errors at larger angular orientations. In this sense, then, data from the threshold angles is probably more reliable than the data from the supra-threshold angles.

A more conservative estimate of threshold magnitude would be 15 degrees, a value probably more consistent with the "naked eye" appearance of Figure 5. At 15 degrees, the

obtained slope would indicate a rate of rotation of approximately 265 degrees per second, a rate much greater than displayed by any individual subject. This rate is also much greater than that obtained in other studies using the Shepard and Metzler (1971) figures and is, in fact, more consistent with the rates obtained with the use of much less complex figures (e.g., Hochberg & Gellman, 1977; Petrusic, et al., 1978).

In any event, it seems that there exists for the three-dimensional line figures used in the present study a threshold for mental rotation of 15 to 18 degrees.

An alternative interpretation of the data is possible, however, in which small angles are rotated at an extremely rapid rate. The idea of differential rates of rotation which depend upon the initial extent of the angular orientation of a figure seems less parsimonious, though, than the relatively simple concept of a threshold. Such a point of view would require the postulation of a mechanism which accelerates rotation as the internal representation of an object approaches standard orientation. There is no clear a priori reason why this should occur.

At the present time, the mental rotation process can be described adequately by two mechanisms: one which rotates the internal representation into standard form and a second, the template-matching system, that then makes a "same-different" judgement. The threshold concept of mental rotation requires a modification of this model with respect

to the template-matching system, which becomes flexible to the extent that small angular departures from standard orientation can be accommodated without rotation. This mechanism is completely described simply by a specification of the size of the threshold.

The acceleration hypothesis, however, requires a modification of the rotational process so that the rotation rate accelerates as the internal representation of an object approaches standard orientation. This hypothesis requires a specification of the rate of acceleration of the rotation process. As with all accelerations, this rate would have to be expressed as an inverse exponential function, for example, in degrees per second per second. While such a specification would not be difficult, it is clear that acceleration is a more complex concept than the much simpler concept of a threshold.

Of course, within the bounds of experimental error in the present experiment, it is not possible to rule out the possibility of extremely rapid rotation rates for "threshold" angles. In fact, by the methods used in Experiment I, it is probably not possible to distinguish between these alternative hypotheses, for such methods will always contain some degree of measurement error. In fact, both processes may occur, interrelated in some complex fashion, or even separately on different trials. Nevertheless, it is probably safer to adopt, at the present time, the theoretically less cumbersome and more meaningful

concept of a threshold for mental rotation.

Sex Differences

The results of Experiment I have, for the most part, not supported the hypothesis of sex-related differences on the mental rotation task. Although there was a tendency for males to respond faster on both "same" (by 22 msec) and "different" (by 136 msec) trials, neither difference approached statistical significance. Intercept was faster for females than for males (by 118 msec) although, again, the difference was not significant.

The variables of primary interest with respect to the hypothesis of sex differences are the rate of rotation and the size of the threshold. It is these variables which should exhibit sex-related differences if, indeed, there are male-female differences in cognitive spatial ability. In Experiment I, males were found to rotate the stimulus figures at a rate of nearly 80 degrees per second. For females this rate was about 68 degrees per second, about 12 degrees per second slower than for males. While this difference appears large proportionately--males rotate nearly 20% faster than females--the difference is actually not statistically significant.

Tables 10 and 11 show that a wide range of individual differences in the rate at which the stimulus figures were rotated was found, with considerable overlap in the distribution of the rates between males and females. Rotation rates for females ranged from 47.8 to 155.1 degrees

per second (see Table 10), while for males the range was from 53.4 to 159.4 degrees per second (see Table 11). Data for individual subjects is not often given in mental rotation studies but is available in a few instances. In the original Shepard and Metzler (1971) study, which used stimulus figures essentially identical to those used in Experiment I, the range of rotation rates obtained was from 40 to 75 degrees per second (Metzler & Shepard, 1974; their Figure 4). In a subsequent experiment, again using the three-dimensional line drawings as stimulus figures, rotation rates ranged from 30 to 70 degrees (Metzler & Shepard, 1974; their Figure 12). These ranges are smaller than found in Experiment I; in neither case, however, was the sex of subjects reported.

Petrusic, et al. (1978) also reported individual rates of rotation, although they used much simpler stimulus figures than were used in the present study. They found that individual subjects varied considerably in ability to rotate, with rates ranging from 89 to 481 degrees per second. Unlike the present study, however, Petrusic found substantial sex differences in the speed of mental rotation. Rotation rate for females was 128 degrees per second, but for males was 227 degrees per second. They also found no significant intercept difference between males and females (males faster by 190 msec), but the slopes diverged considerably for the two groups of subjects, giving a significant Sex by Angle interaction. This interaction was

not significant in the present study (see Table 2). The difference in rotation rate in the Petrusic study amounts to a 75% advantage in rotation speed for males over females, nearly four times that found in Experiment I.

How can we account for these conflicting findings? The basic difference between Experiment I and the Petrusic, et al. (1978) study is that different stimulus figures were used in the two studies, with more complex figures used in the present study. It might tentatively be suggested, then, that sex differences in rotation rate only appear with fairly simple stimulus figures. Consistent with this proposal is the finding by Corballis, Nagourney, Shetzer, and Stefanatos (1978) of no sex differences in rotation rate with a more complex figure than used in the Petrusic, et al. (1978) study.

This hypothesis is, however, opposite to what is expected based on the findings of greater spatial ability for males than for females reported by a number of researchers (Maccoby & Jacklin, 1974). Rotation rates for relatively simple figures should be less affected by individual differences in spatial ability than for more complex figures, which should be more easily accommodated by subjects with greater spatial ability. As stimulus complexity increases, subjects with less spatial ability should find it increasingly difficult to rotate figures, and thus should begin to lag behind their more gifted counterparts. Accordingly, greater disparities in rotation

rate for the sexes should be evident on complex figures, and not on simple figures. The opposite pattern seems to hold if the results of both the present experiment and the Petrusic, et al. (1978) study are taken as veridical.

While no difference between males and females for rotation rate was found, a small difference in threshold size was evident. Regression analyses revealed a threshold of 18 degrees for females and 21 degrees for males, apparently consistent with a view of greater spatial ability for males than for females. Thus, it seems that the flexible template-matching mechanism for males is more accommodating, i.e. more flexible, for males than for females, presumably because of the greater spatial ability possessed by males.

Since reliable estimates of individual thresholds were not obtainable in this study, a direct statistical test for the difference in threshold was not possible. However, there are at least two reasons why the difference may not be significant, a weak statistical reason and a strong functional reason. The statistical consideration lies in the overall ANOVA results (see Table 2). A difference in threshold between males and females means, essentially, that the shape of the reaction time function over levels of Angle should differ for the two sexes. Thus, a significant Sex by Angle interaction should have been obtained. As we have already seen, this interaction was not significant. This argument is not strong, however; when the number of levels

of a factor are fairly high, small discrepancies in the shape of two functions may be masked in the overall interaction test (Winer, 1971). The 3 degree difference in threshold amounts to less than 2% of the range of angles covered in the present study. The problem is roughly analogous to that of detecting a threshold of only three degrees in Experiment I: with 16 levels of Angle it is doubtful that a trend analysis would have revealed a departure from linearity of only 3 degrees. Similarly, a small but reliable threshold difference may exist between the two groups even though the Sex by Angle interaction is not significant.

Whether the 3 degree difference in thresholds is statistically significant or not is secondary to the consideration of the practical or functional significance of such a difference. The literature on sex differences in spatial ability does not, unfortunately, allow a precise prediction as to the size of a threshold difference between the sexes, only that we should expect to find such a difference. Nevertheless, most observers would probably agree that a larger threshold advantage for males than obtained would be more consistent with the results of other spatial ability studies showing a clear superiority for males (Maccoby & Jacklin, 1974). A difference in thresholds an order of magnitude larger than actually found would not have been especially surprising. With respect to the sex differences literature, the obtained 3 degree threshold

difference is tantamount to no difference at all. Even if the difference is reliable, it is not clear that a functional advantage in the ability to spatially manipulate internal representations is thereby conferred to males. Findings of individual differences in the speed of mental rotation, both in the present experiment and in others (Petrusic, et al., 1978), as well as such differences found in other perceptual tasks (Cooper, 1976b), suggest that appropriately designed research will find such differences in the size of the threshold for mental rotation as well. Whether such differences will be sex-related, as Petrusic's results suggest they might be, is a question only such research can answer.

It is hard to reconcile the findings of Experiment I with the main body of literature on sex differences in spatial ability. Males and females did not differ significantly in the speed with which they rotated internal representations and, while a 3 degree difference in threshold magnitude was obtained, it is likely that the difference is so small as to be functionally negligible.

Besides stimulus considerations, another potential source of the negative sex differences finding may be due to a selection bias in subject sampling. Female subjects were highly educated and for this reason may have been more adept at spatial tasks than female subjects typically included in spatial abilities studies. Although there is evidence that training per se does not increase spatial abilities for

females (McGee, 1978a, 1979), recent studies have also indicated that experiential factors may be important in the development of spatial skills (Nash, 1975; Sherman, 1978).

Selection bias may also have operated on male subjects included in the study. Although also highly educated, it seems at least possible that males who select careers in psychology possess less spatial ability than males in general. Thus, selection bias may have operated in opposite directions to minimize sex differences in the present study, although it must be admitted that these speculations are post hoc.

Coltheart has suggested that the occasional failure to find clear or consistent sex differences in visuospatial tasks may be the result of "impurities" in the task, that is, due to the verbal components of a spatial task or to the spatial components of a primarily verbal task (Coltheart, Hull, & Slater, 1975). However, it seems unlikely that the mental rotation task is "contaminated" by verbal components. Only one subject, a female (Subject #10), claimed not to use visual imagery in performing the mental rotation task. Yet this subject's data are among the most reliable of any subject, and her rate of rotation among the fastest (see Table 10). This subject may actually have used visual imagery, her introspective claims to the contrary, rather than some propositional scheme, for it is difficult to see how a verbal approach to what appears to be an entirely visual-spatial task could produce such fast and reliable

responding. At any rate, data recently collected by Jorm (1979) indicate that even the purely visual and verbal tasks used by Coltheart, et al. (1975) in obtaining sex differences in imagery and reading occasionally produce findings of no sex differences.

It is tempting to conclude that differences in the cognitive spatial abilities of males and females simply do not exist, at least not for the highly educated observers used in Experiment I. In view of the extensive literature on such sex differences, however, it may be premature to advance such a hypothesis, even limited to the mental rotation paradigm. Not enough evidence has yet been collected for firm conclusions to be drawn concerning the relationship between sex and the parameters of the mental rotation task.

PART II

THE PERCEPTION OF ANGULAR DISPARITY

CHAPTER 5

Introduction

Experiment I has demonstrated the existence of a threshold for mental rotation of about 18 degrees. From this result it was inferred that the template-matching mechanism which performs "same-different" comparisons is flexible to the extent that angular disparities between standard and comparison figures of less than 18 degrees need not be rotated. Thus, subthreshold disparities are immediately accommodated by the flexible template system. The existence of a threshold implies that angular disparities of 0 to 18 degrees are psychologically equivalent to the standard orientation, that is, a physical angular disparity of zero degrees.

The question that immediately arises concerns the extent to which the psychological zero region is dependent upon a sensory threshold (putting aside, for the moment, consideration of the statistical nature of sensory thresholds; cf. Swets, 1961). Thus, it may be that a threshold of 18 degrees was obtained, not because the template-matching mechanism is flexible to that degree, but because an angular disparity of 18 degrees between two similar figures is simply not detectable by observers.

At first, such a proposition appears extremely unlikely. It is well known, for example, that human visual acuity is

exceedingly fine, with a limit under ideal seeing conditions of 0.5 sec of arc (Hecht & Mintz, 1939). For the normal eye, the minimum visual angle that can be discriminated is usually specified as 1 min of arc, although the precise value is dependent upon a number of variables related to both the type of test used to determine the observer's sensitivity and the viewing conditions under which the test is conducted (Corso, 1967; Riggs, 1971).

But visual acuity, as usually defined, refers to an observer's ability either to detect the presence of a single line or to resolve the separation between two lines. In this sense, visual acuity may have little to do with the perception of angular disparity: an observer presented with two lines differing in orientation by only one minute of arc would be hard pressed indeed to detect the difference! Furthermore, visual acuity is known to depend on the orientation of the test object (Fmsley, 1925; Leibowitz, 1953), a phenomenon generally known as the oblique effect: both humans and animals show a sometimes marked superiority in performing a variety of visual discriminations when stimuli are horizontal or vertical rather than oblique (Appelle, 1972; Boltz, Harwerth, & Smith, 1979).

Data on the discrimination of angular disparity may be gleaned from several lines of research. One such line comes from the literature on figural aftereffects (Deutsch, 1964; Ganz, 1966a, 1966b; Graham, 1951; Hochberg, 1971a, 1971b; Woodworth & Schlosberg, 1954). This research originated

with Gibson's (1933; see also Eales & Follanshee, 1935) incidental discovery that curved lines, after steady inspection, appear to lose their curvature. It was subsequently noticed that tilted lines also appear to lose their tilt (Gibson, 1937a; Gibson & Radner, 1937; Vernon, 1934). Gibson (1937a, 1937b) attempted to explain the effect as one of "normalization", an adaptation process similar to that found in brightness and color vision. Kohler and Wallach (1944) alternatively proposed that inspection of any line created an area of "satiation" in the visual cortex from which the boundaries of a subsequently presented line appeared to be displaced. A vigorous debate followed most recently contributed to by Coltheart (1971), who explained the effects in terms of the adaptation of orientation-specific units in the visual system.

At any rate, many of the studies designed to decide between the normalization and satiation hypotheses used the method of parallel alignment to secure data. In this task observers are usually required to rotate a comparison or test line until it appears parallel to a similar standard or inspection line. There are many variations of the method but in general the task may be considered in terms of angular disparity; thus, observers err on the task to the extent that angular disparity in orientation between the standard line and the comparison line is to some degree not apparent.

One study which used the parallel alignment technique

was reported in a monograph by Kohler and Wallach (1944), who provided observers with an inspection line and required them to rotate a test line until parallel with the inspection line. Average deviation of the test line from the orientation of the inspection line depended on the angular inclination of the inspection line (the oblique effect). Average deviation was $1^{\circ} 21'$ for horizontal and vertical inspection line orientations and $2^{\circ} 44'$ for oblique orientations.

Prentice and Beardslee (1950) also used the parallelism method, although in their variation subjects were not allowed to rotate the test line. Instead, the method of constant stimuli was used: subjects were asked to judge whether a test line was more or less tilted than an inspection line. In three separate experiments an inspection line was oriented 10 degrees from horizontal or vertical. Average constant error for the three experiments was $2^{\circ} 1'$, 2° , and $2^{\circ} 8'$. In a subsequent experiment the inspection line was vertical and average constant error was much lower, only 16 min of arc.

Heinemann and Marill (1954) replicated the Prentice and Beardslee (1950) experiments and found essentially similar results. Three different experiments produced average constant errors of $1^{\circ} 57'$, $1^{\circ} 36'$, and 29 min of arc. In a later study, Morant and Harris (1965) required subjects to inspect isolated lines of various tilts and then rotate these lines until parallel to a vertical standard. Average

deviation depended, not surprisingly, on the tilt of the inspected line, ranging from 6 to 60 min of arc and averaging 31 min of arc.

A second line of research from which we may infer the extent to which angular disparity between lines is not visible to observers--research on the perception of angles--has a long and controversial history, constituting some of the earliest research conducted under the heading of experimental psychology. Early studies on illusions conducted by Wundt, Helmholtz, Hering, and Fechner seemed to indicate that observers must overestimate acute angles and underestimate obtuse angles. This pattern was for several decades considered "common sense" but was successfully challenged by Jastrow (1892), initiating a debate which has not yet been resolved (Beery, 1968; Bouma & Andriessen, 1968; Emerson, Wenderoth, Curthcys, & Emonds, 1975; Fisher, 1969, 1971; Lennie, 1971). The aim of such research has been towards explanations of illusions which seem to depend, at least in part, on the presence of tilted lines, such as the Poggendorff (Green & Holye, 1964; Leibowitz & Toffey, 1966), Zollner (Judd & Courten, 1905; Wallace, 1964), Hering and Wundt (Crassini & Over, 1978) illusions.

Several different methodological techniques have been used to study angle perception, which might account for the conflicting findings (Emerson, et al., 1975). Two of these techniques--absolute estimation and dot alignment--are not directly relevant to the perception of angular disparity and

need not concern us further. However, the parallel alignment and angle matching methods are relevant, although the latter technique loses its applicability under certain circumstances (as in the reproduction variation, where an angle is matched from memory).

Perhaps the earliest psychophysical study of acuity for tilt was that conducted by Jastrow (1892), who required subjects to rotate a disk on which a line was drawn so that the orientation of the line matched that of another line on a similar disk. Orientation of the standard line was varied in 10 degree increments from 10 to 180 degrees from an imaginary horizontal line. Jastrow found for the setting of the comparison line an average deviation from standard orientation of $1^{\circ} 33'$, suggesting that an angular disparity in orientation for line stimuli of about one and a half degrees was not visible to his subjects. Jastrow also used the angle matching technique, finding an average deviation of $1^{\circ} 50'$.

Rochlin (1955) used a parallelism task very similar to that used by Jastrow. Rochlin, however, reported a much lower average error--about 17 min of arc (0.3°)--perhaps due to the proximity of standard and test lines in his study. Using the angle matching method Maclean and Stacey (1971) found average deviations of $3^{\circ} 38'$ and $4^{\circ} 53'$, depending on the presence or absence of horizontal and vertical line cues.

Research on angle misperception has recently been

stimulated by the discovery of "orientation detectors" in both animal (Hubel & Wiesel, 1959, 1962) and human (Andrews, 1965, 1967a, 1967b; Cambell & Kulikowski, 1966) visual systems. Blakemore, Carpenter, and Georgeson (1970) used a variation of the parallel alignment technique to demonstrate lateral inhibition between orientation detectors: a comparison line was manipulated by subjects until it appeared parallel to the base line of an angle which could be varied in size. Maximum average error of $1^{\circ} 59'$ occurred when angle size was 10 degrees; overall average error was 46 min of arc. This result indicates that two lines of different orientation interact with each other so that they seem to be displaced from one another in orientation, perhaps through mutual inhibition between neighboring columns in the visual cortex.

When the size of the "angle" was either 0 or 180 degrees, subjects' task was reduced, essentially, to the more usual parallel alignment technique used by most investigators. Under these circumstances average error was only 17 min of arc, identical to the value obtained by Rochlin (1955). The greater sensitivity of subjects to angular disparity in the Blakemore, et al. (1970) study as compared to the performance of subjects in other studies may be due, as in the Rochlin (1955) study, to the proximity of the comparison line and the base line, which never exceeded two degrees of visual angle.

A recent study conducted by Martin and Drivas (1979)

broke from the traditional methods and used a signal detection paradigm to investigate acuity for orientation. Observers viewed a standard line tilted at any of several angles from 0 to 90 degrees in 15-degree increments. A comparison line was then presented and observers were required to decide whether the comparison line was more or less tilted than the standard. Because of their method of data collection, average constant errors are not reported for the Martin and Drivas subjects. While they deny finding any evidence for a threshold, Martin and Drivas nevertheless present some data suggestive of such a threshold. This evidence takes two forms: 1) the slope of the psychometric function; and 2) the isodiscriminability curves, especially when the discriminability index (d') equaled zero.

The psychometric function is a plot of d' as a function of the separation between standard and comparison lines. The intercept of this function indicates the size of the threshold. For one subject average intercept was $1^{\circ} 49'$, while for the other subject average intercept was less than the smallest separation used in the experiment, which was 30 min of arc. Thus, the psychometric functions indicate thresholds of $1^{\circ} 49'$ for one subject and less than 30 min of arc for the second subject.

An isodiscriminability curve is a plot of integral values of d' as a function of standard line orientation. Since d' is a measure of observer sensitivity (Swets, Tanner, & Birdsall, 1961), a d' of zero indicates zero

sensitivity, which may be construed as a threshold (but see Swets, 1961). For the first subject average value of the isodiscriminability curve for $d'=0$ was $1^{\circ} 16'$, while for the second subject this average value was only 38 min of arc. The two methods of determining thresholds for the Martin and Drivas (1979) subjects agree tolerably well.

Overall, the reported values in a series of studies of the angular disparity between lines which cannot be discriminated by observers varies greatly, from 16 min of arc to nearly five degrees, although most estimates seem to fall in the vicinity of one and a half to two degrees. It is clear then that even the largest estimate is much smaller than the threshold for mental rotation obtained in Experiment I. Yet there are several reasons why it might be pertinent to pursue the matter further.

First, every study cited above, and apparently every study which has been conducted on angle perception and tilt aftereffects, has used simple line stimuli. It is by no means obvious that the degree of angular disparity not visible to observers for simple line stimuli will generalize to more complex figures, such as the three-dimensional block figures used in Experiment I. The tilt aftereffect has been demonstrated using line stimuli tilted in the third dimension, a phenomenon sometimes referred to as the median-plane tilt aftereffect (Bergman & Gibson, 1959; Kohler & Emery, 1947; Wenderoth, Redger, & Curthoys, 1968). This aftereffect has been explained in terms of feature

analyzers and orientation-specific cells in the visual system in a manner analogous to that usually offered for the corresponding two-dimensional tilt aftereffect (Coltheart, 1971). While this three-dimensional tilt aftereffect has also only been studied with simple line stimuli, there is evidence that the three-dimensional aftereffect may be larger than the two-dimensional one (Kohler & Emery, 1947).

A second, and perhaps more important reason is that the complex three-dimensional figures used in Experiment I consist of many line segments arranged at several different angular orientations. These stimuli are large, extending over many degrees of visual angle, whereas most studies cited above have used only two or three line segments easily incorporated into a much smaller field of view. This, plus the fact that the nature of the mental rotation task itself requires many successive eye fixations before a "same-different" judgement can be reached (Just & Carpenter, 1976) suggests that an angular disparity greater than one or two degrees for these figures might easily escape an observer's scrutiny.

Whether this disparity will be so large as to entirely account for the 18-degree threshold for mental rotation is the question Experiment II is designed to answer. Although it seems very unlikely that a sensory threshold of 18 degrees will be found, the results of Experiment II should prove interesting in their own right as an extension of the research on acuity for angular orientation using lines as

stimulus figures. While such studies have taught us much it is important to realize that isolated line segments rarely occur in the "real world". The environment is composed primarily of objects extended in three-dimensional space. As Neisser (1976) has recently pointed out, cognitive psychology must investigate the real world if it wishes to become a relevant science. While the stimulus figures used in Experiments I and II are merely schematic representations of three-dimensional forms, the use of such figures constitutes a step in the right direction.

The purpose of Experiment II, then, is to determine the extent to which angular disparity between two stimulus figures such as used in Experiment I is not visible to observers. A number of traditional methods could have been employed for this purpose but were rejected for various reasons. Absolute judgement methods, in which observers make verbal reports about perceived orientation, have been used by some investigators (Fisher, 1969, 1974; Jastrow, 1892), but in general such techniques are coarse and unreliable. The more usual psychophysical methods have produced conflicting results, as noted previously, and have been criticized in several recent papers (Emerson, et al., 1975; Fisher, 1973; Wenderoth, Beh, & White, 1978). In a direct comparison of two commonly used psychophysical methods Emerson, et al. (1975) found completely opposite results, and concluded that at least one of the techniques could not measure perceived tilt.

Because none of the traditional methods seemed satisfactory, it was decided to explicit a relatively new technique, as Matin and Drivas (1979) had done with the introduction of the signal detection method to the study of perceived orientation. Functional measurement analysis was developed by Anderson (1962a, 1962b, 1970b, 1974, 1977, 1979) for the study of information integration, a basic problem in the study of perception. The essential idea of the functional measurement approach lies in the stimulus integration function that describes the synthesis of separate stimulus components into a unitary perception or judgement. In Experiment II, the orientations of two Shepard and Metzler (1971) figures were integrated by observers into a single impression or judgement of total angular orientation.

The theoretical approach of functional measurement is based in both substantive theory and in measurement theory. The substantive aspect is concerned with problems of information integration; for example, are adding or averaging models more descriptive of information integration (Anderson, 1971, 1973; Hedges, 1973)? Extensive use is made of algebraic models to represent integration processes, and a number of such processes have been successfully described, including subjective time duration (Blankenship & Anderson, 1976), impression formation (Anderson, 1962a, 1965, 1967), weight judgement (Anderson, 1970a, 1972; Anderson & Jacobson, 1968), judgement of social class (Himmelfarb &

Senn, 1969), nonverbal communication (Mehrabian & Ferris, 1967), clinical judgement (Hoffman, Slovic, & Rorer, 1968), greyness averaging (Weiss, 1972), loudness judgements (Marks, 1979), and judgement of angle size (Weiss & Anderson, 1972).

The measurement aspect of the approach is derived from the substantive aspect and provides the scales required for the algebraic models. The aim of scaling is to relate a physical dimension or stimulus characteristic to its underlying psychological dimension or response characteristic (Engen, 1971; Guilford, 1954), that is, to describe what Stevens (1974) has termed input-output functions. The functional measurement approach to scaling is to consider the question of measurement as integrally and intimately related to the development of substantive theory. Thus, Anderson considers the problem of scaling as inseparably bound to substantive theory, with the final validation of the scale dependent on the establishment of the empirical validity of the theory. This empirical approach to measurement is of general importance since it is not based on the more popular formal approach to measurement, such as espoused by Stevens (1957, 1974), and should be of increasing interest to experimental psychologists (e.g., Jones, 1974; Zinnes, 1969). The scaling aspect of functional measurement is critical in Experiment II for revealing the extent to which angular disparities between varicously oriented figures are not

apparent to observers.

Technically, there are three main features of functional measurement: 1) reliance on factorial designs; 2) quantitative response measures; and 3) a monotone rescaling procedure (Anderson, 1970b). The monotone rescaling aspect is sometimes necessary to show that the ordinal scale of the subject's overt response is in fact an interval scale. Monotone rescaling is also useful in removing response nonlinearity from the data. Neither application will be useful in Experiment II, as all data analysis will be conducted on the untransformed, raw data. Therefore, the monotone rescaling feature of functional measurement analysis need not concern us further. However, factorial design and quantitative response measures constitute the main features of Experiment II.

The observer's task in Experiment II was to judge the total of the angles of orientation of two sequentially presented Shepard and Metzler (1971) figures, such as were used in Experiment I. Angular orientation of each figure was varied parametrically, and each observer saw all possible combinations of angular orientations, so that a complete two-factor design was run on each observer. Observers rated their impression of combined angular orientation graphically, by making a mark along an unnumbered line. Although tedious to score, the graphical rating method was chosen in preference to the more commonly used rating scale method because of certain advantages in

the use of the graphical technique. For example, the graphical method avoids observer number preferences as well as memory effects (Andersson, 1970b, 1974).

The simplest assumption to make about the observer's subjective impression of total orientation is that it follows a simple weighted-sum (additive) model of the form:

$$R(ij) = w(1)s(i) + w(2)s(j).$$

Here R is the observer's response (in arbitrary numerical units), $s(i)$ and $s(j)$ are the observer's subjective impressions of the orientations of the first and second figures, respectively, and $w(1)$ and $w(2)$ are the weights that reflect the subjective importance or relative contributions of the first and second figures, respectively, to the total judgements.

This simple linear model is easily tested by the analysis of variance. Because of the additive form of the model, the interaction of the two main effects (angular orientations of first and second figures) should be nonsignificant if the model is correct (Andersson, 1970b, 1974). A simple proof of this assertion is given in Appendix G. Thus, the interaction term of the analysis of variance provides a test of the goodness-of-fit of the data to the additive model.

In applying the analysis of variance to the functional measurement paradigm, two further assumptions are made (Anderson, 1970b). First, it is assumed that there are no contextual effects; that is, the subjective value of a

stimulus is assumed to be independent of the subjective value of the stimulus with which it is paired on any particular trial. Second, it is assumed that the row and column weights, $w(1)$ and $w(2)$ respectively, are independent of row and column levels i and j , respectively.

If the model passes the test of fit, that is, if the interaction term is not significant, the model may be used to estimate the subjective values of the stimuli. The main effects of the analysis of variance test the assumption that observers are able to discriminate among the levels of orientation of the first and second stimulus figures. More precisely, the row and column marginal means give the scale values of the subjective impressions of the angular orientations of the first and second stimulus figures, respectively.

Ordinarily, the main effects tests are of little interest in functional measurement analysis, because the levels of the independent variables chosen are usually easily discriminable by observers. However, in the present case one or more levels of the independent variables may be subjectively equal to zero. If all levels of a factor were subjectively equal to zero, then the main effect for that factor would not be statistically significant. A more likely outcome might be that only the lowest levels of the independent variables are subjectively equal to zero, with higher levels having increasingly greater subjective values. In this case main effects would be statistically

significant, and a follow-up test such as the Tukey (Winer, 1971) could be used to determine which levels of the independent variables were subjectively equivalent to zero.

Finally, it is worth noting that Experiment II is similar to an experiment conducted by Weiss and Anderson (1972), with two major exceptions. In the Weiss and Anderson study, observers judged the average inclination of simple line stimuli; furthermore, angle of orientation, while varied over a large range, was never less than 15 degrees. In the present study, angle of orientation of the Shepard and Metzler (1971) figures was varied systematically in 6 degree increments, from 0 to 30 degrees, so that the data collected might reflect observers' perception of angular disparity for complex figures in the range of the threshold for mental rotation.

CHAPTER 6

Method

Subjects

A total of five subjects served as observers in Experiment II: two female psychology graduate students, and three upper division undergraduate psychology majors, two females and one male. All subjects were students at the University of Rhode Island, and none had taken part in Experiment I. Subjects ranged in age from 21 to 30 years, with a mean age of 24.2 years ($SD=3.5$) and a median age of 23.0 years. All subjects had normal, or corrected to normal vision. Subjects participated in the experiment at the request of the experimenter and received no compensation for so doing.

Materials

Stimuli were perspective line drawings of three-dimensional block figures oriented at angles of 0, 6, 12, 18, 24, and 30 degrees. The stimulus pattern used was the same as the practice figure used in Experiment I (see Figure 2C) with a left-hand orientation (Orientation A in Experiment I). Details of stimulus construction are given in the Materials paragraph of the Method section for Experiment I.

Apparatus

Apparatus used in Experiment II were a Kodak Ektagraphic RA-960 Random Access slide projector with remote control unit, a GAF ESP 2000AV slide projector with Randax 20 remote

control unit, and a Kodak Ektagraphic slide projector, Model No. AF-2.

Design

Design of Experiment II was a 4 X 6 X 4 (number of angular orientations for the first stimulus figure X number of angular orientations for the second stimulus figure X replications) factorial. All factors conformed to the fixed-effects (Winer, 1971) analysis of variance model and were within-group (repeated measures) factors. A complete specification of the experimental design is given in Table 13. The first stimulus figure could take on any of four

Table 13¹

Design Specification for Experiment II

Second Angle	0°	First Angle		
		6°	12°	18°
0°	0-0	6-0	12-0	18-0
6°	0-6	6-6	12-6	18-6
12°	0-12	6-12	12-12	18-12
18°	0-18	6-18	12-18	18-18
24°	0-24	6-24	12-24	18-24
30°	0-30	6-30	12-30	18-30

¹The experimental design includes four complete replications of the design given above for each of five subjects.

orientational values: 0, 6, 12, and 18 degrees; the second stimulus could assume any one of six possible orientations: 0, 6, 12, 18, 24, and 30 degrees. Each subject viewed all of the 24 possible stimulus combinations, and completed five replications of the design. The first replication was

considered a practice set and was not figured into the analysis.

Procedure

Subjects were asked to participate in an experiment designed to measure "how people see angular orientation". Subjects were seated in a dimly lit room 193 cm in front of a blank white wall, which served as the stimulus projection screen. The experimenter explained that two stimulus figures would be projected sequentially, and that the subject's task was to judge the total angle of orientation of the two figures by making a vertical pencil mark through a 10 cm horizontal line. Subjects were instructed to mark greater totals towards the right end, and lesser totals towards the left end of the unnumbered response lines. A zero was placed at the left end and a slash mark (/) at the right end of each response line as an aid to observers' responding.

To aid observer's judgement, special anchor stimuli were present throughout the experimental session. These consisted of stimulus figures of 0 and 30 degrees orientation continuously projected to the left and right, respectively, of center, where the sequentially presented test stimuli were projected. Thus, a maximum of three stimulus figures were projected at any one time, subtending a total visual angle of approximately 40 degrees.

Anderson (1970b, 1974) has noted that the presence of anchor stimuli is a critical feature of the functional

measurement method. Such stimuli help set the frame of reference for the observer. Anchor stimuli also tie down the ends of the scale, and thus help eliminate floor and ceiling effects. Ordinarily, anchor stimuli are chosen so that both the smallest and largest stimulus pairs are present throughout the experimental session, but in the present case such a procedure was not practical. Therefore, only the single smallest and largest stimuli--the 0 and 30 degree figures--were used as anchors. However, the smallest and largest stimulus pairs were shown at the start of each replication. Subjects were told that the anchor stimuli represented the end points of the rating scale and were required to mark the ends of the rating scale accordingly, that is, at the extreme left end of the scale for the 0°-0° pair and at the extreme right end of the scale for the 18°-30° pair.

Each replication consisted of 26 trials: the 24 possible pairwise combinations of orientations of the first and second stimulus figures, plus the two anchor pairs. Each stimulus figure was projected for 5 seconds, separated by a 0.5 sec interval during which a dim red square was projected. After the second figure of each pair had been presented, subjects had 5 seconds to mark their impression of total orientation, whereupon the next trial began. Only the dim red square was projected between the anchor stimuli during this response period.

Each subject completed five replications of the design,

each of which lasted about 15 minutes. A two minute break was provided between replications, during which the experimenter collected the subject's completed response form and gave the subject a new response form. Each response form consisted of two pages, on which there was printed a total of 26 10 cm horizontal lines, enough for one replication (including lines to mark the anchor stimuli presentations at the beginning of each replication).

Before the start of each replication the experimenter encouraged the subject to make use of the entire length of the response line to mark impressions of total orientation. Furthermore, the experimenter stressed that objective accuracy was not required, but that subjects should only mark their subjective impressions.

The experimenter measured subjects' responses to the nearest mm from the left hand edge of the horizontal line. This measurement constituted the dependent variable in the experiment. The first replication was considered a practice session and was omitted from the analysis, as were subjects' responses to the anchor stimuli presentations at the beginning of each replication.

CHAPTER 7

Results

Group Data

A preliminary three-way repeated measures analysis of variance, using BMDP2V (Dixon, 1977), was performed on the rating data to insure that the Replications factor was not significant. These results appear in Table 14.

Table 14

ANCOVA for Rating Data

Source	SS	df	MS	F
First Angle (F)	50202	3	16734	45.13*
Error	4450	12	371	
Second Angle (S)	178086	5	35617	85.06*
Error	8375	20	419	
FS	2652	15	177	1.42
Error	7485	60	125	
Replications (R)	583	3	194	0.80
Error	2929	12	244	
FR	1118	9	124	1.03
Error	4340	36	121	
SR	879	15	59	0.57
Error	6205	60	103	
FSR	3310	45	74	0.84
Error	15747	180	87	

*p < .001

Since Replications was not significant ($F=0.80$, $df=3,12$, $p > .05$) and entered into no significant interactions, data was collapsed over the four levels of this factor. Table 15

below gives the mean ratings of total orientation in mm as a function of first and second stimulus figure orientations for the grouped data. Standard deviations are given in parentheses. Mean rated total orientation as a function of first and second figure orientations is plotted in Figure 6.

Table 15¹

Grouped Rating Data

Second Angle	First Angle			
	0°	6°	12°	18°
0°	3.4 (4.4)	12.5 (8.2)	24.3 (6.2)	32.2 (7.1)
6°	10.6 (7.0)	13.0 (12.1)	26.7 (12.6)	35.0 (11.9)
12°	28.0 (7.5)	30.5 (12.0)	35.2 (12.6)	53.2 (12.7)
18°	37.0 (9.8)	43.0 (12.0)	45.2 (13.8)	62.5 (14.6)
24°	51.1 (5.1)	55.0 (13.0)	61.3 (6.5)	78.5 (10.5)
30°	60.2 (8.5)	58.8 (9.7)	73.5 (9.5)	88.6 (9.9)

¹Table 15 gives the mean ratings (in mm) of total orientation as a function of first and second stimulus figure orientation. Standard deviations appear in parentheses. (N=5)

The collapsed data was subjected to a two-way repeated measures analysis of variance. These results are given in Table 16. The main effects for both the first ($F = 45.13$, $df = 3, 12$, $p < .001$) and the second ($F = 85.06$, $df = 5, 20$, $p < .001$) stimulus figures were statistically significant and large, accounting for over 90% of the total variance. The interaction of these main effects was, however, not significant ($F = 1.42$, $df = 15, 60$, $p > .05$).

Tukey tests were conducted as follow-up tests to the significant main effects. Marginal means and standard

Figure 6. Mean Rated Total Orientation as a Function
of First and Second Figure Orientation. Mean rated
total orientation is in mm.

Table 16

ANOVA for Mean Rated Total Orientation

Source	SS	df	MS	F	w ²
First Angle (F)	12551	3	4184	45.13*	.200
Error	1112	12	93		
Second Angle (S)	44521	5	8904	85.06*	.709
Error	2094	20	105		
FS	663	15	44	1.42	--
Error	1871	60	31		

*p < .001

deviations are shown in Table 17. Tukey tests on these marginals revealed that, for both First and Second Angles, only the 0 and 6 degree orientations did not differ significantly from each other.

Table 17

Marginals for First and Second Angles

Orientation	First Angle		Second Angle	
	Mean ¹	SD	Mean	SD
0°	31.8	5.5	18.1	5.2
6°	35.5	10.5	21.4	10.2
12°	44.4	8.9	36.7	10.5
18°	58.3	5.8	46.9	10.6
24°	--	--	61.5	4.8
30°	--	--	70.3	8.4

¹Means and standard deviations in mm.

Since the interaction term of the analysis of variance

was not significant (see Table 16), it is appropriate to construct subjective scale values for the separate impressions of orientation from the marginal means of the factorial design (Andersen, 1970b, 1974). Figure 7 shows the psychophysical function relating subjective orientation (in arbitrary units) to physical angle of orientation. This psychophysical orientation function corresponds to the average curve of Figure 6, collapsed over the four levels of First Angle. The plotted points are the marginal means for Second Angle shown in Table 17.

A trend analysis, summarized in Table 18, was conducted on the psychophysical function. The linear trend was significant ($F = 419.29$, $df = 1,20$, $p < .001$), but higher order trend components were not ($F = 1.84$, $df = 4,20$, $p > .05$). The correlation associated with the linear trend was high ($r=0.969$).

Table 18

Trend Analysis for Psychophysical Function					
Source	SS	df	MS	F	η^2
Linear	10944	1	10944	419.29*	.939
Higher Orders	192	4	48	1.84	--
Error	522	20	26		
*p < .001					

Individual Data

One appealing aspect of the functional measurement method is that enough information is generated to enable

Figure 7. Psychophysical Orientation Function for Group Data. Subjective orientation is plotted as a function of physical orientation. Subjective orientation is based on observers' mean rated total orientation (in mm) collapsed over levels of orientation for First Angle.

data analysis on individual subjects. Means and standard deviations for rated total orientation as a function of first and second figure orientations for each subject is given in Appendix H.

Separate analyses of variance were conducted on the data for each subject. These results are summarized in Tables 19 through 23. For all subjects main effects were significant and large, accounting for a total of from 83 to 90% of the total variance. The interaction term was significant for only one of the five subjects (IA) and was a small effect, accounting for only 4% of the total variance in that subject's data.

Table 19

ANOVA for Mean Rated Total Orientation

Subject 1 (EE)					
Source	SS	df	MS	F	η^2
First Angle (F)	9486	3	3162	44.93*	.173
Error	633	9	70		
Second Angle (S)	36901	5	7380	70.00*	.672
Error	1581	15	105		
FS	1885	15	126	1.29	--
Error	4390	45	98		
*p < .001					

Tukey tests were conducted on each subject's data as follow-up tests for the significant main effects. These results are summarized in Table 24 and show that, for four

of the five subjects, the mean rated total orientation for the 0 and 6 degree angles did not differ significantly for either the first or second stimulus figures. For one of these subjects, for the first stimulus figure, the 12 degree

Table 20

ANOVA for Mean Rated Total Orientation

Subject 2 (TA)					
Source	SS	df	MS	F	w ²
First Angle (F)	12614	3	4205	113.35*	.181
Error	334	9	37		
Second Angle (S)	50202	5	10040	129.70*	.720
Error	1161	15	77		
FS	3086	15	206	3.91**	.044
Error	2366	45	53		

Table 21

ANOVA for Mean Rated Total Orientation

Subject 3 (JE)					
Source	SS	df	MS	F	w ²
First Angle (F)	8213	3	2738	10.96*	.167
Error	2248	9	250		
Second Angle (S)	33193	5	6639	94.82*	.673
Error	1050	15	70		
FS	1019	15	68	0.86	--
Error	3569	45	79		

**p < .05 *p < .001

Table 22

ANOVA for Mean Rated Total Orientation

Subject 4 (IC)

Source	SS	df	MS	F	w ²
First Angle (F)	9721	3	3240	25.11*	.157
Error	1162	9	129		
Second Angle (S)	41770	5	8354	50.50*	.673
Error	2482	15	165		
FS	2023	15	135	1.23	--
Error	4925	45	109		

Table 23

ANOVA for Mean Rated Total Orientation

Subject 5 (NO)

Source	SS	df	MS	F	w ²
First Angle (F)	14618	3	4873	40.57*	.312
Error	1081	9	120		
Second Angle (S)	24395	5	4879	90.36*	.521
Error	810	15	54		
FS	2124	15	142	1.67	--
Error	3807	45	85		

*p < .001

orientation was also not rated differently from the 0 and 6 degree orientations. For three of the four subjects, for the second stimulus figure, an additional pair of angles differing by only six degrees in physical orientation did not differ in rated orientation.

Table 24

Tukey Results for Individual Subjects¹

Subject	First Angle	Second Angle
1	6°-12°	18°-24°
2	0°-6°	0°-6°; 24°-30°
3	0°-6°	0°-6°; 12°-18°
4	0°-6°	0°-6°
5	0°-6°-12°	0°-6°; 24°-30°

¹Angular orientations separated by a hyphen did not differ significantly ($p > .05$) in rated orientation.

Scale values for the subjective impression of total orientation were constructed for individual subjects in a manner similar to that used for the group data. Marginal means for Second Angle, collapsed over levels of First Angle, are given in Table 25. The psychophysical functions based on these marginals are shown in Figure 8 for each of the five subjects.

Trend analyses were conducted on each subject's psychophysical function. These analyses are summarized in Table 26. All subjects displayed large linear trends, accounting for from 86 to 94% of a subject's total variance. Correlations associated with these linear trends were also

Figure 8. Individual Psychophysical Orientation Functions. Subjective orientation is plotted as a function of physical orientation for each observer. Subjective orientation is based on an observer's mean rated total orientation (in mm) collapsed over levels of orientation for First Angle.

high, ranging from 0.928 to 0.971. Higher order trends were significant for a few subjects, but in each case accounted for only a small proportion of the total variance. ANOVA summary tables for individual trend analyses appear in Appendix H.

Table 25

Marginals for Second Angle

Individual Data

Second Angle	EF		TA		JE		LC		NO	
	Mean ¹	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0°	23.2	16.2	10.7	10.1	14.7	12.8	21.1	15.0	20.7	11.8
6°	37.2	14.5	9.2	8.1	20.6	12.5	17.6	13.5	22.2	12.5
12°	49.5	10.0	20.6	8.8	40.1	12.8	34.7	9.6	38.7	17.7
18°	62.8	12.8	34.3	11.6	40.8	10.1	47.8	4.6	48.9	20.7
24°	69.7	8.9	61.9	23.2	59.1	10.0	58.5	12.4	58.2	14.2
30°	81.0	11.5	66.0	19.7	66.4	9.2	77.0	17.4	60.9	12.2

¹Means and standard deviations in mm.

Table 26

Individual Trend Analysis Results

Trend Order	EH		TA		JE		LC		NO	
	w ²	r	w ²	r	w ²	r	w ²	r	w ²	r
1	.943	.971	.861	.928	.936	.968	.899	.948	.879	.938
2	ns ¹		.031	.176	ns		.031	.176	ns	
3	ns		.036	.190	ns		ns		ns	
4	ns		ns		ns		ns		ns	
5	ns		ns		.033	.183	ns		ns	

¹ns = not significant (p > .05)

CHAPTER 8

Discussion

The results of Experiment II generally support the proposed additive model for orientation integration. This conclusion is based on the results of the analysis of variance shown in Table 16, in which the interaction of the two independent variables is not significant (see also Figure 6). Furthermore, as shown in Tables 19 through 23, the interaction term is not significant for four of five subjects. The exception is Subject #2 (see Table 20), for whom a small but statistically significant interaction was obtained. This interaction may indicate a defect in the additive model for this subject. However, the deviation from parallelism accounted for less than 5% of the total variance in this subject's data.

An alternative explanation for this subject's interaction is indicated in Table 26, in which small but statistically reliable second and third order trends are shown for this subject. It may be that a small, nonlinear bias in this subject's response scale is the cause of the interaction rather than a failure of the model. Response nonlinearity can be removed by application of the monotone rescaling feature of functional measurement (Anderson, 1970b, 1974). This was not done, however, as it seemed preferable to include only the raw data in this report. At any rate, the size of the interaction effect is small enough that serious qualification of the additive model does not

appear to be warranted.

Because the additive model was not rejected by the data, scale values for the subjective impression of angular orientation are directly available from the marginal means of the independent variables (Anderson, 1970b, 1974). Table 17 shows that the zero and six degree orientations were rated similarly for both independent variables. Tukey tests showed that these ratings were not statistically different. Table 24 shows that this pattern of results was mirrored by four of the five subjects. The exception here is Subject #1, whose data will be discussed more fully below.

Figures 7 and 8 show graphically the subjective scale values as a function of physical orientation for the group and individual data, respectively. These figures show clearly the similarity of perceived orientation for the zero and six degree angles. As mentioned above, Subject #1 (EH) seems to be an exception. Figure 8 shows for this subject a very nearly linear increase in perceived orientation from zero to 30 degrees. Subject #3 (JB) also displays an increase in perceived orientation from zero to six degrees, although this increase is not significant (see Table 24). However, the remaining three subjects clearly display no increase between zero and six degrees; in fact, for two of these subjects the function reverses between these points.

These results imply that angular disparities between relatively complex figures such as the Shepard and Metzler (1971) figures are to some extent not apparent. For four of

the five subjects in Experiment II the extent of this effect was six degrees. Subject #1 was able to perceive angular disparities in this range. Subject #3 may also be able to see such angular disparities; although the statistical data does not support this contention, this may be due to the fact that the statistical results are based on only four replications. Paucity of data points may also be the reason that second order trends were not obtained for Subjects #3 and 5, or for the overall group trend analysis, which was based on only five data points at each level of orientation. At any rate, the results of Experiment II support the idea that the threshold for mental rotation obtained in Experiment I is not a simple sensory threshold. The 18-degree threshold obtained in Experiment I is three times as large as the largest angular disparity not visible to subjects in Experiment II.

It may be surprising to some that angular disparities even as great as six degrees are not visible to most observers. It is well known, for example, that smaller angular disparities are clearly visible for line stimuli. Although the various methodologies which have been applied to this problem have produced somewhat conflicting findings (Emerson, et al., 1975), few studies have indicated that angular disparities greater than three degrees are not apparent to observers, and several studies have indicated that the size of the effect is less than one-half a degree of arc.

The greater extent of the effect for the Shepard and Metzler (1971) figures than for simple line stimuli may in some way be due to the greater complexity of the former. Although the Shepard and Metzler figures are composed of many line segments, it seems likely that the central processing of the entire figure is mediated by the complex cortical feature detectors (Hubel & Wiesel, 1962) rather than by the lower-order simple orientation detectors suspected of mediating line detection in the human visual system (Andrews, 1965, 1967a, 1967b; Campbell & Kulikowski, 1966).

Several explanations which have been applied to the problem of figural aftereffects may also be advanced with respect to more complex figures. One such explanation is that of "satiation" proposed by Kohlers and Wallach (1944). The satiation view involves a physiological process of fatigue, which presumably would affect the complex cells. Recent theorizing on this issue suggests lateral inhibition as the mechanism of the effect (Deutsch, 1964; Ganz, 1966a, 1966b).

A problem with the satiation approach is that the occurrence of figural aftereffects is not dependent upon a period of steady stimulus fixation. Both Ganz (1966a, 1966b) and Logan (1960) have noted this problem, suggesting that figural aftereffects may be considered simultaneous illusions. Thus, satiation may be a sufficient though not a necessary cause of figural aftereffects. Even so, it is not

apparent why satiation should produce a larger angular disparity effect for complex figures than for simple line stimuli. If anything the reverse should be true because the greater role of eye movements over extended figures should reduce fatigue-like effects.

An alternative explanation for figural aftereffects has been advanced by Dodwell (1970). It is well known that simple orientation detectors are very sensitive to small changes in angular orientation. A cell tuned to a particular orientation will exhibit greatly reduced responding to stimuli oriented only $5-10^\circ$ to the preferred orientation (Hubel & Wiesel, 1962). Furthermore, at the level of the simple orientation detectors there is no interaction between cortical units tuned for different orientations. It may be expected, then, that strong interactions between detector cells will only occur if the receptive fields of these cells are nearly parallel to each other.

As with simple cells, the orientation of the stimulating contour is critical for maximum responding of complex cells; such responding decreases rapidly with small changes in the orientation of the test figure (Hubel & Wiesel, 1962). But it is not yet clear whether the cortical interactions mentioned above for simple cortical units take place for the higher-order complex cells as well. Since such cells appear to consist of a hierarchical organization of the lower-order simple cells, it is possible that the higher-order cells

also exhibit a lack of cortical interactions for units of different preferred orientations. Even if this is the case, it does not explain why different angular disparities are not visible for complex figures than for simple line stimuli.

A possible solution to the problem of the size of the effect comes from consideration of the nature of the hierarchical organization of simple, complex (Hubel & Wiesel, 1962) and hypercomplex cortical cells (Hubel & Wiesel, 1965). The research of Hubel and Wiesel indicates that the input to higher-order units is from a set of lower-order units all of the same preferred orientation.

Little is known about the mechanism of information flow from one level to another, and what is known is based primarily on electrophysiological recordings from cats and monkeys. For obvious reasons such recordings cannot be obtained from humans. Evidence on detector cells in the human visual system has been obtained by psychophysical techniques (Andrews, 1965, 1967a, 1967b; Elakemore, et al., 1970; Bouma & Andriessen, 1968; Campbell & Kulikowski, 1966).

Andrews' (1967a, 1967b) papers indicate that output from lower-order detector cells is subjected to statistical evaluation at higher levels. If this view is correct, then the variance of orientation selectivity is likely to be greater at higher levels of organization. This follows from the additive rule which gives the variance of combined

statistical distributions (Nunnally, 1978). The result of this increase in variance would be a decrease in orientation selectivity for complex cells.

The extent of this decrease in sensitivity would not have to be great to account for the present findings. Complex detectors would still have preferred orientations, but the drop-off in the rate of responding would be more gradual than for simple cells. Assuming that there is no interaction between complex cells tuned for different orientations, as appears to be the case for simple cells, then interactions which do occur between complex cells will involve cells whose receptive fields are nearly parallel, but not necessarily as parallel as for the simple cell interactions.

This statistical argument gives a reasonably plausible explanation for why greater angular disparities between complex forms than between simple lines may not be apparent to observers. However plausible, though, this explanation is very speculative, especially in view of how little is actually known about feature detectors in the human visual system. Strong conclusions about complex edge and form detectors based on the present data are premature. In fact, it is probably risky in general to make inferences about one level of behavior based on observations of another level. Certainly the methodology used in the present study, and the data thereby obtained, do not provide a direct route to knowledge about the underlying neural circuits. To obtain

such knowledge more direct methods will be needed, including direct electrophysiological techniques such as evoked-potential recordings (Campbell & Maffei, 1970) and electroencephalogram recordings (Gevins, Zeitlin, Doyle, Yingling, Schaffer, Callaway, & Yeager, 1979). Of great potential is a technology recently developed enabling researchers to directly monitor magnetic fields induced by the electrical activity of the human brain.

While indirect, psychophysical studies can nevertheless provide valuable insights about behavioral correlates of suspected neural events, as well as provide some information about these events. Much has already been learned about the neuropsychology of the human visual system, and several books have appeared dealing with human pattern recognition (Dodwell, 1970; Reed, 1973).

In particular, the functional measurement technique should prove very useful. One obvious immediate application would be to the problem of figural aftereffects. Using line segments as stimuli, the functional measurement approach might help resolve some of the conflicting findings which have plagued this literature, as well as provide information about simple feature detection, discrimination, and recognition.

In addition to providing support for the contention that the threshold for mental rotation is not simply a sensory phenomenon, Experiment II has yielded some basic results which bear upon the processing of complex forms by the human

visual system. The information gained represents only a first approximation to knowledge about complex pattern recognition and thus needs to be replicated.

Replication is necessary in any event since Experiment II represents, in a sense, the first experiment of its kind. Thus, more prosaic accounts of the data need to be firmly ruled out. For example, lack of a difference in rated impression for the zero and six degree orientations might be due to the fact that these orientations, while discriminable to subjects, simply appear similar and are thus rated alike. The flatness of the function from zero to six degrees would, by this view, not be a sensory event, but instead be due to compression of an observer's response scale in this region. Future studies might handle this problem by application of the monotone rescaling procedure of functional measurement. However, a nonlinear response bias probably cannot account for the results of Experiment II. This follows from the occurrence of point reversals from zero to six degrees for two of the subjects: it is hard to see how nonlinear bias could produce such an effect. Certainly no transformation (or only the most exotic) could produce a linear scale from such data.

Nevertheless, the present study needs to be replicated in order to rule out completely the possibility of response bias effects. The presence of anchor stimuli are designed to help eliminate floor and ceiling effects. Since for some subjects there was indication that the entire response range

was not always utilized, it might be necessary to frequently remind subjects to do so. This might be conveniently done at the beginning of each replication.

Replication of Experiment II should include smaller angular orientations than used in the present study. The six-degree increments used in Experiment II were sufficiently small to provide information concerning the sensory extent of the threshold for mental rotation. Inclusion of smaller angular increments, preferably of only one or two degrees, should provide some interesting information concerning the perception of complex forms.

Such increments will yield a more refined estimate of the size of the angular disparity effect for complex forms. Since Experiment II utilized only six-degree increments in orientation, the minimum estimate of the size of the effect must necessarily be six degrees. Although there is no reason to suspect that the observers used in Experiment II were in any way exceptional, the possibility remains that six degrees represents an upper bound to the effect, attained by only a few subjects. The size of the effect for Subject #1, for example, might be no more than usually obtained for simple line stimuli. In fact, the six-degree increment was originally chosen because it was thought to be larger than the sensory threshold for orientation discrimination: strictly linear relationships were expected for the psychophysical functions. With respect to the perception of complex forms, then, the results of Experiment

II have been serendipitous. Replication of this study should to be undertaken in order to confirm the presence of an effect not originally sought, and which might have important implications for the perception of complex forms by the human visual system.

SUMMARY

The primary finding of Experiment I is that there is a threshold for mental rotation. Reaction time for recognizing that comparison stimulus figures were the same as standard stimulus figures was a constant 1109 msec for orientations of the comparison stimuli of up to 18° with respect to the standard. For orientations greater than 18° reaction time was a linear function of orientation. The intercept of this function was 1116 msec, while its slope was $13.76 \text{ msec deg}^{-1}$, indicative of a rate of rotation of $72.7^\circ \text{ sec}^{-1}$. These results suggest that when the difference in orientations between standard and comparison figures is 18° or less, no rotation is necessary for a "same" decision to be reached.

The primary finding of Experiment II is that angular disparities of 6° between objects seem not to be apparent to observers. Although further research will be necessary to rule out completely the possibility of response bias effects, the results clearly confirm as a psychological effect the threshold for mental rotation obtained in Experiment I. Thus, a figure oriented at 18° or less with respect to a standard figure appears psychologically identical to the standard in orientation. A figure oriented at 6° or less with respect to a standard appears physically identical to the standard in orientation.

At the present time, the mental rotation process is

usually described by two mechanisms: one which rotates or transforms an internal representation into standard form, and a second, the template-matching system, that then makes a "same-different" judgement. The results of Experiments I and II demonstrate that a modification of this model is necessary. The threshold concept indicates that the template-matching mechanism may be flexible to the extent that small angular departures from standard orientations are accommodated without rotation. Thus, subthreshold disparities between standard and comparison figures seem to be immediately accommodated by a flexible template system.

However, the converse proposition, that objects with supra-threshold angular disparities need be rotated only into the threshold or psychological zero region for a comparison to occur, is not supported by the data. Instead, rotation of comparison objects with supra-threshold angular disparities appears to continue all the way to standard orientation. This result is surprising, since a more efficient use of processing capacity would be to discontinue mental rotation as soon as the rotated figure attained subthreshold disparity with respect to the standard.

The solution to this problem may lie in the limited amount of practice received by the observers in Experiment I. In performing a relatively novel task, observers may have adopted a cautious strategy. Rotation may have continued to zero degrees disparity in order to maintain a high degree of accuracy in an unfamiliar task. Further

research needs to be conducted to determine whether there may be another, more theoretically important reason for continuing to standard orientation rotation of comparison figures with supra-threshold angular orientations.

An alternative interpretation of the data of Experiment I suggests that rotation through small angles does occur, but at an extremely rapid rate. In fact, the rate of rotation might increase as the orientation of the comparison figure approaches that of the standard figure. However, the idea of differential rates of rotation which depend upon the initial extent of the angular orientation of a figure seems less parsimonious than the relatively simple concept of a threshold.

Although in general males seem to outperform females on cognitive tasks requiring spatial ability, no significant sex differences were found in Experiment I. The important variables in this regard are rate of mental rotation and size of threshold, both of which reflect the spatial characteristics of the mental rotation task. The rate of mental rotation was $79.8^{\circ} \text{ sec}^{-1}$ for males and $68.2^{\circ} \text{ sec}^{-1}$ for females. While this difference appears large proportionately--males rotate nearly 20% faster than females--the difference was not statistically significant. In fact, there was a wide range of individual differences in the rate at which rotation was performed, with considerable overlap in the distributions for males and females (see Tables 10 and 11).

Only a 3° difference in threshold size was evident between the two sexes: 18° for females and 21° for males. It was not possible to test the statistical significance of this difference. However, even if the 3° difference were statistically significant, it is unlikely that a functional advantage in the ability to spatially manipulate internal representations would thereby be conferred to males. Moreover, the findings of Experiment II suggest that a difference of 3° in angular disparity may not even be apparent to most observers.

The failure to find significant sex differences does not mean that such differences do not exist for spatially-oriented tasks, especially in view of the extensive literature supporting such differences. The results of the present study may be an indication of a lack of such differences only for highly educated observers, perhaps limited to the mental rotation task. However, mental rotation is a highly spatial ability, unlikely to be contaminated by verbal components. The finding of no sex-related differences on two parameters indexing the spatial characteristics of the mental rotation task should, therefore, be carefully considered, especially since recent studies have indicated that the degree of sex differences on visuospatial tasks may be overestimated (e.g., Jorm, 1979).

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APPENDIX A

Subject Data for Experiment I

The following table gives the sex, status (graduate or undergraduate), age, and preferred hand (right, left, or ambidextrous) of the 20 observers used in Experiment I.

Subject #	Sex	Status	Age	Hand
1	F	G	32	R
2	F	G	24	R
3	F	G	25	R
4	M	G	25	R
5	M	G	31	R
6	M	G	30	R
7	F	G	27	A
8	F	U	22	R
9	M	G	26	R
10	F	G	28	R
11	F	G	22	R
12	F	G	26	R
13	M	G	37	A
14	F	G	24	R
15	M	G	27	R
16	F	G	24	R
17	M	G	32	R
18	M	U	22	R
19	M	U	28	L
20	F	U	20	R

The following listing summarizes some of the data given in the table above:

Characteristic	n
Female	11
Male	9
Graduate	16
Undergraduate	4
Graduate Female	9
Graduate Male	7
Undergraduate Female	2
Undergraduate Male	2
Right-Handed	17
Left-Handed	1
Ambidextrous	2

The following table gives the sex, status, age, and preferred hand for the five subjects discarded from the experiment for excessive error rates. The table also gives the number of errors of commission (Type A) and of omission (Type B), the total number of errors, and the overall error rate for each subject. See Appendix F for more information on errors and error types.

Subject	Sex	Status	Age	Hand	Number of Errors		Total	% Errors
					A	B		
BO	M	G	30	F	2	16	18	28.1
LG	F	G	29	F	14	1	15	23.4
EM	M	G	29	F	2	10	12	18.8
RK	F	U	23	R	19	0	19	29.7
AK	F	U	19	F	9	11	20	31.2
Mean			26.0		9.2	7.6	16.8	26.2
SD			4.8		7.5	6.9	3.3	--

APPENDIX E

Mini-Experiment Results

Because of possible variations in the performance of the slide projector, the physical angle of orientation of a projected stimulus sometimes differed from the nominal angle. A "mini-experiment" was run to determine the extent to which this occurred. One side of the standard figure was used as the baseline (zero degree) orientation. The 32 comparison slides were the "subjects": each slide was projected five times and its angle of orientation measured by means of a protractor. The table below gives the means and standard deviations of the measured angles for each nominal orientation for both stimulus figures.

Stimulus 1			Stimulus 2		
Orientation	Mean	SD	Orientation	Mean	SD
0°	0.4°	0.55	0°	0.6°	0.89
3°	2.4°	0.55	3°	2.2°	0.45
6°	6.4°	0.55	6°	6.0°	0.00
9°	9.0°	0.00	9°	8.6°	0.55
12°	12.6°	0.55	12°	12.0°	0.00
15°	15.4°	0.55	15°	14.2°	0.45
18°	17.2°	0.84	18°	17.8°	0.45
21°	20.6°	0.89	21°	20.4°	0.55
24°	24.6°	0.55	24°	24.0°	0.00
27°	27.4°	0.55	27°	26.8°	0.44
30°	30.4°	0.55	30°	29.4°	0.55
60°	61.0°	1.00	60°	61.4°	0.55
90°	90.8°	1.10	90°	90.4°	1.14
120°	120.8°	0.84	120°	120.8°	1.64
150°	151.6°	0.55	150°	151.2°	0.45
180°	179.6°	0.55	180°	179.0°	0.71

Any deviation greater than 1° for stimulus orientations from zero to 30 degrees, and any deviation greater than 3° for stimulus orientations from 60 to 180 degrees were

corrected by the author. This occurred for the 6° and 15° slides for Stimulus 1 and for the 18° slide for Stimulus 2. To correct the angle of a stimulus figure, the author dismantled the slide, reoriented the figure with the aid of a protractor, and then mounted the slide. All values given above are for the final stimulus figures used in the experiment.

APPENDIX C

Calculation of Outliers for Experiment I

The table below shows the original means and standard deviations for each angular orientation and the three standard deviation cutoff point for each angle.

Angle	Mean	SD	+3 SD Cutoff
0°	1092	326	2070
3°	1164	380	2304
6°	1141	339	2158
9°	1043	293	1922
12°	1193	439	2510
15°	1169	341	2192
18°	1201	512	2737
21°	1248	402	2454
24°	1453	535	3058
27°	1414	430	2704
30°	1766	773	4085
60°	2241	735	4446
90°	2521	762	4807
120°	2969	1041	6092
150°	3168	1036	6276
180°	3668	1001	6671

Latencies at any angular orientation which were greater than the 3 standard deviation cutoff for that orientation were omitted from the analysis. However, such omissions were not counted as errors against the observers.

The table below shows, by subject, the angles omitted and the corresponding reaction time (in msec) as well as the z score associated with the omitted value.

Subject #	Angle	Reaction Time	<u>z</u> Score
1	150°	6364	3.08
3	0°	2099	3.09
5	90°	5065	3.34
5	180°	6780	3.11
6	120°	7138	4.00
7	180°	7193	3.52
8	6°	2922	5.25
8	12°	2615	3.24
9	27°	2790	3.20
9	60°	5551	4.50
11	3°	2698	4.04
12	12°	2621	3.25
12	30°	4618	3.69
14	15°	2672	4.41
20	0°	2195	3.38
20	24°	3344	3.53

APPENDIX D

Individual Reaction Time Data

The table below gives the average reaction time for each subject at each angular orientation for "same" response data.

Subject Number										
Angle	1	2	3	4	5	6	7	8	9	10

0°	875	1044	744	984	946	734	556	2006	945	980
3°	1074	1274	992	680	1044	806	690	1684	918	1406
6°	1012	956	736	856	1173	1266	632	1377	976	1547
9°	1171	860	670	1287	990	754	598	1614	1406	992
12°	1434	963	866	746	1016	724	529	1727	940	1192
15°	976	881	981	1082	884	884	621	1712	1306	961
18°	1024	1078	1244	1167	1216	752	488	2082	1091	1053
21°	1137	1128	1238	851	1100	997	594	1912	1126	972
24°	1118	1506	813	918	1880	982	638	2381	1663	944
27°	1458	1166	1422	812	1932	1317	830	1922	1260	993
30°	1100	1212	1838	974	3620	1323	1142	2414	2154	1108
60°	3002	1708	1533	1748	2540	3371	1832	2768	2825	1174
90°	2274	2508	2503	1498	1798	1488	2144	2545	2364	1378
120°	2214	4388	4168	1732	3690	2193	2073	2454	3458	1899
150°	3083	2626	4372	2559	4070	1836	4250	3148	4128	1898
180°	3384	3500	3284	4846	5509	2928	2468	3840	3374	2017

Subject Number										
Angle	11	12	13	14	15	16	17	18	19	20

0°	1188	1118	1302	819	861	990	960	1315	1170	1042
3°	1702	1285	1352	862	824	1032	1307	1662	1288	900
6°	1166	1432	1158	953	698	1278	1336	1296	1098	1094
9°	852	1329	1016	801	684	991	1380	1088	1484	896
12°	1006	1124	1126	1504	798	1231	1246	1610	1926	956
15°	910	1574	1101	584	858	1042	1836	1179	1586	1384
18°	782	2524	2182	816	716	1310	902	1096	1363	1130
21°	2194	1644	1046	1181	666	1189	1672	1586	1564	1160
24°	1846	2242	1696	1648	726	1010	1498	1493	1770	1212
27°	1068	1665	1264	1284	986	1612	1237	1742	2415	1133
30°	1683	2447	2323	1722	1100	1128	1507	2430	1602	1408
60°	2318	2720	1817	1944	1855	1390	2528	1778	1958	2648
90°	3315	4092	2765	2735	1843	1818	2422	2194	3829	3275
120°	3795	4248	1874	4294	1980	2724	2114	3558	1971	2073
150°	3148	5200	2134	3614	2158	2002	2788	3038	3668	1997
180°	4081	4625	3166	4153	2518	2984	3284	4856	2642	2912

APPENDIX F

"Different" Response Data

Summary Data

The table below gives the means, standard deviations, and standard errors of the mean for "different" responses.

Angle	Mean	SD	SEM
0°	2008	558	214
3°	2119	690	154
6°	2023	540	210
9°	1935	792	177
12°	2362	1329	297
15°	2138	950	212
18°	2147	793	177
21°	1982	1175	263
24°	2072	729	163
27°	2054	675	151
30°	2325	824	184
60°	3411	1320	295
90°	3660	1313	294
120°	3581	1270	284
150°	3435	1601	358
180°	3611	1451	324

Analysis of Variance Results

The following table gives the results for the one-way repeated measures analysis of variance computed on the "different" reaction times for Angle.

ANCOVA Summary Table for Angle					
Source	SS	df	MS	F	w ²
Angle	145892288	15	9726152	11.94*	.386
Error	232064064	285	814260		
*p < .001					

A Tukey test was used as follow-up to the significant F obtained in the analysis of variance. Tukey test results are summarized below:

----- Tukey Test Results ¹ -----															
0°	3	6	9	12	15	18	21	24	27	30	60	90	120	150	180°

¹Underlined ranges of angles did not differ significantly in reaction time ($p > .05$).

Trend Analysis

There is some evidence that reaction times for "different" scores will display a linear trend similar to that usually obtained for "same" scores under certain conditions. Metzler and Shepard (1974) noted that if only a single stimulus figure were used in the mental rotation paradigm, subjects might be encouraged to adopt a strategy for discriminating "different" pairs in which a salient feature of the comparison figure is rotated into correspondence with the same feature on the standard figure. Subject would then decide "same" or "different" based on whether or not the rest of the features matched. (Because "different" pairs were mirror images, the occurrence of such salient features is assured.) Metzler and Shepard (1974) then conducted an experiment in which linearity was obtained for "different" figures. In an effort to replicate these results, a trend analysis was conducted on the "different" scores obtained in Experiment I. These results are

summarized in the table below:

Trend Analysis Results					
Source	SS	df	MS	F	w ²
Linear	115890048	1	115890048	142.37*	.307
Quadratic	13503984	1	13503984	16.58*	.036
Higher Orders	16498256	13	1269097	1.56	--
Error	232064064	285	814260		
*p < .001					

The results of the trend analysis are not consistent with the findings of Metzler and Shepard (1974), and indicate a significant second-order trend in the reaction time data. Reaction time increased in a roughly linear fashion from 0 to 60 degrees, remaining nearly constant above this point.

A linear regression analysis was conducted on these data in spite of the significant higher order trend. Intercept was 2028 msec (S.E. = 1392) and slope was 11.00 msec deg⁻¹ (S.E. = 1.01), significantly different from zero ($t = 10.929$, $df = 637$, $p < .001$). The line obtained from the regression analysis is the line shown fitted to the data points in the figure on the following page. As is clear from this figure, the linear regression line does not describe the data points very well; the correlation of all points to this line, not surprisingly, is not very impressive ($r = 0.397$). Correlation of the average reaction time at each angle to this regression line, while high ($r = 0.891$, $df = 14$, $p < .001$, $r^2 = 0.794$), is not nearly as

Figure Caption. "Different" Reaction Time as a Function of Angular Orientation. Mean reaction time for "different" stimulus figures are depicted as a function of angular orientation. Means, in msec, are surrounded by standard error bars. The regression line is based on all data points and was fit by a least-squares procedure. The slope of this regression line is $11.00 \text{ msec deg}^{-1}$ and the intercept is 2028 msec.

impressive as the corresponding correlation for the "same" response data (for which $r = 0.988$).

The slope of the regression function indicates that "different" figures were rotated at a rate of approximately 90 deg sec^{-1} , in fairly good correspondence with the rate obtained by Metzler and Shepard (1974). However, it is not clear what is meant by rotation of "different" figures; certainly the process is not the same as occurs with "same" figures. It is possible that the rotation of "different" figures of large angular disparities (greater than 60 degrees?) will be followed by rechecking before the response lever is engaged. The much longer reaction times for "different" responses than for "same" responses may constitute evidence for this view.

Instead of forcing the mental rotation interpretation on the "different" data, an alternative view might be considered. It has already been noted that the reaction time function is nearly constant from 60 to 180 degrees. Although much noisier, the reaction time function from 0 to 30 degrees might also be characterized as relatively flat. One interpretation of this rather strange result might go something like this: from 0 to 30 degrees "different" responses are made fairly rapidly (for "different" responses) in a threshold-like fashion. Somewhere between 30 and 60 degrees there exists a critical angle or range of angles for which threshold-like responding is not possible. For angles from 60 to 180 degrees rotation and

matching is more difficult than for smaller angular disparities, but within this range difficulty is approximately equivalent.

This interpretation is highly speculative and post hoc, and need further research to establish their validity (or lack thereof). However, while "different" response data are largely ignored by researchers utilizing the mental rotation paradigm, these speculations and the data which give rise to them indicate that "different" response data may be potentially interesting and worth study in their own right.

APPENDIX F

Error Summary for Experiment I

Errors committed by subjects were classified into two categories: errors of commission (Type A) and errors of omission (Type B). A commission error occurred when a subject responded incorrectly to a stimulus pair. For example, if a subject responded "same" to a "different" stimulus pair, an error of commission was recorded. Errors of omission occurred when subjects failed to respond at all within 10 seconds of a stimulus presentation. Subjects who accumulated more than 15% total errors (the sum of Type A and Type B errors) were discarded from the study. Appendix A contains summary information on discarded subjects. Total error rates for individual subjects are given in Tables 10 and 11.

<u>Same Pairs</u>				<u>Different Pairs</u>			
Angle	Error Type		Total	Angle	Error Type		Total
	A	B	Rate		A	B	Rate
0°	1	0	.025	0°	0	0	.000
3°	2	0	.050	3°	1	0	.025
6°	0	0	.000	6°	1	0	.025
9°	0	0	.000	9°	1	0	.025
12°	1	0	.025	12°	1	0	.025
15°	0	0	.000	15°	0	0	.000
18°	1	0	.025	18°	1	1	.050
21°	1	0	.025	21°	0	1	.025
24°	0	0	.000	24°	2	0	.050
27°	1	0	.025	27°	2	0	.050
30°	0	0	.000	30°	1	0	.025
60°	2	0	.050	60°	1	0	.025
90°	2	0	.050	90°	4	0	.100
120°	5	0	.125	120°	3	0	.075
150°	5	0	.125	150°	2	2	.100
180°	14	0	.350	180°	3	1	.100
Total	35	0	.055		23	5	.044

Since a total of 1280 stimulus pairs were shown during the experiment, the overall error rate was $(35 + 0 + 23 + 5)/1280 = 63/1280 = .049$. Similarly, the total error rate for "same" pairs was $35/640 = .055$. Overall error rate for "different" pairs was $28/640 = .044$.

The table below shows the breakdown of total errors on "same" and "different" pairs for male and female subjects.

	Same	Different	Total
Females	20	12	32
Males	15	16	31
Total	35	28	63

Because an unequal number of male and female subjects were used in Experiment I, error rates for male and female subjects were based on different numbers of stimulus presentations. Error rate for females was $32/704 = .045$. Error rate for males was $31/576 = .054$.

APPENDIX G

Parallelism Proof

Linear models of the form

$$R(ij) = w(1)s(i) + w(2)s(j)$$

are easily tested. Because of its additive form, this equation leads to a prediction of parallelism, as can be seen from the following proof, adapted from Anderson (1974).

Let $R(1j) - R(2j)$ be the difference between an observer's subjective impressions of the orientations of the first and second levels of the first stimulus figure. Then,

$$R(1j) - R(2j) = [w(1)s(1) + w(2)s(j)] - [w(1)s(2) + w(2)s(j)].$$

Cancellation and distribution yields

$$R(1j) - R(2j) = w(1)[s(1) - s(2)].$$

Since the right side of this equation is independent of the second factor, j , it follows that the difference between any two levels of the first factor, i , is always a constant and independent of the level of the second factor. Thus, if curves are fitted to the data in $i \times j$ fashion, then, across levels of j , a parallel family of curves should be formed by the i -levels of the first factor. The interaction term of the analysis of variance constitutes a rigorous statistical test of the prediction of parallelism.

APPENDIX H

Individual Data for Experiment II

Individual Rating Data

The tables below give the means (and standard deviations in parentheses) for rated total orientation as a function of first and second figure orientations for each of five subjects. All ratings are in mm.

Subject 1 (FH)

Second Angle	First Angle							
	0°		6°		12°		18°	
0°	0.8	(1.0)	22.0	(5.1)	33.5	(7.1)	36.5	(5.0)
6°	18.2	(2.2)	34.0	(16.3)	46.2	(6.3)	50.5	(8.9)
12°	37.0	(5.3)	47.5	(9.0)	52.8	(11.1)	60.8	(13.7)
18°	47.0	(15.3)	60.5	(12.9)	65.8	(14.9)	78.0	(12.4)
24°	59.2	(8.5)	78.0	(9.2)	65.5	(14.1)	76.0	(15.5)
30°	71.8	(8.2)	74.0	(3.5)	81.2	(9.7)	97.2	(0.5)

Subject 2 (TA)

Second Angle	First Angle							
	0°		6°		12°		18°	
0°	2.5	(1.0)	2.0	(0.0)	16.2	(4.9)	22.2	(3.6)
6°	2.0	(0.0)	2.5	(1.0)	14.2	(5.7)	18.0	(6.3)
12°	16.8	(6.3)	13.8	(1.3)	18.2	(3.8)	33.5	(10.0)
18°	25.5	(5.6)	26.8	(1.7)	34.2	(3.3)	50.8	(2.8)
24°	45.2	(9.6)	49.8	(18.5)	56.5	(21.2)	96.0	(1.2)
30°	51.0	(3.3)	49.8	(1.9)	72.0	(7.5)	91.2	(10.2)

 Subject 3 (JB)

Second Angle	First Angle							
	0°		6°		12°		18°	
0°	0.2	(0.5)	8.0	(2.8)	23.2	(4.9)	27.5	(4.8)
6°	10.5	(1.3)	9.0	(5.0)	31.8	(9.1)	31.0	(3.3)
12°	31.8	(11.7)	31.2	(5.2)	39.0	(12.8)	58.5	(20.6)
18°	27.8	(5.2)	40.2	(13.3)	43.0	(10.2)	52.2	(14.5)
24°	51.5	(8.4)	50.0	(14.7)	64.0	(7.1)	70.8	(10.2)
30°	59.0	(19.4)	59.0	(4.7)	69.5	(4.8)	78.0	(10.9)

 Subject 4 (LC)

Second Angle	First Angle							
	0°		6°		12°		18°	
0°	2.8	(2.2)	19.5	(14.5)	22.8	(3.7)	39.5	(15.2)
6°	5.8	(5.5)	9.0	(6.1)	20.0	(4.1)	35.8	(11.0)
12°	26.8	(3.3)	28.2	(8.7)	36.0	(8.0)	47.8	(13.8)
18°	44.2	(18.3)	43.5	(5.4)	51.0	(7.0)	52.5	(10.7)
24°	49.5	(21.1)	46.2	(12.3)	68.0	(18.2)	70.2	(17.7)
30°	65.5	(11.3)	60.2	(17.4)	84.2	(12.9)	98.0	(0.0)

 Subject 5 (NO)

Second Angle	First Angle							
	0°		6°		12°		18°	
0°	11.0	(7.0)	11.0	(5.9)	25.8	(3.9)	35.0	(7.6)
6°	16.8	(9.1)	10.8	(3.3)	21.2	(10.3)	39.8	(3.9)
12°	28.0	(14.9)	31.8	(12.7)	29.8	(13.0)	65.2	(5.7)
18°	40.8	(11.8)	44.0	(7.7)	31.8	(16.7)	79.0	(7.4)
24°	50.0	(2.8)	50.8	(1.7)	52.5	(17.7)	79.5	(8.1)
30°	53.8	(4.1)	51.0	(3.2)	60.5	(12.1)	78.2	(3.9)

Individual Trend Analyses

The tables below give the ANCOVA summaries for the trend analyses conducted on each subject's psychophysical function (see also Table 25).

Subject 1 (EH)					
Source	SS	df	MS	F	w ²
Linear	9138	1	9138	291.96***	.943
Higher Orders	83	4	21	0.66	--
Error	470	15	31		

Subject 2 (TA)					
Source	SS	df	MS	F	w ²
Linear	11480	1	11480	222.92***	.861
Quadratic	412	1	412	8.00*	.031
Cubic	483	1	483	9.40**	.036
Higher Orders	181	2	90	1.76	--
Error	772	15	51		

Subject 3 (JB)					
Source	SS	df	MS	F	w ²
Linear	8011	1	8011	471.52***	.936
Quadratic	0	1	0	0.00	--
Cubic	4	1	4	0.25	--
Quartic	2	1	2	0.13	--
Quintic	285	1	285	16.80***	.033
Error	255	15	17		

Subject 4 (IC)					
Source	SS	df	MS	F	w ²
Linear	9833	1	9833	291.78***	.899
Quadratic	339	1	339	10.05**	.031
Higher Orders	254	3	254	2.51	--
Error	506	15	34		

Subject 5 (NC)					
Source	SS	df	MS	F	w ²

Linear	5823	1	5823	164.96***	.879
Higher Orders	272	4	68	1.93	--
Error	530	15	35		

*p < .05 **p < .01 ***p < .001					