

Mental Rotation, Mental Representation, and Flat Slopes

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The "mental rotation" literature has studied how subjects determine whether two stimuli that differ in orientation have the same handedness. This literature implies that subjects perform the task by imagining the rotation of one of the stimuli to the orientation of the other. This literature has spawned several theories of mental representation. These theories imply that mental representations cannot be both orientation-free and handedness-specific. We present four experiments that demonstrate the contrary: mental representations can be both orientation-free and handedness-specific. In Experiment 1 we serendipitously discovered a version of R. N. Shepard and J. Metzler's (1971) "mental rotation" task in which subjects accurately discover the handedness of a stimulus without using "mental rotation," i.e., in which reaction time to compare the handedness of two forms is not a function of the angular disparity between the two forms. In Experiment 2 we generalize this finding to different experimental procedures. In Experiment 3 we replicate this finding with a much larger group of subjects. In Experiment 4 we show that when we preclude the formation of an orientation-free representation by never repeating a polygon, subjects carry out the handedness comparison task by performing "mental rotation." © 1993 Academic Press, Inc.

A key to understanding one aspect of the mental representation of forms is to find the conditions under which people must mentally reorient forms to process them. If subjects cannot process a form without mentally reorienting it, we infer that their mental representation of that form is orientation-bound (Takano, 1989); otherwise we infer that their mental representation of the form is orientation-free. In other words, if a representation is orientation-bound, then subjects code it as it looks in a given orientation. Subjects recognize it more readily in the orientation in which they have coded it than in any other orientation. If the representation of a form is orientation-free, then subjects code it without reference to an external system of coordinates, and therefore they can recognize it equally well in any orientation.

Several theories of mental representation have addressed this problem.

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According to Takano (1989) all types of information carried by mental representations are orientation-free, except for handedness information. According to Rock and Di Vita (1987) and Tarr and Pinker (1989) mental representation is never orientation-free. In this paper we present data inconsistent with both theories; i.e., we have evidence that mental representation can be both orientation-free *and* contain handedness information.

The term "mental rotation" is often used in this context. But the term is ambiguous. It sometimes refers to a *mental operation* that involves an imagined reorientation of form, and sometimes refers to a *task* assumed to require the mental operation. In this paper we will show that not all "mental rotation tasks" require an imagined reorientation of form. To keep our terminology clear we will use the term "mental rotation" to refer to an imagined reorientation of form (and to emphasize our uncertainty about its status, we will keep it between quotation marks) and terms such as "handedness recognition" to refer to tasks.

"MENTAL ROTATION"

A task that requires the subject to determine whether two forms—of the same shape and in different orientations—are mirror images of each other or identical except for orientation is a *handedness recognition task*. Two decades of research, beginning with R. N. Shepard and J. Metzler (1971), have shown that subjects use "mental rotation" to solve the handedness recognition problem. All these demonstrations have met two criteria that have been necessary conditions of "mental rotation": (1) *Positive slope criterion*: Subjects take an amount of time that is an increasing function of the amount by which they must rotate the form, i.e., their RT is a monotonically increasing function of angular disparity (α). (2) *Limiting rate criterion*: "The subject . . . can perform this analog process ['mental rotation'] at no faster than some limiting rate" (J. Metzler & R. N. Shepard, 1974; quoted from R. N. Shepard & Cooper, 1982, p. 43). Metzler and Shepard thought that this limiting rate corresponded to a slope of about 17.5 ms/degree (a rate about 55 to 60°/s). Recently the limiting rate has gone up: 1 ms/degree (1000°/s) appears to be the shallowest allowable slope. For Corballis, Zebrodoff, Shetzer, and Butler (1978, p. 100), a slope of 0.97 ms/degree (1034°/s) "scarcely resembles those observed in experiments devised . . . to investigate . . . mental rotation . . ." For Takano (1989, p. 35, footnote 16) rates of more than 1000°/s (corresponding to a slope of 1 ms/degree) are "too large to be considered as results of mental rotation." For Tarr and Pinker (1989, p. 256) "a slope of 0.78 ms/degree (1282°/s) . . . [is] a hypothetical rate of rotation generally con-

sidered too high to reflect a mental rotation process." To be sure, any particular value of the limiting rate is to a certain extent arbitrary. For the sake of consistency with the investigators just cited, we adopt 1 ms/degree as the limiting value in interpreting the data we present in this article.

L. A. Cooper and R. N. Shepard (1973) proposed a more persuasive criterion and used it only once; we call it the *analog process criterion*: When subjects are asked to imagine the rotation of a shape from orientation A to orientation C, they produce handedness recognition responses most rapidly to probe shapes presented in an intermediate orientation B.

Tasks in which subjects must discriminate between stimuli of different shapes are called *form identification* tasks. In such tasks subjects name, label, classify, or compare letters or shapes in various orientations, and they do not engage in handedness discrimination. In contrast to handedness recognition, there is no reason to think that form identification requires "mental rotation." Although such experiments often show a small effect of orientation, experimenters have invariably judged the slope to be too shallow to satisfy the limiting rate criterion for "mental rotation" (Corballis et al., 1978; Jolicoeur & Landau, 1984; Jolicoeur, 1985; Takano, 1989).

Until recently, it was possible to summarize the past two decades of research on "mental rotation" by a single *Empirical Rule*: "mental rotation" is necessary for the performance of *handedness recognition* tasks, but not for the performance of *form identification* tasks. Tarr and Pinker (1989), to whom we will return presently, cast doubt on the validity of this summary.

MENTAL REPRESENTATION

The traditional interpretation of the handedness recognition findings (which we glean from R. N. Shepard & Cooper, 1982) and the form identification findings depends on two assumptions: (1) that mental representations are independent of the task of the perceiver and (2) that the limiting rate criterion correctly separates "mental rotation" from other processes. These assumptions and the Empirical Rule jointly imply that *orientation-free representations do not contain handedness information*.

Takano (1989) does not deviate from this tradition. He draws a distinction between orientation-free information—descriptions that remain constant as the orientation of the object changes (such as the curvature of a line)—and descriptions that change with changes in the object's orientation (such as the properties of being-to-the-right-of-X or being-above-Y). According to Takano's theory of information types, all mental representations contain both orientation-free information and orientation-bound

information. "When the former is critical in discriminating rotated forms, form perception will appear to be independent of orientation; when the latter is critical, form perception will appear to be dependent on orientation" (Takano, 1989, p. 7). When Takano tested his theory, he found a strong effect of orientation in a handedness recognition task, but only a marginal effect of orientation in a form identification task. Invoking the limiting rate criterion, Takano disregarded the latter trend.

Unlike Takano (1989), Rock does not make a distinction between orientation-bound and orientation-free information. In a series of single-trial form identification experiments, Rock (1956; Rock & Heimer, 1957; Rock, Di Vita, & Barbieto, 1981; Rock & Di Vita, 1987) demonstrated that subjects did not recognize forms presented in a different orientation from a single previous exposure as readily as forms presented in the same orientation. Recognition error rate increased directly with angular disparity. Rock concluded that the subjects' representation is not orientation-free, and that "object-centered descriptions are not spontaneously achieved" (Rock & Di Vita, 1987, p. 282).

Tarr and Pinker (1989) put forward different evidence from Rock's in support of the assertion that all representations are orientation-bound. In a handedness recognition experiment they showed subjects three letter-like asymmetric characters in four orientations 206 times each (the 2472 "practice" trials) after which they presented the same characters in four new orientations 32 times each (the 384 "surprise" trials). During the last 206 practice trials the slope was about 1 ms/degree, which Tarr and Pinker considered too shallow to represent "mental rotation," invoking the limiting rate criterion. This datum implies that subjects had either (a) memorized the three characters in each of the four practice orientations (i.e., they had formed 12 orientation-bound representations) or (b) formed orientation-free representations of the three characters. In their surprise trials they observed steeper slopes, consistent with "mental rotation." This result rules out alternative b, that is, subjects had not formed orientation-free representations of the three characters, and therefore had to "mentally rotate" them to the upright. In a second experiment Tarr and Pinker reported essentially the same results for a form identification task.

In Table 1 we present a summary of current models of mental representation. In the cells of the table we describe the data one would expect from form identification and handedness recognition tasks. Keep in mind that these models are not necessarily mutually exclusive. For instance, Takano believes that the characteristics of two of the mental representations in the table are present in all mental representations. In the General Discussion we will argue that the visual system is flexible, and that subjects may construct *all* the previously proposed mental representations when appropriate.

TABLE I
Summary of Models of Mental Representation and Their Empirical Implications

Handedness information	Orientation		
	Free	Single representation	Bound Multiple representations
Absent	No "mental rotation" for any orientation (i.e., the slope of $RT = f(\alpha)$ is flat) for form identification tasks and inability to perform handedness recognition tasks (R. N. Shepard & Cooper, 1982; Takano, 1989).	"Mental rotation" to a single overlearned orientation for form identification tasks and inability to perform handedness recognition tasks. (Such a representation has not been proposed.)	"Mental rotation" to the closest of several overlearned orientations for form identification tasks and inability to perform handedness recognition tasks. (Such a representation has not been proposed.)
Present	No "mental rotation" for any orientation (i.e., the slope of $RT = f(\alpha)$ is flat) for both form identification and handedness recognition tasks (this paper).	"Mental rotation" to a single overlearned orientation for both form identification and handedness recognition tasks (Rock & Di Vita, 1987; R. N. Shepard & Cooper, 1982; Takano, 1989).	"Mental rotation" to the closest of several overlearned orientations for both form identification and handedness recognition tasks (Tarr & Pinker, 1989).

FLAT SLOPES

In this paper we report four experiments. In the first we serendipitously discovered how to virtually eliminate the slope in a handedness recognition task. In the second we extended and generalized this finding. In the third we replicated the essential part of the second experiment, with a large number of subjects. In the fourth we found conditions under which we could reduce, but not eradicate, the slope.

These findings have grave consequences for current theories of mental representation. If it is possible to eliminate the slope in a handedness recognition task, then the information on which the subjects base their responses must be orientation-free and contain handedness information.

EXPERIMENT 1

This experiment compared—for the first time in a single experiment—

three handedness recognition paradigms commonly used to study "mental rotation." We have summarized these three paradigms schematically in Fig. 1.

In handedness recognition tasks we ask the subject to determine whether two shapes, called the *standard* and the *probe*, are the same or differ-

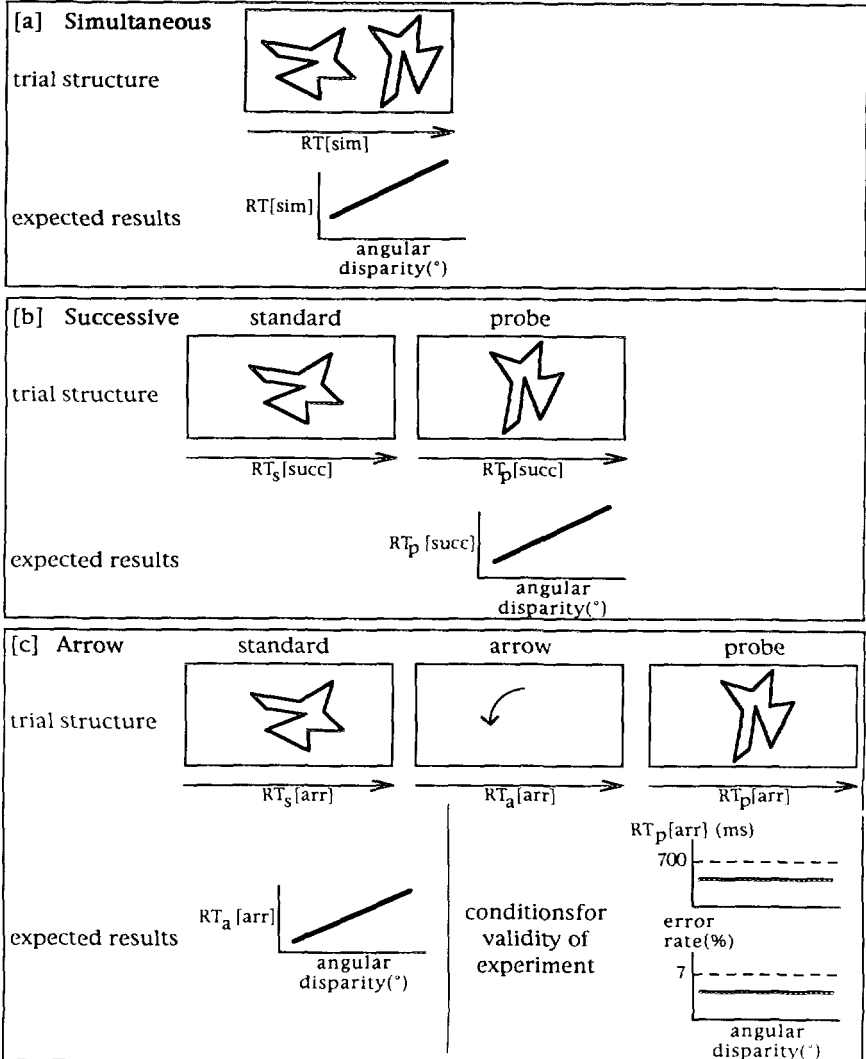


FIG. 1. Three experimental paradigms and predictions derived from conventional accounts of "mental rotation."

ent. The correct response is "same" if and only if the probe is an image of the standard under a rotation and/or a translation. The correct response is "different" either if the probe is not congruent with the standard (i.e., it is a perturbed image of the standard) or if it is an image of the standard under a reflection. The introduction of perturbed probes prevents the subject from solving the perceptual problem by imagining the rotation of part of the stimulus, and the introduction of reflected probes prevents the subject from solving the perceptual problem by feature-matching.

The Simultaneous Presentation Paradigm (Fig. 1a)

In the simultaneous presentation (which we abbreviate *sim*) paradigm (R. N. Shepard & J. Metzler, 1971), we present the standard and probe (interchangeable labels in this paradigm) side by side. By convention (R. N. Shepard & Cooper, 1982) the same/different reaction time (RT-[*sim*]) is the sum of the durations of four processes (see also Just & Carpenter, 1976): (a) *Stimulus identification*. (b) *Search*: The subject finds corresponding segments in the standard and the probe to determine the orientation of the probe. (c) "*Mental rotation*": The subject imagines the standard or the probe rotating to eliminate the angular disparity between them. (d) *Confirmation*: The subject compares the imagined transformed shape to the other and gives a same/different handedness response. Of these four processes, "mental rotation" is of central interest.

If we assume that the stimulus identification and the confirmation processes are independent of α , they should contribute only to the intercept of the function $RT[*sim*] = f(\alpha)$. The only processes affected by α should therefore be the search and "mental rotation." We assume the search process to be quick and that its effect on the slope of $RT[*sim*] = f(\alpha)$ is negligible.

The Successive Presentation Paradigm (Fig. 1b)

In the second paradigm (which we abbreviate *succ*), we present the standard and probe successively at the same place. The subjects study the standard *ad libitum*, trigger its replacement by the probe, and then make a same/different handedness response as quickly as they can. We obtain two RTs. The first, $RT_s[*succ*]$, is the time the subject takes to study the standard; we usually assume that this RT reflects only the stimulus identification process, and that the second, $RT_p[*succ*]$, comprises the remaining processes: search, "mental rotation," and confirmation. We also assume that the confirmation process is independent of α and that therefore the slope of $RT_p[*succ*] = f(\alpha)$ reflects the search process and "mental rotation," and it should not differ from the slope of $RT[*sim*] = f(\alpha)$ obtained in the simultaneous paradigm. Because $RT_p[*succ*]$ does not in-

clude the identification process, the intercept of $RT_p[\text{succ}] = f(\alpha)$ should be lower than the intercept of $RT[\text{sim}] = f(\alpha)$ in the simultaneous paradigm.

The Arrow Paradigm (Fig. 1c)

A trial in the third paradigm (which we abbreviate *arr*) consists of three phases: *standard*, *arrow*, and *probe* (we are describing the version of this paradigm used in the present study). First the subjects see the standard. The time they take before terminating the standard is $RT_s[\text{arr}]$. Next they see an arrow that specifies the orientation of the probe and must imagine the standard in the specified orientation of the probe ("mental rotation") as quickly as they can. The time they take is $RT_a[\text{arr}]$. When they indicate having imagined the rotation, the probe replaces the arrow. The time they take to make the same/different handedness judgment is $RT_p[\text{arr}]$. In this paradigm we assume that we have isolated the identification, search, and confirmation processes from "mental rotation." Since we assume that the identification and confirmation times are unrelated to α , their removal from $RT_a[\text{arr}]$ should only lower the intercept of $RT_a[\text{arr}] = f(\alpha)$ (compared to the intercept of $RT_p[\text{succ}] = f(\alpha)$ in the successive paradigm) and $RT_a[\text{arr}]$ should reflect only "mental rotation." Since this paradigm either shifts the search process to $RT_p[\text{arr}]$ (which may lead to a small slope in $RT_p[\text{arr}] = f(\alpha)$) or eliminates it altogether, its removal from $RT_a[\text{arr}]$ may slightly decrease the slope of $RT_a[\text{arr}] = f(\alpha)$ compared to the slope of $RT_p[\text{succ}]$.

Because subjects do not terminate the arrow with a judgment that can be correct or incorrect, we impose three conditions that the data must meet to ensure that subjects do not continue performing "mental rotation" in presence of the probe: (a) The subject's same/different response must be accurate (e.g., an error rate of less than 7%); (b) the subject's same/different response must be fast (e.g., $RT_p[\text{arr}] \leq 700$ ms); (c) the subject's same/different response must be independent of α (Fig. 1c). We borrowed the numerical values for these criteria from Bethel-Fox and R. N. Shepard (1988).

METHOD

Subjects

We recruited 16 University of Virginia undergraduates by poster and paid them \$30 to participate in this experiment. We did not analyze the RT data of 4 of these subjects, whose error rates exceeded 13% for more than two conditions.

Stimuli

We used two stimulus types: 3×3 matrices (see top two rows in Fig. 2) and irregular polygons (see bottom two rows in Fig. 2).

We copied two 3×3 matrices from Bethel-Fox and R. N. Shepard (1988) of different degrees of complexity, the simplest and the most complex of their stimuli. For each we created a reflected (see column 2 of Fig. 2) and a perturbed version (column 3 of Fig. 2). We perturbed the simple matrix by filling an additional cell in the simple matrix and moving a filled cell in the complex one.

We used two polygons: a "simple" one with 10 sides and a "complex" one with 16 sides. For each we created a reflected and a perturbed version. We perturbed the polygon by moving one vertex (with the origin roughly at the centroid of the polygon, we multiplied the abscissa of a randomly selected vertex by .65 and its ordinate by .75).

Design

We combined six independent variables in a within-subjects design.

Experimental paradigm. We studied three experimental paradigms: simultaneous, successive, and arrow. We described these procedures in the introduction to Experiment 1.

Stimulus type. We used two types of stimuli: polygon and matrix (described in Stimuli). *Complexity.* We used two levels of complexity (described under Stimuli).

Probe type. We used three types of probe: same as the standard, reflected, and perturbed. We presented as many "same" trials as "different" trials (reflected and perturbed); half of the "different" trials were reflected and half perturbed.

Angular disparity. We studied eight values of α , which ranged from 0 to 315° in 45° steps.

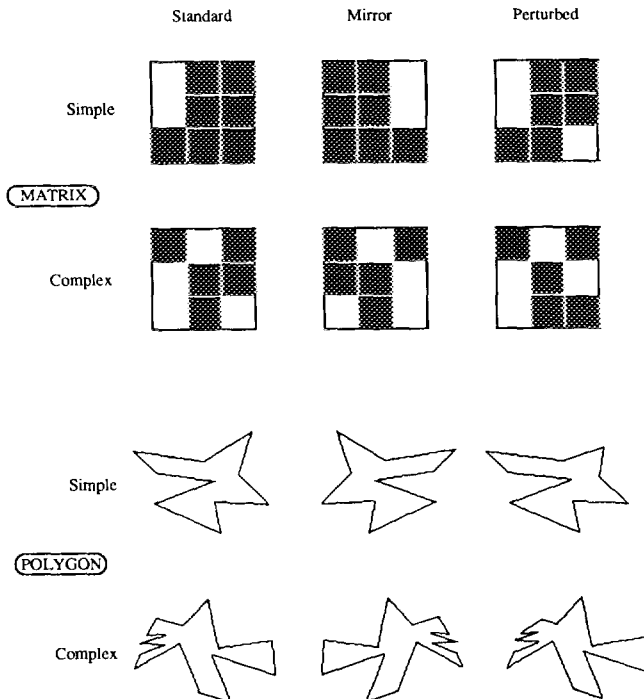


FIG. 2. Figures used in Experiment 1.

Blocks. Each session consisted of six blocks. Each block consisted of 64 trial types, i.e., all combinations of complexity, angular disparity, and probe type.

General Procedure

Each subject participated in six 1-h sessions. Each session consisted of a single experimental paradigm and one stimulus type. No two subjects received the same order of paradigm \times stimulus type combinations. Each paradigm \times stimulus type combination appeared equally often in each session serial position.

Not counting error trials, a session consisted of 64 practice trials (1 block, 64 trials/block) and 384 experimental trials (6 blocks). We programmed the computer to beep after errors and to randomly reschedule the trial within the same block. Subjects whose error rates exceeded 13% (in fewer than three conditions) repeated those conditions. (Four subjects repeated two conditions and three subjects repeated one condition. There were no significant differences between the slopes produced by the subjects who repeated the conditions and those who did not.)

We displayed the stimuli on a 19-inch Aurora monitor driven by a Masscomp 5500 computer. A black hood covered the monitor and kept the subjects 24 inches (0.61 m) from the screen. At that distance, the stimuli subtended 6.6 degrees. In the simultaneous presentation paradigm, we presented the standard stimulus on the left in a fixed orientation. We presented the probe stimulus 6° to the right of the standard. In the other two paradigms we presented the standard in the center of the screen *in the same fixed orientation*. We did this to ensure that in all paradigms the subjects could imagine a rotation of the probe back to a familiar standard. We randomized the stimulus-response mapping of the same/different buttons between subjects.

After the practice block, we gave the subjects an untimed break. We gave them similar breaks after multiples of 128 trials.

To urge subjects to respond quickly to the probe stimuli in the arrow paradigm (our pilot studies showed that otherwise RTs to the probe were intolerably long), we programmed the computer to sound two beeps whenever the subject's latency exceeded 700 ms (we did not discard these data). If the subject made a fast wrong response, the computer sounded one beep. If the subject made a slow wrong response, the computer sounded three beeps. During blocks 4-6, subjects met the 700-ms deadline in 94% of the trials.

No two subjects received the six types of sessions in the same order. Each paradigm appeared equally often in each ordinal position in the sequence of sessions.

RESULTS

Unless otherwise noted, we based our statistical inferences on data from responses to the "same" probes on blocks 4-6; the RTs for these blocks were relatively stable (see Fig. 3). In Table 2 we present the interested reader with data from blocks 1-3 as well as blocks 4-6. We recoded angular disparity as follows: if $\alpha > 180$, $\alpha \rightarrow 360-\alpha$; else $\alpha \rightarrow \alpha$. The RTs for each condition come from the stage in each trial during which one expects "mental rotation" to occur (see Fig. 1). In the simultaneous condition it is the only RT, RT[sim]. In the successive condition it is the RT to the probe, RT_p[succ]. In the arrow condition it is the time during which the subject allowed the arrow to be visible, RT_a[arr]. The data for "different" probes were consistent with the data for "same" probes and their analysis did not yield new insights into the processes under examination.

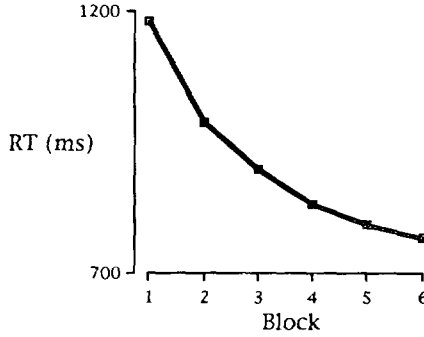


FIG. 3. Experiment 1: Mean RT for correct "same" responses as a function of block (averaged over sessions).

Paradigm Effects

Slopes. The slopes differed among the paradigms (Table 2). The slope for the simultaneous presentation paradigm was greater than the slope for the successive presentation paradigm [$t(11) = 2.8, p < .02$], and the slope for the successive presentation paradigm was greater than the slope for the arrow paradigm [$t(11) = 5.5, p < .001$], which does not differ from zero [$t(11) = 1.3, ns$]. (In blocks 1-3 the arrow paradigm's slope was significantly greater than 0: $t(11) = 3.9, p < .005$.) This pattern may be seen in the data pooled across subjects (Fig. 4).

Intercepts. The intercept for the simultaneous presentation paradigm was greater than the intercept for the successive presentation paradigm (880 vs 627 ms: $t(11) = 4.0, p < .001$), and the intercept for the successive presentation paradigm was greater than the intercept for the arrow paradigm (627 vs 400 ms: $t(11) = 6.9, p < .001$).

Other Effects

The slope for polygons did not differ from the slope for matrices (1.45

TABLE 2
Experiment 1: Slopes, Intercepts, and Error Rates for Three Experimental Paradigms

Paradigm	Blocks					
	Slope (ms/degree)		Intercept (ms)		Error rate (%)	
	1-3	4-6	1-3	4-6	1-3	4-6
Simultaneous	3.98	2.94	1,112	880	5.1	3.2
Successive	1.85	1.79	762	627	3.4	2.1
Arrow	2.12	0.20	446	400	7.3	3.2

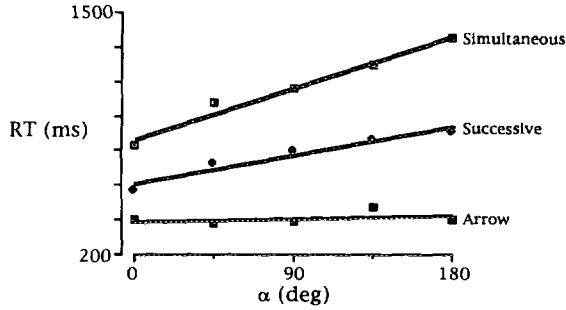


FIG. 4. Experiment 1: Reaction time as a function of angular disparity (α) for three experimental paradigms.

vs 1.84 ms/degree: $F(1,11) = 2.4$, ns). The intercept for polygons was greater than the intercept for matrices (719 vs 552 ms: $F(1,11) = 11.5$, $p = .006$).

Complexity had no effect on slope (1.66 (simple) vs 1.64 ms/degree (complex): $F(1,11) < 1$), but the intercept for the complex stimuli was greater than the intercept for the simple stimuli (671 (complex) vs 600 ms (simple): $F(1,11) = 5.9$, $p = .03$).

Error Rates

Error rates in the three paradigms were low (see Table 2). Even so, these estimates are inflated compared to standard procedures because we rescheduled error trials. We saw no indication of a speed-accuracy trade-off.

Validating the Arrow Paradigm

The data met the first two conditions stipulated to validate the arrow procedure. (1) Subjects were accurate: their error rate was less than 4%. (2) Subjects responded to the probe stimuli quickly: their $RT_p[\text{arr}]$ was 426 ms. The third condition raises some problems: we observed a slight slope (0.5 ms/degree) in $RT_p[\text{arr}] = f(\alpha)$.

DISCUSSION

As we argued in the introduction to this paper, if all our paradigms had called the same process into play, i.e., "mental rotation," then the slopes for the simultaneous and successive paradigms would have been the same, and the slope for the arrow paradigm would have been slightly shallower. This was not the case: (1) the slope in the simultaneous paradigm was steeper than the slope in the successive paradigm; (2) the slope in the arrow paradigm did not differ from zero.

Our most important finding was serendipitous. We can state it (some-

what redundantly) as follows: The slope we obtained in the arrow paradigm (1) is lower than the slope for the other two paradigms, (2) does not differ from R. N. Shepard and Cooper (1982) compared the arrow to the successive paradigm: the slopes were roughly the same. Two other articles contained slopes for the simultaneous and the arrow paradigms (Bethel-Fox & R. N. Shepard, 1988; Folk & Luce, 1987): the median slope for the arrow paradigm was higher than but not reliably different from the median slope for the simultaneous paradigm. There is one precedent for finding a flat $RT_a[\text{arr}] = f(\alpha)$ function in a handedness recognition task, but in the successive rather than the arrow paradigm. Kaushall and Parsons (1981) found that—after about 1000 trials—the slopes for three subjects did not differ from 0. The RTs of a fourth subject were unrelated to α after 72 trials.

Given the inconsistency of our arrow paradigm data with most of the published data, could the flat $RT_a[\text{arr}] = f(\alpha)$ function we obtained be artifactual? There are three ways in which subjects could produce flat functions:

(1) Our subjects could be using an inefficient strategy, e.g., slowing down their responses to small rotations or using a verbal strategy (see Bethel-Fox & R. N. Shepard, 1988). An inefficient strategy would imply a flat function with a high intercept. Our data do not support this prediction: *the intercept of $RT_a[\text{arr}] = f(\alpha)$ in the arrow paradigm was lower than the intercepts in the other two paradigms.*

(2) Tarr and Pinker (1989) suggest that subjects may—after considerable amounts of training—memorize a small set of forms in a small number of orientations. We used only four stimuli. Our subjects could have memorized the stimuli in the eight presented orientations. Had they memorized the forms in their specific orientations, this information would have been available to them in all the paradigms and would have produced flat rotation functions in the other paradigms. Our data do not support this prediction.

(3) Our subjects could be rotating during the probe presentation instead of the arrow presentation. We have some evidence in favor of this hypothesis: the slope of $RT_p[\text{arr}]$ is 0.5 ms/degree. However, this slope is much shallower than that traditionally associated with “mental rotation.”

Our second finding, a slope in the simultaneous paradigm steeper than that in the successive paradigm, is consistent with data obtained in other laboratories: whoever compared these paradigms (Steiger & Yuille, 1983; S. Shepard & D. Metzler, 1988; Takano, 1989) found a higher slope for the simultaneous paradigm. S. Shepard and D. Metzler (1988) explain this slope difference by proposing that “individuals can more rapidly imagine the rotation of an object . . . when they are imagining it rotated into an orientation that has previously been learned” (p. 9). We can rule out this

explanation. In our simultaneous condition we always showed the standard stimulus on the left in a fixed orientation. Therefore in both the simultaneous and the successive condition subjects knew equally well the orientation to which they should rotate the probe.

In the next two experiments we explore the serendipitous finding that subjects can perform the handedness recognition task without engaging in "mental rotation." From this point on we do not use the data of this experiment to buttress any of the major conclusions of this article.

We will not use the arrow paradigm in the next three experiments for the following two reasons: (1) It is susceptible to demand characteristics, because the subjects terminate the critical duration as soon as think they are ready to see the probe. There is much leeway in such a criterion. The other paradigms have the advantage of measuring the latency of a *correct response*. (2) The greatest drawback of the arrow paradigm is this: suppose $RT_a[\text{arr}]$ and $RT_p[\text{arr}]$ were flat, their sum would exceed the longest times in the successive paradigm, $RT_p[\text{succ}]$, when rotation *does* occur. This makes the interpretation of the arrow data difficult.

EXPERIMENT 2

We suspected that the increased pressure placed on the subjects to reduce response times in the arrow condition in Experiment 1 caused the flat slopes. In this procedure we wished to ensure that the subject performed all the work of "mental rotation" during the presentation of the arrow, and not perform any "mental rotation" during the presentation of the probe. Therefore we signalled the subject if his/her response to the *probe* exceeded 700 ms. Although we had intended this pressure to affect the subjects' speed of response to the probe and not to the arrow, we may have inadvertently done the latter. To test this hypothesis we conducted an experiment in which we varied the pressure applied to the subjects. Let us list the changes in procedure between Experiment 1 and the present experiment:

- (1) We vary the RT pressure applied to different groups of subjects.
- (2) We use only the simultaneous and the successive paradigms.

We made three further changes to allow us to infer the nature of the representation that underlies the production of flat slopes:

- (3) We use only two polygons per subject, one per 768-trial session.
- (4) In the simultaneous paradigm we present the standard in the same orientation on all trials. In the successive paradigm we present the standard in the same orientation for 48 practice trials, after which we present only the probe. Thus we are tempting the subjects to form a single orientation-bound representation of the single polygon presented in each session. If they do, we will observe a "mental rotation" function with this orientation as origin (i.e., $RT = f(\alpha)$ is not flat). If they do not, and the

functions $RT = f(\alpha)$ are flat, they might be forming either (a) an orientation-free representation of the stimulus, or (b) multiple orientation-bound representations of the stimulus (Tarr & Pinker, 1989).

(5) To make it impossible for subjects to form *multiple* orientation-bound representations of the stimuli, we present the probe in 360 different orientations (instead of 8 as in Experiment 1). Thus if we obtain flat slopes, we will infer that the subjects created an orientation-free representation.

We made one further change to focus our research on handedness information:

(6) We eliminated the perturbed version of the probe and used only same or reflected probes.

METHOD

Subjects

We recruited 32 University of Virginia undergraduates by poster; they received class credit for their participation in this experiment.

Stimuli

We used the same two irregular polygons used in Experiment 1 (see Fig. 2). For each we created a mirror image.

Design

We combined two between-subjects independent variables and three within-subjects independent variables.

RT Pressure (between subjects). We partitioned the session into blocks of 40 trials for subjects to whom we applied RT pressure. During block n , a deadline based on the RT distribution of block $n - 1$ was usually in effect (see Fig. 5). If an RT in block n exceeded the .85 quantile of the RTs in block $n - 1$ (i.e., the current RT was very slow), the computer sounded a beep after the subject's response. To prevent this procedure from pushing up

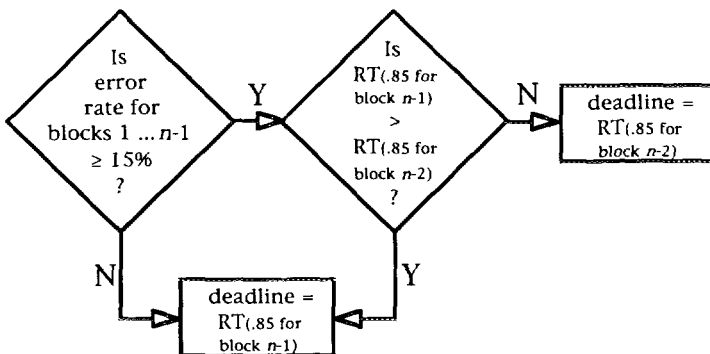


FIG. 5. Experiment 2: Flow diagram for the procedure we used to apply RT pressure to subjects.

error rates, if the overall error rate in blocks 1 through $n - 1$ exceeded .15, and the .85 quantile of the RTs in block $n - 1$ was lower than the .85 quantile for block $n - 2$, then the computer based the deadline on the statistics of block $n - 2$.

Experimental paradigm (between subjects). We studied two experimental paradigms: simultaneous and successive. We describe these procedures in the introduction to Experiment 1.

Complexity (within subjects). We used two levels of complexity (described under Stimuli) between sessions (with order counterbalanced between subjects).

Probe type (within subjects). We used two types of probe: same as the standard and mirror image. "Same" trials were as frequent as mirror image trials.

Angular disparity (within subjects). We studied 360 values of α ; they ranged from 0 to 359° in 1° steps.

General Procedure

Each subject participated in two 1-h sessions. Each session consisted of a single experimental paradigm and one stimulus type (i.e., a 10- or 16-sided random polygon and its mirror image). Not counting error trials, a session consisted of 48 practice trials and 720 experimental trials. We programmed the computer to beep after errors and to randomly reschedule the trial within the same block.

The stimulus displays were identical to those used in Experiment 1.

After the practice block, we gave the subjects an untimed break. We gave them similar breaks after multiples of 200 trials.

RESULTS

To check whether subjects had partitioned the orientations into equivalence sets for each of which they had memorized a prototype, we scanned plots of $RT = f(\alpha)$ for cyclical patterns. There were none.

We analyzed the data by performing a robust regression of RT on α for each level of RT pressure and for each probe type. Our analysis will focus on the responses to the "same" probes. Here is why. An ANOVA on error rates showed no effect of probe type. The slope and intercept data for "different" probes were consistent with the data for "same" probes and their analysis did not yield new insights into the processes under examination. In particular, the intercepts for "different" probes were higher, and the slopes were shallower than the corresponding intercepts and slopes for "same" probes. This pattern is consistent with the notion that "different" trials elicit multiple strategies in the subjects and are therefore less revealing of the important processes we wish to understand.

We summarize our data—responses to the "same" probes—in Table 3.

Effects of RT Pressure

There was an effect of RT pressure on slope (see Table 3) [$F(1,28) = 9.58, p = .004$], but not on intercept [$F(1,28) < 1, ns$]. RT pressure did not interact with other factors. In Fig. 6 we summarize the subject-by-subject distributions of slopes as a function of paradigm and RT pressure (16 slopes per condition: 8 subjects \times 2 levels of complexity). We note that

TABLE 3
Experiment 2: Slopes, Intercepts, Error Rates, and Learning Parameters for Two Experimental Paradigms and Two Degrees of RT Pressure

Paradigm	RT pressure	RT[<i>sim</i>] = <i>f</i> (α)			Learning	
		Slope (ms/degree)	Intercept (ms)	Error rate (%)	Δ Slope/block	Δ Intercept/block
Simultaneous	Yes	0.76	645	10.0	-0.10	-20
	No	1.51	638	4.0	-0.23	-55
Successive	Yes	-0.08	628	14.2	-0.10	-25
	No	1.53	625	2.9	-0.12	-34
Mean	Yes	0.34	636	12.1		
	No	1.52	632	3.5		

although (1) the mean slope obtained under RT pressure was significantly greater than 0 [$t(31) = 2.11, p = .02$] and (2) there was no interaction between paradigm and RT pressure and the mean slope under RT pressure for the successive paradigm did not statistically differ from 0 [$t(31) = -0.43, ns$].

The mean slope of the no RT pressure condition is significantly greater than 1.0 ms/degree [$1.52 \text{ ms/degree}; t(15) = 1.79, p = .047$]. The mean slope of the RT pressure condition is significantly less than 1.0 ms/degree [$0.34 \text{ ms/degree}; t(15) = 4.125, p = .0004$]. In addition, only 12.5% of the

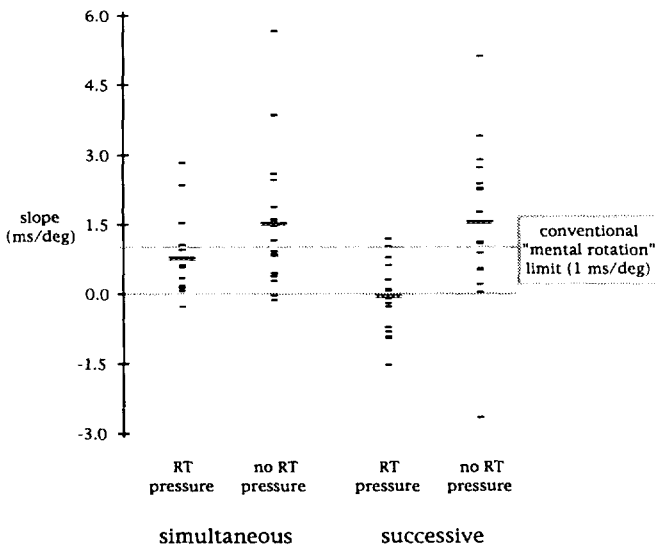


FIG. 6. Experiment 2: Slopes for eight subjects in each of two paradigms and two levels of RT pressure. The heavier horizontal bars represent the means.

subjects under RT pressure had slopes over 1.0 ms/degree, while 62.5% of the subjects not subjected to RT pressure had slopes over 1.0 ms/degree [$t(15) = 4.237, p = .0003$].

Other Effects

Paradigm had no effect on slope [$F(1,28) = 1.15, ns$], or on intercept [$F(1,28) < 1, ns$].

Complexity had no effect on slope (0.78 (simple) vs 1.08 ms/degree (complex): $F(1,28) = 1.32, ns$), but the intercept for the complex stimuli was greater than the intercept for the simple stimuli (657 (complex) vs 610 ms (simple): $F(1,28) = 4.91, p = .04$).

Error Rates

We observed significantly higher error rates when we applied RT pressure [$F(1,28) = 21.99, p = .0007$]. We wish to show that our results were not due to a speed-accuracy trade-off. Table 3 suggests such a trade-off: where slopes are high error rates are low, and vice versa. This apparent trade-off could take one of three forms: As subjects' RT slope decreases, the slope of the error rate may (a) decrease; (b) remain unchanged; (c) increase. In the first two cases the error rate cannot account for the change in RT slope; only the third case is an instance of genuine speed-accuracy trade-off. To determine in which of the three cases our data fall, we plotted the error distributions for the two paradigms (simultaneous and successive) for the two levels of RT pressure. They are respectively the marginal histograms in Figs. 7 and 8. At the top of Fig. 7 we plot the histogram of errors (over α) for the RT pressure condition in the simultaneous paradigm whereas on the right of Fig. 7 we plot the analogous histogram for the no RT pressure condition. (Note that the origin of the α axis for this condition is at the bottom of the graph, so that if you turn the page 90° counterclockwise to inspect the histogram, the α axis will run from right to left.) We normalized these histograms so that their areas are equal (which is why the "proportion per bar" scales are the same for both), even though there are more errors under RT pressure than in its absence (which is why the "count" scales for the two histograms are different: .1 of the cases under RT pressure represents just under 60 cases, whereas .1 of the cases under the no RT pressure conditions represents just under 20 cases).

With these histograms in hand, we reformulated the question of whether the slope of error rate as a function of α falls into one of the three classes mentioned above as follows: when RT pressure diminishes the subjects' RT slope, does the skewness of the error distribution (a) shift toward high values of α (i.e., there are relatively *fewer* errors at high values of α); (b) remain unchanged; (c) shift toward low values of α (i.e.,

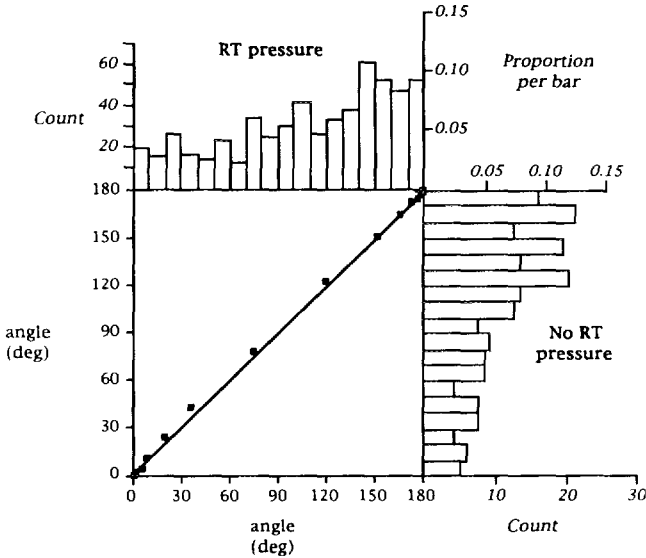


FIG. 7. Q-Q plot for Experiment 2 (simultaneous paradigm) for two levels of RT pressure, with the corresponding distributions of errors. The data fall on the diagonal. Thus the distributions are essentially the same. This implies that there is no correlation between speed and accuracy.

there are relatively *more* errors at high values of α ? In the first two cases the error distribution cannot account for the change in RT slope; only the third case is an instance of genuine speed-accuracy trade-off.

To determine the relation between the skewness of the error distributions under the two levels of RT pressure we made a Q-Q plot (Wilk & Gnanadesikan, 1968) for each paradigm (also shown in Figs. 7 and 8). Consider the points in Fig. 8. The median (half the area under the histogram) of the error distribution under RT pressure is at 100°; the median of the error distribution in the no RT pressure condition is at 113°. We place a point at coordinates (100, 113). The two lower quartiles (a quarter of the area under the histogram) of these two distributions are respectively at 45 and 67°. Now we place a point at coordinates (45, 67). The corresponding two upper quartiles yield a point at coordinates (145, 150). We proceed outward into the tails of the distributions, while we halve the tail area, thus producing eighths, sixteenths, . . . 128ths. We observe that the value of α for a given quantile is invariably higher for the no RT pressure condition than for the RT pressure condition. Hence, more errors lie *above* a given α for the no RT pressure condition than for the RT pressure condition. Thus the "slope" of the $p(\text{error}) = f(\alpha)$ is greater for the no RT pressure condition than for the RT pressure condition. Since the slope of

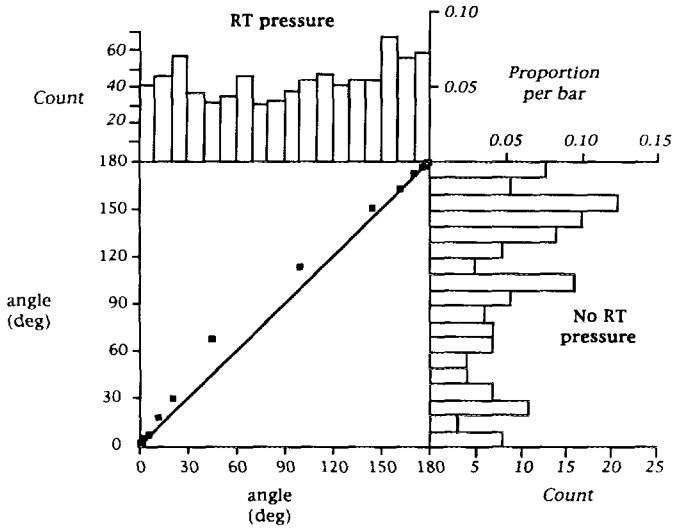


FIG. 8. Q-Q plot for Experiment 2 (successive paradigm) for two levels of RT pressure, with the corresponding distributions of errors. The data fall above the diagonal. Thus the faster responses are also more accurate.

the $RT = f(\alpha)$ function is greater for the no RT pressure condition than that for the RT pressure condition, RT and $p(\text{error})$ do not trade off, hence speed and accuracy do not trade off.

In our case, (a) if the error distribution for the RT pressure condition is skewed toward high values of α compared to the distribution for no RT pressure, the Q-Q plot will be concave downwards; (b) if the skewness of the two error distribution is the same, the Q-Q plot will be a straight line; (c) if the error distribution for the RT pressure condition is skewed toward low values of α compared to the distribution for no RT pressure, the Q-Q plot will be concave upwards. Figure 7 allows us to see that the comparison of the two error distributions falls under case b or (weakly) under case a. Figure 8 shows that the data fall under case a. None of our data falls under case c; therefore we cannot account for our data by a speed-accuracy trade-off.

Learning

To fit regressions to the change in slope and intercept over trials, we divided the 360 "same" trials in each session into six blocks of 60 trials. For each subject and each block in two sessions we performed a regression of $RT = f(\alpha)$. Because of the obviously skewed distribution of the RTs, we used for this purpose the function *rreg* (from the statistical package S; Becker & Chambers, 1984), which fits a linear model by iteratively

reducing the effect of observations with large residuals. We then subtracted the subject's mean slope and intercept from the 12 obtained slopes and intercepts for that subject and obtained least-squares regressions for slope = $f(\text{block})$ and intercept = $f(\text{block})$. The results appear in Table 3. In general, slopes did not change significantly over blocks. Only in the simultaneous condition with no RT pressure did the slope decrease significantly over blocks (-0.23 [ms/degree]/block \pm 0.09 [standard error]). In contrast, all intercepts decreased significantly over blocks. In Table 3 we show only the linear components of this decrement. From the small quadratic components we observed in all of them we inferred that most of the learning occurred in the first two or three blocks.

DISCUSSION

In the RT pressure condition of this experiment we reduced the slope to below what is traditionally found in "mental rotation" experiments. Recall that we presented each of the two polygons in only one privileged orientation (the orientation of the standard). Subjects saw each polygon only once in any other orientation (as probe). We thus gave no other orientation(s) a privileged status from which subjects could memorize the polygons in multiple specific orientations. Tarr and Pinker's (1989) research suggests that subjects can partition the orientations into equivalence sets and memorize a prototype for each. We found no evidence that subjects memorized some orientations in preference to others. Therefore, if subjects performed this task by memorizing the polygons, whatever they memorized (the so-called representation) must have been orientation-free. Subjects show such an ability in form-identification tasks, in which handedness information is of no importance. This experiment allows us to go further: the orientation-free representation must also contain handedness information.

In the no RT pressure condition, subjects did form a single orientation-bound representation of the standard polygon, to which they rotated the probe.

We discuss the effects of learning in the General Discussion, because we find it easiest to understand them considering Experiment 4.

Because of the importance of these findings, we found it prudent to replicate Experiment 2.

EXPERIMENT 3

We replicated Experiment 2 to increase our confidence in its results. We studied a large number of subjects to estimate the proportion of subjects in each condition who "mentally rotated" (i.e., had a slope over 1 ms/degree). This experiment was a simplified version of Experiment 2. We used the successive paradigm with and without RT pressure.

METHOD

Subjects

We recruited 100 University of Virginia undergraduates by poster; they received class credit for their participation in this experiment.

Stimuli

We created one 12-sided irregular polygon and its mirror image (see Fig. 2).

Design

We combined one between-subjects independent variable and two within-subjects independent variables:

RT pressure (between subjects). For subjects to whom we applied RT pressure, a deadline based on the RT distribution of a moving temporal window consisting the preceding 40 trials was usually in effect (see Fig. 9). If the current RT exceeded the 85th percentile of the RTs in the temporal window (i.e., the current RT was very slow), the computer sounded a beep after the subject's response. To prevent this procedure from pushing up error rates, if the overall error rate in *all* the preceding trials exceeded 15%, and the 85th percentile of the RTs in the current window was lower than the 85th percentile for the preceding temporal window, then the computer based the deadline on the statistics of the preceding temporal window.

Probe type (within subjects). We used two types of probe: same as the standard and reflected. "Same" trials were as frequent as "different" trials.

Angular disparity (within subjects). We studied 360 values of α ; they ranged from 0 to 359° in 1° steps.

General Procedure

Each subject participated in a single 1-h session. Each session consisted of 48 practice trials and 720 experimental trials (not counting error trials). We programmed the computer to beep after errors and to randomly reschedule the trial within the same block.

The stimulus displays were identical to those of Experiment 2.

After the practice block, we gave subjects an untimed break. We gave them similar breaks after multiples of 200 trials.

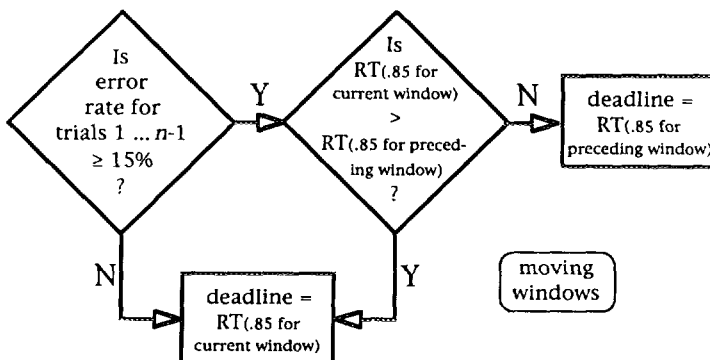


FIG. 9. Experiment 3: Flow diagram for the procedure we used to apply RT pressure to subjects.

RESULTS

We analyzed the data by performing a robust regression of RT on α for each level of RT pressure and for each probe type. We observed slightly fewer errors on “same” trials (6%) than on “different” trials (7.5%). An ANOVA confirmed this effect ($F(1,98) = 12.993, p = .0005$). Otherwise, we observed no differences between the slopes and intercepts for “different” probes and “same” probes. Therefore—as in the previous experiments—we focus our attention on the “same” probes only.

We summarize our data—responses to the “same” probes—in Table 4.

Effects of RT Pressure

There was an effect of RT pressure on slope (see Table 4) [$F(1,98) = 3.79, p = .044$], and on intercept [$F(1,98) = 10.09, p = .002$]. The mean slope of the no RT pressure condition is not significantly different from 1.0 ms/degree [$t(49) = 0.375, ns$]; whereas the mean slope of the RT pressure condition is significantly lower than 1.0 ms/degree [0.55 ms/degree; $t(49) = 4.09, p = .00008$]. In addition, only 20% of the subjects under RT pressure had slopes over 1.0 ms/degree, whereas 48% of the subjects not subjected to RT pressure had slopes over 1.0 ms/degree [$t(49) = 4.444, p = .00002$].

Error Rates

We observed significantly higher error rates under RT pressure [$F(1,98) = 35.455, p < 10^{-5}$]. We used the method introduced in Experiment 2 to show that our results were not due to a speed–accuracy trade-off. In Fig. 10 we show the two RT distribution and the Q–Q plot. The comparison of the two error distributions falls under case a (weakly) or case b, but not c; therefore our RT results were not due to a speed–accuracy trade-off.

DISCUSSION

In the RT pressure condition of this experiment we again reduced the slope to below what is traditionally found in “mental rotation” experiments. As in Experiment 2, we presented the polygon in only one privi-

TABLE 4
Experiment 3: Slopes, Intercepts, and Error Rates for Two Degrees of RT Pressure

RT pressure	RT[<i>sim</i>] = <i>f</i> (α)		
	Slope (ms/degree)	Intercept (ms)	Error rate (%)
Yes	0.55	596	11
No	0.94	705	3.9

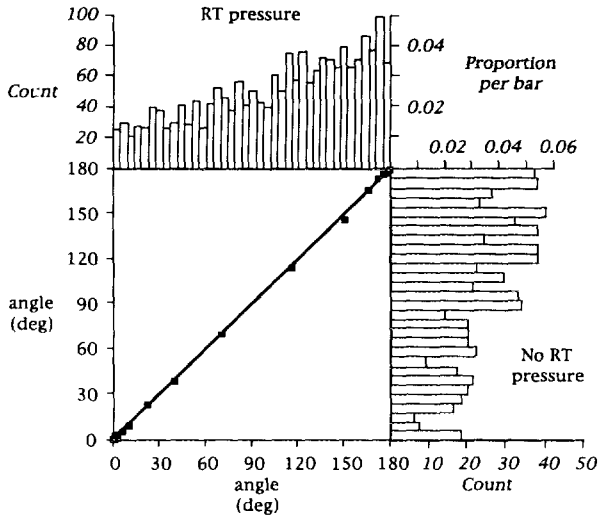


FIG. 10. Q-Q plot for Experiment 3 (successive paradigm), for two levels of RT pressure, with the corresponding distributions of errors. The data fall on the diagonal. Thus the distributions are essentially the same and there is no correlation between speed and accuracy.

leged orientation (the orientation of the standard). Subjects saw the polygon only once in any other orientation (as probe). We thus gave no other orientation(s) a privileged status from which subjects could memorize the polygons in multiple specific orientations (as did Tarr & Pinker, 1989). Furthermore, we found no evidence that subjects memorized some orientations in preference to others. What the subjects memorized (the so-called representation) must have been orientation-free if they performed this task by memorizing the polygons.

In the no RT pressure condition, subjects' mean slope did not significantly differ from 1.0 ms/degree, suggesting that subjects did form a single orientation-bound representation of the standard polygon, to which they rotated the probe. Nevertheless, the relative shallowness of the slope prompted us to look closer at the data. As stated earlier, subjects need not "rotate" to complete this task. By looking at individual subjects' data, we found that about half (48%) of the subjects in this condition did not "rotate" to complete this task. We have no explanation for this. However, this provides further evidence that subjects need not "rotate" to complete the task. The remaining half of the subjects in this condition did form a single orientation-bound representation of the standard polygon, to which they rotated the probe.

In the RT pressure condition, 20% of subjects exhibited slopes consis-

tent with "mental rotation." Thus, although RT pressure discourages the use of "mental rotation," it does not prohibit it.

The results of Experiment 3 replicated the results found in Experiment 2 and provide substantial evidence that subjects do not need to perform "mental rotation" to complete a handedness task.

The significantly shallower mean slope found in the presence of RT pressure (0.34 ms/degree in Experiment 2 and 0.61 ms/degree in Experiment 3) than in its absence (1.52 ms/degree in Experiment 2 and 0.94 ms/degree in Experiment 3) suggests that RT pressure gives subjects an incentive to memorize the forms. We have proposed the hypothesis that subjects gave flat RT functions under RT pressure in the handedness-recognition task because they had memorized orientation-free *and* handedness-specific information about the polygons. To test this memorization hypothesis we can prevent subjects from memorizing the polygons in the expectation that their RT function will no longer be flat, even under RT pressure. We did this in Experiment 4.

EXPERIMENT 4

To test whether memorization (i.e., the formation of an orientation-free representation) is necessary for flat RT functions to occur, we modify the stimulus sets of Experiments 2 and 3: instead of showing subjects *two* polygons and their reflections, we show subjects *all different* polygons. This makes memorization useless to the performance of the task, and thus makes the formation of any representation (*a fortiori* an orientation-free representation) impossible. Because subjects find it prohibitively difficult to perform the successive paradigm under such conditions, we use only the simultaneous paradigm in this experiment. In all other respects Experiment 4 is identical to Experiment 2. We expect to observe some decline in slopes due to RT pressure, but no elimination of slopes as observed in Experiments 2 and 3.

METHOD

Subjects

We recruited 16 University of Virginia undergraduates; they received class credit for their participation in this experiment.

Stimuli

We created 720 10-sided and 720 16-sided irregular polygons (see Fig. 2). For 360 polygons in each set we created a reflected version.

Experimental Paradigm

We studied one experimental paradigm: simultaneous. We described this procedure in the introduction to Experiment 1.

Design

We combined one between-subjects independent variable, and three within-subjects independent variables:

RT Pressure (between subjects). We used the same algorithm for applying RT pressure as in Experiment 3 (see Fig. 9).

Complexity (within subjects). We used two levels of complexity (described under Stimuli), between sessions (with order counterbalanced between subjects).

Probe type (within subjects). We used two types of probe: same as the standard and reflected. "Same" trials were as frequent as "different" trials.

Angular disparity (within subjects). We studied 360 values of α ; they ranged from 0 to 359° in 1° steps.

General Procedure

Each subject participated in two 1-h sessions. Each session consisted of one stimulus type (i.e., a 10- or 16-sided random polygon and its reflection). Not counting error trials, a session consisted of 48 practice trials and 720 experimental trials. We programmed the computer to keep after errors and to randomly reschedule the trial within the same block.

The stimulus displays were identical to those used in Experiment 1.

After the practice block, we gave subjects an untimed break. We gave them similar breaks after multiples of 200 trials.

RESULTS

An ANOVA on error rates showed no effect of probe type. The slope and intercept data for "different" probes were consistent with the data for "same" probes and their analysis did not yield new insights into the processes under examination. As in Experiment 2, we therefore focus our attention on the "same" probes only.

We summarize our data—responses to the "same" probes—in Table 5.

Effects of RT Pressure

There was an effect of RT pressure on slope (see Table 5) [$F(1,31) = 7.25, p = .018$], but not on intercept [$F(1,31) = 1.63, ns$]. We found no interaction of RT pressure with any of the other factors.

TABLE 5
Experiment 4: Slopes, Intercepts, Error Rates, and Learning Parameters for Two Degrees of RT Pressure

RT pressure	RT[<i>sim</i>] = $f(\alpha)$			Learning	
	Slope (ms/degree)	Intercept (ms)	Error rate (%)	Δ Slope/ block	Δ Intercept/ block
Yes	3.93	1427	18.6	-0.20	23
No	7.61	1739	11.7	-0.73	-21

Other Effects

Complexity had no effect on slope (5.60 (simple) vs 5.94 ms/degree (complex): $F(1,31) < 1$, ns), or intercept (1516 (simple) vs 1650 ms (complex): $F(1,31) < 1$, ns).

Error Rates

RT pressure did not significantly affect error rates [$F(1,14) = 1.69$, ns]. We used the method introduced in Experiment 2 to show that our results were not due to a speed-accuracy trade-off. In Fig. 11 we show the two RT distributions and the Q-Q plot. The comparison of the two error distributions falls under case a (weakly) or case b, but not c; therefore our RT results were not due to a speed-accuracy trade-off.

Learning

We analyzed the learning in Experiment 4 in the way described under Results of Experiment 2. We show the results in Table 5. There were significant changes in slope over blocks for both conditions (RT pressure: -0.20 [ms/degree]/block ± 0.10 ; no RT pressure: -0.73 [ms/degree]/block ± 0.20). Neither condition showed significant changes in intercept over blocks.

DISCUSSION

The error rates were high in this experiment compared to the previous experiments. This was probably due to the difficulty of the task: we presented a new pair of polygons on each trial.

RT pressure reduced the slope of the RT function by a factor of two, but did not reduce it to the point where we could entertain doubts regarding the operation of "mental rotation." This supports our hypothesis that flat RT functions will occur only when we give subjects the opportunity to memorize the forms we ask them to compare.

GENERAL DISCUSSION

We have discovered conditions under which subjects can perform a task—hitherto thought always to involve a rate-limited "mental rotation" process—rapidly, at a latency that is nearly independent of α . These conditions are: (1) a small set of forms; (2) RT pressure.

From the data collected using the arrow paradigm in Experiment 1 and from the data of Experiments 2 and 3 we concluded that subjects could accurately perform a handedness recognition task without using "mental rotation." Because in Experiment 1 we presented four stimuli in eight orientations, we could not tell whether the flat slopes were due to the formation of multiple orientation-bound representations or a single orien-

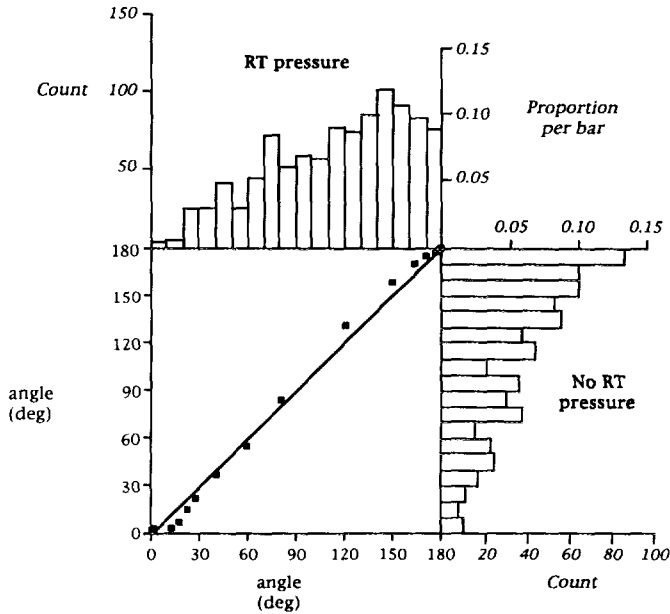


FIG. 11. Q-Q plot for Experiment 4 (simultaneous paradigm), for two levels of RT pressure, with the corresponding distributions of errors. The data fall on the diagonal. Thus the distributions are essentially the same and there is no correlation between speed and accuracy.

tation-free representation. That is why in Experiments 2 and 3 we presented the probe polygons in many different orientations (preventing the subject from creating multiple orientation-bound representations). Thus the information subjects memorized in Experiments 2 and 3 (and probably in Experiment 1) must have been *orientation-free*. Because the tasks in these experiments required handedness discrimination, the information the subjects memorized must also have been *handedness-specific*.

Our results challenge the two theories of mental representation outlined in the introduction. Takano (1989) asserts that "mental rotation [has] to be performed in the RO condition [the handedness-recognition task]" (p. 35). He claims that handedness information is of necessity orientation-bound because the internal relations among features take the form of "to the right of" or "below," relations that change when orientation changes. We have shown that subjects can perform handedness recognition without engaging in "mental rotation" as defined in the introduction. Tarr and Pinker (1989) contend that they have refuted "the hypothesis that complex shape recognition is accomplished by matching orientation-independent representations" (p. 276). Even though we do not maintain

that subjects accomplish *all* complex shape recognition this way, we have established that they *can* execute complex shape recognition in this manner. Furthermore, Tarr and Pinker state that "representations used in recognition are specific to a shape in a particular orientation and a particular handedness" (p. 276). Our data refute the first part of this claim (orientation-specificity) and support the second (handedness-specificity).

Experiment 4 demonstrated that we must present subjects with each form more than once and (probably) in more than one orientation to induce them to memorize its orientation-free and handedness-specific characteristics. How can subjects combine orientation-free information with handedness information in a memorized representation? Subjects can achieve an orientation-free representation of a polygon by generating an ordered list of pairs of features [(length 1, angle 1), (length 2, angle 2), . . . , (length n , angle n)] in *clockwise* (cw) or *counterclockwise* (ccw) order. As long as this list includes parts of the figure that are sufficiently different when read in cw and ccw order, it need not encompass the entire figure, i.e., n may be smaller than the number of vertices of the polygon.

Are Mental Representations Invariant?

Tarr and Pinker (1989) have presented evidence that no mental representation is orientation-free. Takano (1989) has presented evidence that only handedness information is orientation-bound. We have presented evidence that mental representations can be orientation-free and handedness-specific. How can we reconcile these three positions? We submit that mental representations are not invariant nor do they manifest themselves independently of motivation. We also contend that not all types of mental representations are equally easy to achieve: an orientation-free, handedness-specific representation is more difficult to achieve than an orientation-free, handedness-free representation or an orientation- and handedness-specific representation.

The efficient performance of different tasks may require subjects to form different mental representations. (1) Multiple orientation-bound representations may have been appropriate for the Tarr and Pinker task because they presented numerous trials containing few stimuli in *few orientations*. Such representations do not require the motivating force of RT pressure. (2) *Either* a single orientation-bound and handedness-specific representation *or* a single orientation-free, handedness-specific representation may have been appropriate for Takano's handedness recognition task (and virtually all other handedness recognition tasks). He found "mental rotation" functions, suggesting a single orientation-bound and handedness-specific representation, because he did not strongly motivate his subjects. We, on the other hand, found flat slopes, suggesting a single orientation-free, handedness-specific representation, when we (a)

motivated subjects with RT pressure and (b) used few stimuli. (3) Finally, a single orientation-bound and handedness-free representation may have been appropriate for Takano's form identification task, in which he found no "mental rotation" functions, because he presented numerous trials containing few stimuli in a *number of orientations*. This representation was achievable without exerting motivational pressure.

Effects of Learning

We first note that learning or practice cannot be the cause of the flat functions we observed: the functions were flat only under RT pressure. We gave the RT pressure subjects in Experiment 2 and 3 the same amount of practice as the non-RT pressure subjects.

In Experiment 2 we observed little change in slope over blocks and a considerable change in intercept. In Experiment 4 we observed considerable change in slope over blocks and no change in intercept. This finding dissociates the processes underlying these two parameters of the rotation function. As we pointed out in the introduction, convention equates the intercept with the identification and comparison stages, and the slope with the search and rotation stages. (The results of Experiment 1 had already suggested that this conventional interpretation is lacking: there was a difference in slope between the simultaneous and the successive paradigms, even though they differ only in the presence of the identification stage.) In Experiment 2 subjects became familiar with the small set of polygons; this process of memorization probably affected the identification stage, and therefore the intercept changed. In Experiment 4 subjects could not become familiar with the shapes; hence we observed no change in intercept.

It is no wonder that the slope does not change in the RT pressure conditions of Experiment 2, since by the time they reach the first block (after about 130 "same" and "different" trials), the subjects' slopes are flat. The change in slope in Experiment 4 might be due to a gradual increase in the rate at which subjects perform "mental rotation." The change in slope is in keeping with the widespread finding that speed of rotation increases with practice in "mental rotation" experiments.

Open Questions

We can say little about the nature of the memorization process observed in Experiments 2 and 3. We do not know the parameters of its acquisition, nor how lasting it is. Nor do we know the capacity of this memory: If we presented each form repeatedly over an indefinitely long stretch of time how large a set of forms could subjects memorize?

We conclude with a cautionary note. Students of the perception, recognition, and comparison of forms in different orientations have thought

that instructing subjects to respond as quickly as they can while minimizing error will produce data that faithfully reflect rate-limited processes. This may be a risky assumption to make, since RT pressure can reduce, or even eliminate, slopes thought to be irreducible. We face several puzzles. What are subjects doing when we do not subject them to RT pressure? Why are their functions linear? Are they unnecessarily performing a slow "mental rotation"? Or does the experimental situation contain demand characteristics that induce the subjects to respond more slowly the greater α ?

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