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# Mental Rotation: Effects of Dimensionality of Objects and Type of Task

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The original studies of mental rotation estimated rates of imagining rotations that were much slower when two simultaneously portrayed three-dimensional shapes were to be compared (R. Shepard & J. Metzler) than when one two-dimensional shape was to be compared with a previously learned two-dimensional shape (Cooper and her associates). In a 2 × 2 design, we orthogonally varied dimensionality of objects and type of task. Both factors affected reaction times. Type of task was the primary determiner of estimated rate of mental rotation, which was about three times higher for the single-stimulus task. Dimensionality primarily affected an additive component of all reaction times, suggesting that more initial encoding is required for three-dimensional shapes. In the absence of a satisfactory way of controlling stimulus complexity, the results are at least consistent with the proposal that once three-dimensional objects have been encoded, their rotation can be imagined as rapidly as the rotation of two-dimensional shapes.

The initial studies of mental rotation were of two types: (a) those by Roger Shepard and Jacqueline Metzler using perspective views of three-dimensional objects and measuring the time to determine whether two simultaneously presented objects, though differing in their orientations, were of the same three-dimensional shape (J. Metzler, 1973; J. Metzler & R. Shepard, 1974; R. Shepard & J. Metzler, 1971) and (b) those by Lynn Cooper and her associates (including R. Shepard) using two-dimensional shapes (alphanumeric characters or random polygons) and measuring the time to determine whether a single object, though differing in orientation from a previously learned object, had the same intrinsic shape as that previously learned object (Cooper, 1975, 1976; Cooper & Podgorny, 1976; Cooper & R. Shepard, 1973). As is summarized in Table 1, the estimated rates of mental rotation were always much lower for the experiments of the first type (ranging between 20 and 140 deg/s) than for the experiments of the second type (ranging between 300 and 600 deg/s).

Variations between experiments within either of these two types can probably be explained by details of the particular experiments. Within experiments of the first type, that the rates estimated by J. Metzler (1973) were about twice the rates estimated in the other experiments may be attributable to her use of simpler stimuli (viz., portrayals of objects containing only 7 cubes and two right-angled bends, rather than 10 cubes and three such bends) and, particularly, to her use of easier rotations (viz., rotations about the natural axis of the object, rather than about an arbitrary axis; see J. Metzler & R. Shepard, 1974, and, for a related finding, Just & Carpenter, 1985). Moreover, that the rates estimated by Just and Carpenter (1976) were the slowest may be attributable to their use of relatively less practiced subjects. Within experiments of the second type, that the rates estimated by Cooper and Shepard (1973) were lower than for the other experiments may be attributable to their use of different stimuli (alphanumeric characters, rather than random polygons), and that the rates estimated by Cooper (1976) and by Cooper and Podgorny (1976) were the fastest may be attributable to the more extensive practice of their subjects.

The much larger differences between the two types of experiments remain to be explained. These differences could be primarily a consequence of either or both of two obvious factors that were confounded in this set of earlier experiments: namely, (a) the nature of the stimuli, which were portrayals of three-dimensional objects for the first type and of two-dimensional objects for the second (and which may have differed in complexity as well) and (b) the nature of the experimental task, which required subjects to compare two externally presented stimuli in the first type and to compare a single external stimulus against an already available internal representation in the second type. However, there are reasons to suppose that these two factors might have different chronometric effects.

More time might be required to construct an internal representation of a three-dimensional object from a two-dimensional picture of that object than would be required to

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The first author is responsible for the planning and execution of the experiment and for the written report. The second author contributed to the experimental design and carried out the statistical analyses. (We hope that the present publication of an experiment on the phenomenon of mental rotation, originally demonstrated by R. Shepard and J. Metzler, 1971, but now by a different Shepard and a different Metzler, will not prove too confusing!) The experiment was first reported by Shenna Shepard at the annual meeting of the Psychonomic Society in Boston, November 1985.

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Table 1
*Summary of Previous Results for Two Types of Experiments on Mental Rotation*

| Experiment and type *of rotation (for 3D)* | RT at 0° *(in s)* | Estimated rate of rotation *(deg/s)* |
|---|---|---|
| Two 3D objects compared with each other | | |
| Metzler & Shepard (1974; Experiment 1) | | |
| In plane | 1.0 | 46 |
| In depth | 1.2 | 64 |
| Metzler & Shepard (1974; Experiment 2, mixed) | | |
| In plane | 1.9 | 50 |
| In depth | 2.0 | 40 |
| Metzler & Shepard (1974; Experiment 2, pure) | | |
| In plane | 1.9 | 47 |
| In depth | 1.8 | 38 |
| Metzler (1973; Experiment 1) | | |
| In plane | 1.2 | 100 |
| In depth | 1.2 | 138 |
| Just & Carpenter (1976) | 1.0 | 21 |
| One 2D object compared with an internal representation | | |
| Cooper & Shepard (1973) | 0.55 | 327 |
| Cooper (1975; Experiment 1) | 0.78 | 450 |
| Cooper (1975; Experiment 2) | 0.56 | 369 |
| Cooper & Podgorny (1976) | 0.58 | 600 |
| Cooper (1976) | 0.53 | 621 |

*Note.* RT = reaction time. 2D, 3D = two-, three-dimensional.

interpret a two-dimensional pattern simply as that two-dimensional pattern. If so, the extra initial encoding time for three-dimensional objects would manifest itself as an increase in reaction time even when there is no angular discrepancy between the objects compared. In agreement with this expectation, the left column in Table 1 shows that the reaction times at 0° were indeed consistently longer for the experiments using three-dimensional objects. The representation of three-dimensional objects could also entail additional processing throughout the imagined rotation. However, a large effect of the dimensionality of an object on the rate at which one can imagine its rotation would seem to be at variance with two previous findings: the finding that rate of mental rotation is independent of stimulus complexity (Cooper, 1975; Cooper & Podgorny, 1976)—at least for well learned stimuli (see Bethell-Fox & R. Shepard, 1988)—and the indications, from eye-fixation records, that differences between two- and three-dimensional conditions in the slope of the function relating reaction time to angular difference are primarily attributable to processes of search and confirmation rather than the process of mental rotation per se (Carpenter & Just, 1978).

The question of whether the dimensionality of the stimuli affects rate of mental rotation nevertheless remains one of considerable theoretical importance. Some theories of the representation of objects and their transformations have focused primarily on the two-dimensional case (e.g., Kosslyn, 1980; also see Ullman, 1979). Yet there are reasons to believe that the three-dimensional case is of greater importance (e.g., Attneave, 1972; J. Metzler & R. Shepard, 1974; R. Shepard, 1981, 1984). In particular, R. Shepard (1981) has argued that the purpose of internal representation is to model what is going on in external three-dimensional space and that it is this internally constructed representation that is then subject to mental transformation. On this view, all objects are represented as in three-dimensional space, and the difference between what we call a three-dimensional and a two-dimensional object is, in a sense, only the difference between two types of three-dimensional objects—one that is thick and one that is very thin. If so, the rate at which we imagine the rotation of an object in space might be the same in both of these cases.

Attempts to assess the effects of what has been called dimensionality are complicated, however, by the difficulty of separating dimensionality from stimulus complexity. Some researchers have attempted to control complexity by equating the pictures of two- and three-dimensional objects with respect to the numbers of visible line segments of which they are composed (e.g., Cooper & Farrell [described in R. Shepard & Cooper, 1982, pp. 178–181]; Jolicoeur, Regehr, Smith, & Smith, 1985). However, if it is the internal representation of the object in three-dimensional space that is mentally transformed, the numbers of such surface features of the two-dimensional projection may be largely irrelevant (see J. Metzler & R. Shepard, 1974). Moreover, attempts to control surface complexity in this way may weaken the manipulation of dimensionality. For example, outlines of three-dimensional objects, though themselves two-dimensional, may still be seen as three-dimensional objects in silhouette. If so, additional lines arbitrarily drawn within those outlines (in order to match the number of lines in the standard portrayal of the three-dimensional objects—see Jolicoeur et al., 1985) may be perceived only as a sort of texture of the silhouette and may not entirely preclude a three-dimensional interpretation. In any case, to the extent that such lines are perceived as irrelevant to the three-dimensional structures of the objects, those lines may not appreciably increase the perceptual complexity of the objects.

In the absence of a measure of perceived complexity applying across stimuli of different dimensionalities, our strategy has been to attempt a strong manipulation of perceived dimensionality (flat vs. solid appearance) and to forego the attempt to control complexity as such. As a consequence, we forfeit the possibility of a definitive specification of how much our results are attributable to dimensionality, as such, and how much they are attributable simply to complexity. However, we offer reasons for supposing that the results that we obtain for our two types of stimuli are not primarily attributable to the complexities of the two types of stimuli themselves but, rather, to the complexities of the mappings from the two-dimensional stimuli to the two- and three-dimensional objects that those stimuli represent in the two cases.

Quite apart from the nature of the stimuli, the nature of the task might be expected to have an appreciable effect on rate of processing. Comparison between two objects that are simultaneously presented, with each in an unpredictable orientation (as in experiments of the first type), might require more time than comparison between one object and an internal representation of an object in one, already well-learned standard orientation (see R. Shepard & Cooper, 1982). In the case of simultaneous presentation, individuals do tend to look back and forth between the two presented objects while performing the mental rotation (Just & Carpenter, 1976; also see J. Metzler & R. Shepard, 1974). This suggests that people have difficulty maintaining adequate representations of two arbitrarily oriented objects in memory during the process of mental transformation. In order to ensure accuracy in this two-stimulus task, therefore, subjects may have to proceed more slowly throughout the imagined rotation.

In short, the three findings suggested to us by earlier indications are the following: (a) The dimensionality of the stimuli affects the overall height of the reaction-time function, so that stimuli perceived as three-dimensional yield the higher function. (b) Dimensionality, however, has a relatively small effect on the slope of the reaction time function. (Even if dimensionality has no effect on rate of imagined rotation, the slope of the obtained reaction-time function might be slightly steeper for the three-dimensional objects because of a small increase in the search and confirmation times with angular departure that may be greater for the three-dimensional objects—again, see Carpenter & Just, 1978.) (c) The primary determiner of the slope of the reaction-time function is, instead, the type of task, with the two-stimulus task yielding the steeper slopes and, hence, the slower inferred rates of mental rotation. In order to obtain more direct evidence relative to these three expectations, we used a 2 × 2 design to assess the separate chronometric effects of the two originally confounded factors of dimensionality of stimuli and type of task. Moreover, in order to ensure both a strong manipulation of dimensionality and a close correspondence with previous studies, we used, in the two-dimensional case, the flat polygons originally employed by Cooper which differed by picture-plane rotations only; and, in the three-dimensional case we used the solid cubical objects employed by Shepard and Metzler, which differed by depth rotations only.

## Method

### *Subjects*

Twenty-six Tufts University undergraduates (14 female, 12 male) were each paid $5.00 for their participation in two 45-min experimental sessions.

### *Stimuli*

The two-dimensional shapes (Figure 1A) were the standard and reflected versions of the 24-point (Attneave-type) polygon used by Cooper (1973, 1975, 1976) and by Cooper and Podgorny (1976). These shapes were displayed in orientations differing by 45° steps in the picture plane. The three-dimensional shapes (Figure 1B) were rigid arm-like structures composed of cubical blocks, like the objects originally used by R. Shepard and J. Metzler (1971). The objects employed here, however, were the simplified ones, consisting of only seven cubes and two right-angled bends, initially described by Shepard in 1969 (see R. Shepard & Cooper, 1982, p. 21) and first experimentally investigated by J. Metzler (1973; also see J. Metzler & R. Shepard, 1974). As in the various studies by R. Shepard and J. Metzler, subjects were presented not with the three-dimensional objects themselves but with two-dimensional perspective views of the objects. The three-dimensional objects were portrayed in orientations differing, again, by 45° steps—but this time around the natural axis of the objects, in depth (see Figure 1B). Single stimuli, of either type, subtended a visual angle of approximately 1.5°. Stimulus onset was controlled by displaying all stimuli in a two-channel tachistoscope (Science Prototype, model N900).

### *Experimental Design*

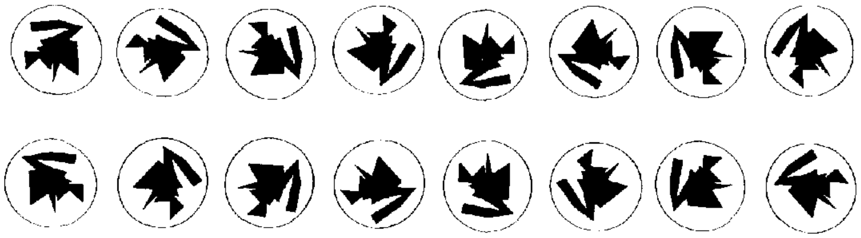
In order to avoid confounding effects of transfer of learning from one task to the other, concerning specific stimuli, we adopted a mixed design in which each subject was assigned to only one of the two types of tasks (one stimulus or two stimuli), but in which each subject undertook the assigned type of task with each of the two types of stimuli (two-dimensional and three-dimensional) on different days (up to a week apart). Thirteen of the 26 subjects were assigned to each of the two tasks, and order of presentation of stimulus type (two-dimensional or three-dimensional) was counterbalanced over each subset of 13 subjects.

*Two-stimulus task.* This is essentially the task introduced by R. Shepard and J. Metzler (1971). The experimenter told subjects that they would be shown pictures of two forms and that their task was to determine whether those two forms were intrinsically of the same shape, despite possible differences in the spatial orientations in which they were portrayed. The experimenter explained that "intrinsically of the same shape" meant that the two objects could be made congruent by rigidly moving one with respect to the other in space; and that "intrinsically different in shape" meant that the two objects, like a left and right hand, could not be brought into congruence by any rigid motion in space. Because we were concerned not with the prevalence of spontaneous mental rotation but, rather, with the rate at which such a process is carried out when it is undertaken, subjects were instructed to make the required judgment of "same" or "different" by first imagining one stimulus rotated into the orientation of the other in its appropriate space (two-dimensional or three-dimensional). The experimenter emphasized that even though two stimuli may initially appear to be quite different, they may nevertheless be found to be identical in intrinsic shape when one is rotated into the orientation of the other. The point was concretely illustrated by physically rotating one of two demonstration stimuli into a match with the other.

Each subject classified (as same or different) 10 practice pairs, and then 80 test pairs of the chosen type (two-dimensional or three-dimensional). For 40 test pairs the correct classification was "same," and for 40 it was "different." Within each pair, the stimuli differed in spatial orientation from 0° to 180°, in 45° steps in either direction. Each of the resulting eight angular differences appeared 10 times. Half of the pairs consisted of shapes that were intrinsically the same, and half consisted of shapes that were irreducibly different enantiomorphs—differing (like a left and right hand) by a reflection in space. In either case, the centers of the two shapes were horizontally separated by a visual angle of 2.6°. Right-handed individuals were instructed to depress the right-hand button as soon as they determined that the forms were intrinsically the same and the left-hand button as soon as they determined that the forms were intrinsically different. The roles of the two hands were reversed for left-handed subjects.

*One-stimulus task.* This task was essentially that described by Cooper (1975). Subjects were given 40 training trials in which they learned to discriminate between 20 standard and 20 reflected (enantiomorphic) presentations of the stimulus in one particular orienta-

**A.** TWO-DIMENSIONAL STIMULI, AND REFLECTED VERSIONS (from Cooper, 1973)



**B.** THREE-DIMENSIONAL STIMULI, AND REFLECTED VERSIONS (from Metzler, 1973)

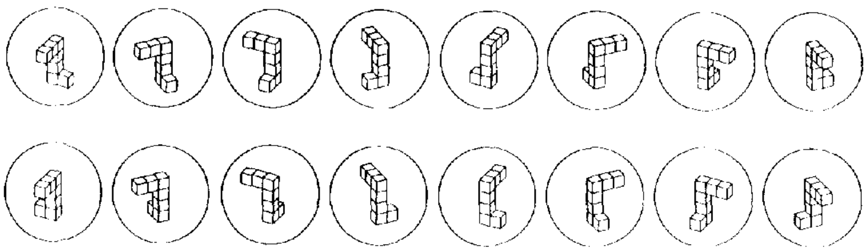


*Figure 1.* Panel A: The two-dimensional 24-point polygon used by Cooper (1973, 1975), displayed in eight orientations differing by 45° steps of rotation in the picture plane (top panel), and the corresponding orientations of the reflected version (bottom panel). Panel B: The three-dimensional seven-cube object displayed, as in the experiment by Metzler (1973), in eight orientations differing by 45° steps of rotation in depth (top), and the corresponding orientations of the reflected version (bottom). (Part A is from "Internal Representation and Transformation of Random Shapes: A Chronometric Analysis" by L. A. Cooper, 1973, doctoral dissertation, Stanford University. Adapted by permission. Part B is from "Cognitive Analogues of the Rotation of Three-Dimensional Objects" by J. Metzler, 1973, doctoral dissertation, Stanford University. Adapted by permission.)

tion (the orientation shown at the far left in each row in Figure 1). They were told that they would then be presented with a series of single stimuli in which the form, in either its standard or reflected version, would be shown in various spatial orientations. In agreement with the instructions for the two-stimulus task, the experimenter explicitly instructed the subjects to imagine the presented shape rotated into its originally learned orientation and then to determine whether the object thus transformed was the standard or the reflected version. The fact that the appearance of a stimulus could change markedly when it was rotated into the proper orientation was concretely illustrated by physically rotating a demonstration object into its previously learned orientation.

Each subject then classified (as standard or reflected) 10 practice stimuli, and then 80 test stimuli of the chosen type (two-dimensional or three-dimensional). For 40 test stimuli the correct classification was "standard," and for 40 it was "reflected." The presented orientations differed from the previously learned orientation from 0° to 180°, in 45° steps—equally often in either direction. Each of the five angular differences (from 0° to 180°, but combined over the two directions of rotation) appeared 16 times (8 times in each of the two, standard or reflected versions). Right-handed individuals were asked to depress the right-hand button to respond "standard" and the left-hand button to respond "reflected." This assignment was reversed for left-handed subjects.

In both tasks, the experimenter called "Ready?" at the beginning of each trial. Upon an affirmative reply, the experimenter operated a switch that displayed the next stimulus or pair in the tachistoscope and simultaneously started the reaction-time clock. Subjects proceeded under the instructions to respond as quickly as possible while keeping errors to a minimum. Whenever an error was made (which happened on an average of 6.5% of the trials), the subject was informed of the mistake, and the trial was repeated later in the session until an errorless reaction time had been recorded for each test stimulus or pair.

## Results

### *Chronometric Data*

As in the original experiments of R. Shepard and J. Metzler (1971; J. Metzler & R. Shepard, 1974), we focus primarily on the latencies of errorless positive responses—that is, responses correctly signaling "same" (in the two-stimulus task) or "standard" (in the one-stimulus task). Reaction times for the response "different" were not reported in the original experiment of R. Shepard and J. Metzler (1971). Moreover, latencies for these negative responses have subsequently proved to be more variable and difficult to interpret, particularly when the orientations differ by large rotations and when, as here, the number of structurally different objects and orientations presented is small. In such cases, subjects are sometimes able to base their negative responses on short-cut nonrotational strategies—at least in the two-stimulus task (see Cooper & R. Shepard, 1982, p. 55; J. Metzler & R. Shepard, 1974).

The two panels in Figure 2 show how mean reaction time for the correct positive responses increased with angular difference for each of the four conditions of the 2 × 2 design. The panel on the left displays the chronometric data from the subjects assigned to the one-stimulus task, and the panel on the right displays the data from the subjects assigned to the two-stimulus task. Within each of these panels, a separate linear function has been fitted (by least squares) to the data for the condition in which the two-dimensional and the condition in which the three-dimensional objects were portrayed (labeled *2D* and *3D*, respectively). Table 2 summarizes the reaction time intercepts, and Table 3 summarizes the rate parameters estimated from the fitted linear functions for these positive trials and compares these with the results (from Table 1) for the comparable earlier experiments. The estimated rates of mental rotation (in degrees per second) are obtained by taking the reciprocals of the corresponding slopes of the fitted linear functions (in milliseconds per degree) and then multiplying these by 1000 ms/s.

## *Agreement With Previous Results*

For those conditions of the present experiment that match the conditions of the original experiments—namely, those combining the one-stimulus task with the two-dimensional objects, or combining the two-stimulus task with the three-dimensional objects—the present results are in reassuring agreement with those of the earlier experiments. In every case, the present mean falls reasonably near the middle of the range of corresponding previous means. Indeed, when only the previous experiments that used exactly the stimuli employed in our experiment are considered—namely, the one-stimulus experiments using Cooper's 24-point polygons (Cooper, 1975, Experiments I & II; Cooper & Podgorny, 1976) and the two-stimulus experiment using the objects composed of just seven cubical blocks and two right-angled bends (J. Metzler, 1973; see J. Metzler & R. Shepard, 1974)—the present means all fall quite close to the means of the corresponding results of those earlier experiments. For these two cells of the 2 × 2 design, then, we have successfully replicated the previous finding that reaction times and estimated rates of mental rotation are slower for the two-stimulus, three-dimensional condition than for the one-stimulus, two-dimensional condition (cf. Cooper & R. Shepard, 1984, p. 111).

## *Separation of Effects of Task and Dimensionality*

Having established the comparability of the present results with the previous results, as summarized in Table 1, we are now in a position to consider the other two cells of our 2 × 2 design. In this way we can assess the separate contributions of the two originally confounded factors of type of task (one-stimulus or two-stimuli) and type of stimulus (two-dimensional or three-dimensional object). Inspection of Figure 2 reveals that for either type of task, the slopes of the fitted functions are nearly the same for the two-dimensional and the three-dimensional objects. (We return later to a consideration of the slightly greater slope for the three-dimensional

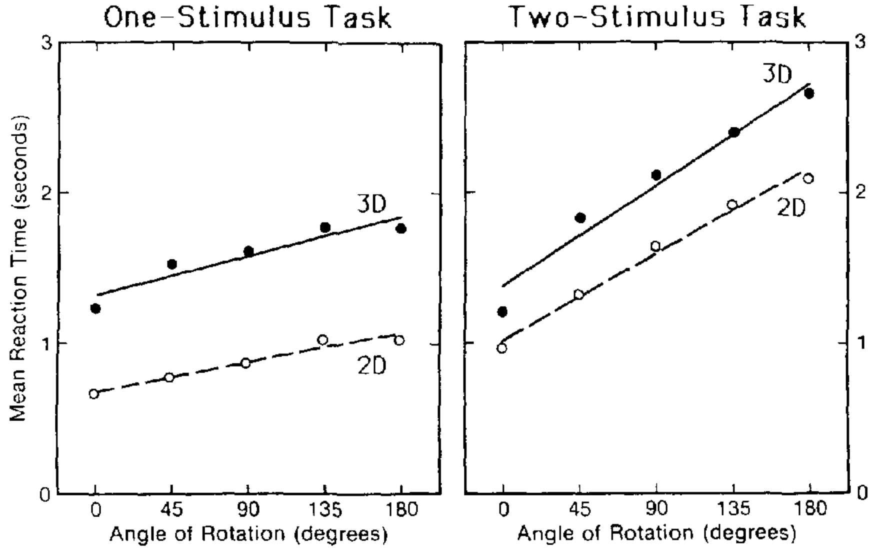


*Figure 2.* Reaction times of correct positive responses, plotted as a function of angular difference for the one-stimulus task (left panel) and for the two-stimulus task (right panel). Within each panel, data and fitted linear functions are shown separately for the two-dimensional and three-dimensional objects (2D and 3D, respectively).

Table 2
*Estimated Reaction Time Intercepts at 0° (in Seconds) for This and Previous Experiments*

| | | Previous results (from Table 1) | | | |
|---|---|---|---|---|---|
| | | All experiments | | Experiments with equivalent stimuli | |
| Task and object | Present *M* | *M* | Range | *M* | Range |
| One stimulus | | | | | |
| 2D | 0.67 | 0.60 | 0.53–0.78 | 0.61 | 0.53–0.78 |
| 3D | 1.32 | | | | |
| Two stimuli | | | | | |
| 2D | 1.02 | | | | |
| 3D | 1.36 | 1.47 | 1.0–2.0 | 1.20 | 1.2–1.2 |

*Note.* 2D = two-dimensional; 3D = three-dimensional.

objects.) However, whereas the slopes for these two types of objects were, respectively, only 2.1 and 2.9 ms/deg for the one-stimulus task (left panel), the corresponding slopes were 6.4 and 7.7 ms/deg for the two-stimulus task (right panel). This translates into an approximately threefold increase in estimated rate of mental rotation for the one-stimulus task over the two-stimulus task (see Table 3). Evidently, the marked difference in rates estimated from the original experiments (as summarized in Table 3) are attributable primarily to the type of task and relatively little to the dimensionality of the objects portrayed.

Clearly, however, the overall heights of the reaction-time functions are greater for the three-dimensional than for the two-dimensional objects (and this is especially apparent in the left panel, for the one-stimulus task). This difference in overall height is, of course, reflected in the intercept data (see Table 2), which provides estimates of the reaction time when there is no angular difference to be removed by a mental rotation. We suggest that the three-dimensional interpretation of the perspective views costs the subjects an additional processing time that is approximately the same for all rotated orientations—although the small portion of the measured time required for search and confirmation, as specified by Carpenter and Just (1978), may increase slightly more with angular difference in the case of the three-dimensional objects.

Table 3
*Estimated Rates of Mental Rotation (Degrees/Second) for This and Previous Experiments*

| | | Previous results (from Table 1) | | | |
|---|---|---|---|---|---|
| | | All experiments | | Experiments with equivalent stimuli | |
| Task and object | Present *M* | *M* | Range | *M* | Range |
| One stimulus | | | | | |
| 2D | 468 | 473 | 327–621 | 510 | 369–621 |
| 3D | 343 | | | | |
| Two stimuli | | | | | |
| 2D | 155 | | | | |
| 3D | 129 | 59 | 21–138 | 119 | 100–138 |

*Note.* 2D = two-dimensional; 3D = three-dimensional.

Our results thus indicate that the consistent differences in intercept found in the original experiments (left-hand column of data in Table 1) are primarily attributable to differences in the stimuli and specifically, we tentatively suggest, to differences in the dimensionalities of the portrayed objects.

Analysis of variance provides quantitative support for these conclusions. Estimated rate of mental rotation (deg/s) yielded a highly significant difference between the one-stimulus and two-stimulus tasks, $F = 30.9$, $p < .001$. The dependence of this rate on the dimensionality of the stimuli was much weaker, though statistically significant, $F = 6.75$, $p < .025$, and manifested no significant interaction with type of task, $F = 0.37$. The intercept data, on the other hand, yielded a highly significant difference between the two-dimensional and three-dimensional stimuli, $F = 69.0$, $p < .001$. The dependence of the intercept on type of task was much weaker, though again statistically significant, $F = 6.16$, $p < .025$. The weak interaction between this dependence and dimensionality was also statistically significant, $F = 6.35$, $p < .025$.

A suggestive additional aspect of the results is that the reaction times to the three-dimensional objects at 0° appear to fall systematically below the fitted linear functions plotted in Figure 2. In fact (as one anonymous reviewer of our manuscript noted), if the times for 0° are eliminated from the analysis, the fitted functions become almost exactly parallel for the two-dimensional and three-dimensional objects, and the dependence of slope on dimensionality becomes nonsignificant, $F = 0.042$, $p > .839$. The suggestion has been made to us (by R. Shepard, personal communication, November 1985, and by the anonymous reviewer just mentioned) that the relatively short reaction times for the three-dimensional objects at 0° (and, perhaps, the weak interaction between dimensionality and type of task) may have the following explanation: The additional time ordinarily required to interpret the three-dimensional objects may not be needed when there is no difference in orientation between the two objects. The subject could then match the two presented pictures directly, as two-dimensional pictures, before completing the three-dimensional interpretation. Such a strategy seems particularly likely in the two-stimulus task, in which subjects have the two stimuli simultaneously in front of them for direct comparison, and in the present experiments, in which the number of alternative stimuli and orientations is more limited than in the earlier of experiments by R. Shepard and J. Metzler and by others. This, then, may explain why the point for the three-dimensional object at 0° is almost as low as the point for the two-dimensional object at 0° in the two-stimulus task (right panel in Figure 2) but not in the one-stimulus task (left panel). In the latter task, the subject, not knowing whether a rotation will be required on a given trial, presumably already has a representation of the three-dimensional object in memory at the time of test.

### Error Rates

The overall error rate for first presentations of stimuli or pairs, that is, excluding the repetitions used to obtain a reaction time for an errorless response to each stimulus or pair, was 6.5% (Inclusion of the repeated trials raises the overall error rate to 7.1%.) For positive trials (i.e., trials in which the correct response is "same" or "standard"), the overall error rate was 8.2% and breaks down as follows: for the two-stimulus task, 9.4% for the 3D objects and 12.1% for the 2D; and, for the one-stimulus task, 8.3% for the 3D objects and 2.9% for the 2D. For negative trials (i.e., trials in which the correct response is "different" or "reflected"), the overall error rate was 4.8% and, when broken down in the same way, yields 5.8%, 6.7%, 5.8%, and 1.0%, respectively. As is typical in experiments on mental rotation, error rates on positive trials were correlated with reaction times, increasing in a roughly linear manner with angular difference. On negative trials, however, the error rates were not systematically related to angular difference. The dependence of reaction time on angular difference, which was very strong on positive trials (Figure 2), was also weaker for negative trials—especially in the two-stimulus task. These reduced influences of angular difference on negative trials appear consistent with our surmise that negative responses were often based on the use of nonrotational strategies (strategies that, as we noted, have been thought to be particularly likely when the number of stimuli and orientations is restricted).

## Discussion

The major factor accounting for the marked differences in estimated rates of mental rotation in the earlier studies appears to be the type of task used. Apparently, individuals can more rapidly imagine the rotation of an object (while preserving its essential structure) when they are imagining it rotated into an orientation that has been previously learned and, hence, that is already internally available for comparison. If they have to imagine the object rotated into the arbitrary orientation of a second, externally presented object, they evidently proceed more slowly. In our experiment they also made about twice as many errors in the two-stimulus task. Perhaps in this task they must repeatedly make comparisons with that externally presented second object during the course of the mental transformation in order to verify that each increment of their transformation is bringing them closer to the target and in order to terminate the process when they have achieved the desired match. In the two-stimulus task some individuals may even imagine the object rotated one piece at a time, which would entail still longer times to complete a mental rotation of the entire object (e.g., see Carpenter & Just, 1978; Pylyshyn, 1979; Yuille & Steiger, 1982; also see Hochberg & Gellman, 1977; Presson, 1982). However, a piece-by-piece strategy seems unlikely in the one-stimulus task. When people are tested with a properly oriented probe stimulus during or immediately following the mental rotation in that task (Cooper, 1976; Cooper & Podgorny, 1976; Cooper & R. Shepard, 1973), they can classify the probe as matching or not matching the imagined object as a whole in less than half a second (for a discussion, see R. Shepard & Cooper, 1982).

Carpenter and Just's analysis of eye movements during mental rotation appears to be generally consonant with this account (Carpenter & Just, 1978; Just & Carpenter, 1976). Using the two-stimulus task, they confirmed that people look back and forth between the two presented objects and that this pattern of eye movements corresponds to the process of mental rotation proper (which takes place between an inital search process and a final confirmation process, each characterized by its own distinct pattern of eye fixations). True, Carpenter and Just (1978) also reported that the slope of the reaction-time function was greater for three-dimensional than for simpler two-dimensional versions of similar objects. However, Carpenter and Just (1978) found evidence in their own eye-fixation records that this difference in slopes was primarily attributable to the briefer stages of search and confirmation rather than to the intervening stage of mental rotation proper.

In our experiment, the difference between two-dimensional and three-dimensional objects had its greatest effect on the overall heights (and hence on the intercepts rather than the slopes) of the reaction-time functions. We have interpreted this to indicate that dimensionality primarily affects the time required to encode or interpret the stimuli, though it may also affect the confirmation as well as the search stages described by Carpenter and Just (1978).

Some additional comparisons can be drawn with three other studies that have attempted to assess the effects on mental rotation of dimensionality of stimuli and/or type of task—namely, two that are as yet unpublished, by Podgorny (1975) and by Cooper and Farrell (for brief descriptions, see R. Shepard & Cooper, 1982, pp. 178–181), and one that appeared since we completed our experiment (Jolicoeur et al., 1985). These studies are not directly comparable with the present experiment because they did not include, within the same study, both the random polygons used by Cooper and the three-dimensional objects introduced by Shepard and Metzler. Instead, in attempts to control stimulus complexity, Cooper and Farrell presented geometrical configurations that were intended to be perceived as flat hexagonal patterns in one case or as three-dimensional cubes in the other; Podgorny (1975) and Jolicoeur et al. (1985) presented Shepard-Metzler objects or two-dimensional patterns with the same outlines as those three-dimensional objects. Moreover, Cooper and Farrell used the two-stimulus task only; and Podgorny and also Jolicoeur et al., while employing (in some experiments) both the one-stimulus and two-stimulus task, required the subjects to imagine rotations in the picture plane only.

In agreement with our findings that dimensionality has little effect on rate of mental rotation, Cooper and Farrell, Podgorny, and (up to 60°, anyway) Jolicoeur et al. found no difference in rate of mental rotation between what they took to be their two-dimensional and their three-dimensional objects. Also in agreement with our results, Podgorny (1975) and Jolicoeur et al. (1985), as well as Steiger and Yuille (1983), estimated a significantly faster rate for the one-stimulus task than for the two-stimulus task.

However, neither Cooper and Farrell nor Jolicoeur et al. found a significant difference in intercepts between their portrayals of two-dimensional and three-dimensional objects. Although their results are different from ours in this respect, their stimuli, also, were very different. In particular, the stimuli that we used (Figure 1)—namely, random polygons differing only by rotations in the picture plane, and cubical objects differing only by rotations in depth—can hardly be interpreted as other than two-dimensional and three-dimensional objects, respectively. But, the difference in the dimensionality of the interpretations of the stimuli intended as two- or as three-dimensional in these studies seems less compelling—especially when only picture-plane rotations were used. In the experiments by Podgorny (1975) and by Jolicoeur et al. (1985) the stimuli intended as two-dimensional could have been interpreted as three-dimensional, and in those experiments, as well as in the study by Cooper and Farrell (see R. Shepard & Cooper, 1982, pp. 178–181), the stimuli intended as three-dimensional could have been rotated as if they were two-dimensional.

Seemingly most at variance with our findings is the claim by Jolicoeur et al. that their results "provide strong evidence . . . that two-dimensional representations are rotated at a faster rate than three-dimensional representations for angular differences between 60° and 180°" (Jolicoeur et al., 1985, p. 125). We suggest, however, that their failure to obtain the usual linear increase of reaction time with angular difference raises questions as to whether their experiments ensured that their subjects consistently used a rotational strategy. In any case, this nonlinearity renders any estimates of the slopes problematic. An alternative interpretation of the results of Jolicoeur et al., suggested by observations originally reported by J. Metzler and R. Shepard (1974; see Cooper & R. Shepard, 1982, p. 55), is as follows: The mental rotation, when carried out, was carried out at the same rate for the two types of stimuli. However, when the stimuli said to be two-dimensional differed by a large angle, subjects sometimes used a faster, nonrotational strategy of comparing the surface features of the stimuli; the result was that the reaction times for large angular differences fell increasingly below the linear function expected for mental rotation.

In short, although there have been some other attempts to separate the effects of dimensionality of stimuli and type of task, we believe our experiment is the first (a) to effect this separation with stimuli that are directly comparable to both the two-dimensional and the three-dimensional stimuli used in the original studies of mental rotation and (b) to ensure a strong manipulation of dimensionality.

A question remains, however, whether the psychologically effective difference between what we have called our two-dimensional and our three-dimensional stimuli is really that of dimensionality. Possibly the effective difference is really some concomitant difference in, say, perceptual complexity. Bethell-Fox and R. Shepard (1988) offer new evidence that until the stimuli are sufficiently well learned, mental rotation proceeds more slowly for more complex stimuli. If one supposes (e.g., with Jolicoeur et al., 1985) that stimuli are more complex when interpreted as three-dimensional than as two-dimensional, then our finding that dimensionality has little effect on rate of mental rotation might seem puzzling. However, R. Shepard (1981; also see J. Metzler & R. Shepard, 1974; R. Shepard & Cooper, 1982) has argued that objects, whether two- or three-dimensional, tend to be mentally represented and manipulated as if in a homogeneous and isotropic three-dimensional space. On this view, manipulation of dimensionality is not in itself a manipulation of complexity. We believe that this view is consonant with our finding that the dimensionality of the objects to be rotated had little effect on rate of mental rotation. Dimensionality affected, rather, the time that it took to form an internal representation of the structure of the object on the basis of the available two-dimensional projection.

A greater complexity may indeed be entailed by the use of three-dimensional objects. But it is not, we suggest, a greater complexity of the internal representation that is to be mentally transformed. It is, rather, a greater complexity of the mapping between the external two-dimensional picture and the internal representation to which it gives rise. Rate of mental rotation, we believe, is primarily determined by factors other than dimensionality—particularly by type of task (one-stimulus or two-stimulus) and perhaps, in the case of unfamiliar stimuli (like those used by Bethell-Fox & R. Shepard, 1988), by complexity.

Nevertheless, as we noted in the introduction, we do not yet have a satisfactory measure of complexity that reflects its perceptual effects (as opposed to the surface features of the physical stimulus) and that applies equally to what we have called two-dimensional and three-dimensional stimuli. In the absence of such a measure, we cannot make a definitive determination of the extent to which estimated rates of mental rotation for objects differing in dimensionality are determined by dimensionality or by possible differences between these two types of stimuli in psychological complexity. As two reviewers of our manuscript (including Pierre Jolicoeur, personal communication, June 1987) have noted, the nearly equivalent slopes in the reaction-time functions for our two- and three-dimensional objects could be a fortuitous result of having chosen, for the two-dimensional case, the most complex of Cooper's polygons (viz., her 24-point polygon) and, for the three-dimensional case, the simplest possible Shepard-Metzler objects (viz., the seven-cube objects used in the experiment by Metzler, 1973). However, the slopes of our reaction-time functions are in good agreement with those arising from previous studies using the same task (one stimulus or two stimuli)—even when those studies employed simpler polygons or more complex three-dimensional objects. Indeed, Cooper (1975) and Cooper and Podgorny (1976) found no difference in estimated rates of mental rotation between their simplest (6-point) and most complex (24-point) polygons.

In conclusion, the similarity in the slopes of our reaction-time functions for the two- and three-dimensional cases may have resulted from a fortuitous compensation between dimensionality and complexity. However, we follow R. Shepard in taking the presently available evidence as favoring, instead, the following notions: (a) Rate of imagined rotation of an object does not itself depend on the dimensionality of that object (see Shepard 1981, 1984). (b) Rate of imagined rotation does, however, depend on whether the axis of the rotation is a natural axis of the object (see Metzler & Shepard, 1974) or, in the case of unfamiliar objects, on the complexity (or number of pieces) of those objects (see Bethell-Fox & Shepard, 1988). (c) The slope of the reaction-time function may, nevertheless, be slightly greater for three-dimensional objects, not because the rate of their imagined rotation is slower but because the different search and comparison processes (like the initial encoding process) take longer in the three-dimensional case (see Carpenter & Just, 1978).

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