Does the size of figures affect the rate of mental rotation?

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Six students were presented with small-, medium-, and large-sized pairs of mental-rotation figures similar to those used by Shepard and Metzler (1971), at near, medium, and far distances in lit and dark rooms. The subjects were asked to judge whether the figures were identical in shape or not, and their reaction time (RT) was measured. Mean RTs obtained for *same* pairs increased linearly with the angular difference between the figures, whereas those for *different* pairs did not. Mean RTs were not affected by viewing distance (with retinal size held constant), overall illumination, or objective size of the figures. Only the retinal size of the figures had an effect on RT: Mean RTs for the small-sized pairs were longer than those for the medium- or large-sized pairs, contrary to Shwartz's findings (cited in Kosslyn, 1980). Analysis showed that, for *same* pairs, this effect consisted of the slope and intercept effects in the lit-room conditions, whereas only the intercept effect was obtained in the dark-room conditions.

Studies on mental rotation have shown that the time required to compare two same-structured but differently oriented figures increases proportionally with angular differences (Shepard & Cooper, 1982; Shepard & Metzler, 1971). This linear function suggests that we may mentally rotate two figures at a constant rate.

What, however, does this constant rate of rotation mean? Does it mean that the angular velocity of rotation is constant regardless of the size of the figures? Or, if the size of the figures varies, does the rate of rotation vary accordingly? The present experiment deals with these questions in terms of retinal size and viewing distance.

Although several experiments have been conducted on the mental transformation of size (e.g., Bundesen & Larsen, 1975; Kubovy & Podgorny, 1981) and on the effect of image size on scanning and inspection time (e.g., Kosslyn & Alper, 1977; Kosslyn, Ball, & Reiser, 1978), only one study has been published on the effect of size on mental-rotation rate. Shwartz (cited in Kosslyn, 1980, pp. 290-291), used small and large Attneave random polygons and had subjects rotate their memory images in an indicated orientation. He found that the large figures required more rotation time than did the small ones. In the present experiment, we were concerned mainly with the effect of the *retinal* size of the figures, and we used Shepard and Metzler's (1971) mental-rotation task. Shwartz's findings would suggest that figures of large retinal size would take more time to be rotated than would those of small retinal size. At the same time, however, Cooper's (1975) finding that such figural factors as pat-

tern complexity have no effect on mental-rotation rate would suggest that figure size would have almost no effect on rotation rate.

To investigate the effect of the retinal size of the figures, we used, as stimuli, figures of three different sizes (the size ratio was 1:2:4). The figures were viewed at three different distances (1, 2, and 4 m). Retinal size was held constant across the three viewing distances by repositioning the slide projector when the viewing distance was changed. Thus, objective size (i.e., size of the figures on the screen) covaried with the viewing distance. Then we introduced lighted- and dark-room conditions as an indirect means of finding the effect of objective size. In a lighted room, where there are many cues for size and distance perception and where size constancy holds well, reaction time (RT) would be expected to depend mainly on the objective size of the figures. In a dark room, these cues are reduced, and the RT would be expected to depend primarily on retinal size. We therefore expected that light conditions would affect RT patterns.

METHOD

Subjects

Six undergraduate students, 4 male and 2 female, served as subjects.

Stimuli

As shown in Figure 1, the stimuli were pairs of two-dimensional perspective views of three-dimensional objects, each composed of 10 small cubes. They were either *same* or *different* pairs. A *same* pair consisted of two identically shaped members, whereas one member of a *different* pair was the left-right mirror-reversal of the other member. These stimuli were same or different in orientation through the frontal parallel plane: 0°, 60°, 120°, and 180° (absolute values of angular differences). The stimuli were made by using four original forms of 10 cubes chosen from the stimuli used by Shepard and Metzler (1971). Left-right mirror-reversal figures were made by

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Figure 1. Examples of the stimuli used in the experiment. From the top down: A small-sized *same* pair, a medium-sized *same* pair, and a large-sized *different* pair.

photocopying the original forms onto sheets of transparent paper. Stimuli were made by systematically changing the reciprocal location (left or right), the orientation, and the angular difference of a pair of figures. As shown in Figure 1, the stimuli were of three different sizes: small, medium, and large (the size ratio was 1:2:4). These pairs of figures were then made into slides.

These stimuli were projected by a slide projector (Kodak Ektagraphic II) onto a white screen, 90×120 cm. Their presentation was controlled by a shutter driver (Takei Kiki Kogyo Co., Ltd.). The center of the screen was set at the subject's eye level. The stimuli were presented in dark and in lighted rooms at three viewing distances: near (1 m from the subject's eyes), medium (2 m), and far (4 m), with retinal size held constant. The combinations of retinal size and viewing distance and their objective sizes are shown in Table 1. In the lit-room condition, the room was illuminated indirectly by a 60-W daylight lamp located 40 cm above the subject's head so that many visual cues for size and distance of the projected stimuli would be available. In the dark-room condition, the room was made completely dark so that these cues would be eliminated. Average luminances of the stimuli on the screen were 201.4, 51.4, and 37.7 fL in the lit-room condition and 199.7, 49.9, and 37.0 fL in the dark-room condition, for viewing distances of 1, 2, and 4 m, respectively.

Procedure and Conditions

The subjects were seated at a table in front of the screen. They were first asked to rotate mentally pairs of figures presented on the screen and then to judge whether or not they were identical in shape. The subjects were to respond by pressing either of two keys on the table. The right-hand key was always used as the *same* key; the left-hand key was the *different* key. The subjects were asked to respond as quickly and as accurately as possible. When the key was pressed, the stimuli were immediately extinguished, and the time interval between the onset of the stimuli and the keypress was

measured as the RT. Two seconds after the keypress, the next pair was presented. The subjects were informed that the rotation would be through the frontal parallel plane.

Each subject was presented with a total of 1,152 test slides in a 4-day period. At the beginning of each day's session, each subject was given 48 practice trials and then 288 test trials, in six blocks: 2 light conditions × 3 viewing distances. The six blocks were arranged so that one condition would not be followed by the same light or distance condition. Four different block orders, out of a possible 24 orders, were presented to each subject. Within each block, 48 pairs (*same* or *different* pairs × 4 angular differences × 3 retinal sizes × 2 of 4 original forms) were presented in random order. A standard rest interval of 3 min was provided between blocks, and an additional 7 min of rest was provided between the third and fourth blocks. Viewing distance was changed during the rest interval by repositioning the subject's table. The slide projector also was moved at the same time so that the objective size (but not retinal size) was changed when the viewing distance changed.

Mean RTs were computed for correct trials only.

RESULTS

The results are shown in Figures 2 and 3, which are plotted in terms of viewing distance and retinal size, respectively.

RTs for Same Trials

Mean RTs for *same* trials increased almost linearly with the angular differences of the figures. The mean RTs of the figures at an angular difference of 180° leveled off from the expected linear function.¹

We performed a four-way analysis of variance (angular difference × light condition × viewing distance × retinal size). Angular difference had a highly significant effect on RT [$F(3,15) = 41.51, p < .001$]. However, the effects of light conditions and viewing distances on RT were not significant [$F(1,5) = 2.18$ and $F(2,10) = 1.46$, respectively]. Retinal size had a large effect on RT [$F(2,10) = 14.59, p < .005$]. No interaction among the conditions was significant ($F < 1$ in all cases).

As for the effect of retinal size, Figure 3 shows that the mean RTs for the small-sized pairs were longer by 100 to 200 msec than those for the medium- and large-sized pairs. Mean RTs for the small-sized pairs were significantly longer than those for the medium- and large-sized pairs [$F(1,5) = 18.11, p < .01$ and $F(1,5) = 21.26, p < .01$, respectively]; there was no difference in mean RT between the medium- and large-sized pairs [$F(1,5) < 1$]. We computed the regression lines for each retinal size in each light condition, with mean RTs for the pairs at an angular difference of 180° excluded because they deviated from their expected linear function. With RT expressed in milliseconds and angular difference (in degrees) represented by d , the following RT functions were obtained for the small-, medium-, and large-sized figures, respectively: RTs = $1,118 + 10.1d$, $1,027 + 7.8d$, and $1,007 + 7.8d$ in the lit-room condition, and RTs = $1,240 + 8.7d$, $1,065 + 8.4d$, and $1,002 + 8.5d$ in the dark-room condition. The slope of these lines shows the mental-rotation rate, while their intercept shows the

Table 1
Objective Sizes of the Stimuli (in cm) on the Screen for All Combinations of Retinal Size and Viewing Distance

Retinal Size	Viewing Distance		
	Near (1 m)	Medium (2 m)	Far (4 m)
Small (2.9°)	5	10	20
Medium (5.7°)	10	20	40
Large (11.5°)	20	40	80

Note—Retinal and objective sizes refer to the center-to-center distances between the two figures in a pair.

Figure 2. Mean RTs for *same* and *different* trials as a function of the angular difference of the figures for each viewing distance.

time taken with motor response and other mental operations, such as encoding, size normalization, and *same-different* judgment. Thus, we obtained both intercept and slope effects in the lit-room condition but only an intercept effect in the dark-room condition. This intercept effect was confirmed by the fact that RTs for the small-sized pairs at an angular difference of 0° were significantly longer than those for medium- and large-sized pairs [in the lit-room condition, $F(1,5) = 7.72$, $p < .05$, for the medium-sized pairs and $F(1,5) = 8.31$, $p < .05$, for the large-sized pairs; in the dark-room condition, $F(1,5) = 7.30$, $p < .05$, for the medium-sized pairs and $F(1,5) = 8.29$, $p < .05$, for the large-sized pairs]. Therefore, in the dark-room condition, the slope (i.e., the mental-rotation rate) for all three sizes was approximately the same, whereas the intercept (i.e., the time taken with other mental operations and motor responses) was larger by 200 to 250 msec for the small-sized figures than for the medium- and large-sized ones. In the lit-room condition, the intercept was larger by 100 msec for the small-sized figures than for the medium- and large-sized ones. This difference was half the difference obtained in the dark-room condition. But the slope was 20% larger for the small-sized figures than for the medium- and large-sized ones. This meant a difference of more than 250 msec at an angular difference of 120° , which was about twice the size of the intercept effect.

In the present experiment, objective size of the figures was confounded with viewing distance. It seems that the objective size of the figures, however, had little effect on

RT, since neither the effect of light conditions on RT nor the retinal size $\times$ viewing distance interaction was significant. For the pairs that had small retinal size, for which the slower RTs were obtained, the mean RTs were not statistically different among the three distance conditions (i.e., three objective sizes) [$F(2,10) = 1.07$ in the lit-room condition and $F(2,10) = 2.18$ in the dark-room condition]. Thus, we can at least say that, in the present experiment, objective size was not a factor in determining RT.

Time of day also affected RT: Mean RTs became shorter as the day progressed [$F(3,15) = 29.81$, $p < .001$]. But the main RT patterns, as mentioned above, were found over 4 days. There was also a day $\times$ angular difference interaction [$F(9,45) = 2.81$, $p < .05$], suggesting that mean RTs tended to be shorter as the day progressed, but this RT pattern was most clearly seen in the pairs at large angular differences. No other day $\times$ condition interactions were significant ($F \leq 1.31$ in all cases). Therefore, it can be said that the number of trials did not affect the main RT patterns.

RTs for Different Trials

Mean RTs for *different* trials ranged from 1.9 to 2.5 sec.² Effects of light conditions and viewing distances were not significant [$F(1,5) = 2.01$ and $F(2,10) < 1$, respectively]. The angular difference of the figures had a significant effect on RT [$F(3,15) = 4.90$, $p < .01$], as did the difference in retinal size [$F(2,10) = 10.22$, $p < .005$]. No interaction among the conditions was significant ($F \leq 1.02$ in all cases).

Figure 3. Mean RTs for *same* and *different* trials as a function of the angular difference of the figures for each retinal size.

As for the effect of retinal size, the mean RTs for the small-sized pairs (2,295 msec), shown in Figure 3, were longer than those for the medium- and large-sized pairs (2,062 and 2,038 msec, respectively). Analysis of variance also showed that the mean RTs for the small-sized pairs were significantly longer than those for the medium- and large-sized pairs [$F(1,5) = 19.86, p < .01$, and $F(1,5) = 20.21, p < .01$, respectively].

As in the *same* trials, we can say that objective size had little effect on RT since neither the effect of light condition on RT nor the retinal size $\times$ viewing distance interaction was significant. For the pairs with small retinal size, for which the slower RTs were obtained, the mean RTs were not statistically different among three distance conditions (i.e., three different objective sizes) [$F(2,10) = 1.63$ in the lit-room condition and $F(2,10) < 1$ in the dark-room condition].

Mean RTs became shorter as the day progressed [$F(3,15) = 41.23, p < .001$]. But the main RT patterns mentioned above were obtained over 4 days, and there were no significant day $\times$ condition interactions ($F < 1$ in all cases). Therefore, it can be said that the number of trials did not affect the main RT patterns.

Error Rates

Mean error rates are shown in Table 2. The mean error rate for *same* pairs (6.1%) was significantly higher than that for *different* pairs (4.5%) [$F(1,5) = 8.21, p < .05$]. Errors for *same* pairs increased almost linearly with the angular differences, whereas those for *different* pairs did not. The angular difference had an effect on the error rate [$F(3,15) = 20.12, p < .001$], and the *same* versus *different* pairs $\times$ angular difference interaction was markedly significant [$F(3,15) = 36.21, p < .001$]. The effects of light condition, retinal size, and viewing distance on the error rate, as well as all other interactions among the conditions, were not significant ($F \leq 1.23$ in all cases).

We had expected that error rates would be higher in the faster RT conditions, but no speed-accuracy tradeoff was found.

Table 2
Mean Error Rates (%) as a Function of
Retinal Size and Angular Difference

Retinal Size	Angular Difference			
	0°	60°	120°	180°
<i>Same Pairs</i>				
Small	1.4	3.9	11.1	13.5
Medium	.3	.7	8.0	13.9
Large	.7	.7	5.6	12.4
<i>Different Pairs</i>				
Small	3.5	6.3	2.4	3.8
Medium	3.8	4.5	5.2	5.2
Large	6.6	5.9	4.5	2.4

DISCUSSION

On the basis of findings concerning the effect of image size on scanning and inspection time (Kosslyn & Alper, 1977; Kosslyn et al., 1978) and the effect of figural size on mental-rotation rate (Shwartz, cited in Kosslyn, 1980), it had been expected that more time would be taken to mentally rotate the large-sized objects than the small-sized ones. However, the present results showed that this was not the case. Actually, mean RTs were longer, not shorter, for the small-sized pairs than for the medium- and large-sized pairs.

The data analyses performed also showed that the mental-rotation rate was constant regardless of viewing distance, overall illumination, and objective size. Retinal size did indeed affect RT: More time, 100 to 200 msec for *same* trials and 100 to 250 msec for *different* trials, was required for the small-sized pairs than for the medium- and large-sized pairs. For *same* trials, this effect was seen both on the intercept of the obtained RT functions and on their slope in the lit-room condition, whereas it was only an intercept effect in the dark-room condition. In both light conditions, retinal size can be considered an "additive factor," in Sternberg's (1969) terminology. The finding that retinal size did not affect the rotation rate for *same* trials in the dark-room condition parallels Cooper's (1975) finding that such figural factors as pattern complexity had no effect on mental-rotation rate. The slope effect obtained for *same* trials in the lit-room condition suggests the following: For the small-sized pairs in the lit-room condition, the subjects might rotate the figures before such preprocessing as size normalization was completed, since the difference in intercept between the small-sized pairs and the large- and medium-sized pairs in the lit-room condition was only half that in the dark-room condition. This incomplete processing, or imperfect normalization, might make the rotation rate slower. That is, there might be some tradeoff between the slope (i.e., the mental-rotation rate) and the intercept (i.e., especially the time taken with a normalization process) for the small-sized pairs in the lit-room condition. Thus, we can conclude that the mental-rotation rate was not affected by the retinal size of the figures in the dark-room condition, but that in the lit-room condition the smaller the retinal size, the slower the rotation rate tended to be. And we can conclude that the large figures did not require more time to be rotated mentally. These results are contrary to Shwartz's findings (cited in Kosslyn, 1980).

Our experimental procedure, however, was different from Shwartz's in some respects. In Shwartz's experiment, following the presentation of the stimulus to be rotated, an orientation cue was presented. The subject's task was to rotate the memorial image of the stimulus in the indicated orientation and to push a button when the image was correctly reoriented. Such a procedure was rather

similar to the procedure used in experiments on image-scanning time (e.g., Kosslyn et al., 1978), but in our experiment the subjects were presented with a pair of figures and required to make *same-different* judgments by mentally rotating the figures. As cited in Kosslyn (1980), Shwartz used the same procedure to examine the effect of image complexity on the mental-rotation rate, and he found that higher image complexity made the rotation rate slower. This result also contradicts Cooper's (1975) findings. We think that Shwartz's findings are probably valid for the simple rotation task, but that for typical mental-rotation tasks, such as those of Shepard and Metzler, our conclusion and Cooper's are more applicable.

We suppose that the difference in intercept of the obtained RT functions reflects a size-normalization process in which the representation of small-sized figures is enlarged mentally before the figures are rotated and compared. This kind of normalization process has been suggested with reference to the processing of irrelevant dimensions in stimulus-comparison tasks (Dixon & Just, 1978) and mental size scaling (Larsen & Bundesen, 1978). It has been further suggested that, following this size normalization, cognitive processing, such as comparison and transformation, might be size-invariant (Chignell & Krueger, 1984; Dixon & Just, 1978). In our study, except for the small-sized figures in the lit-room condition, the mental-rotation rates were not so different among the three different figure sizes. Thus, we can also speculate that, following size normalization, the mental-rotation process is, in general, size-invariant.

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NOTES

1. This deviation can be explained as follows: At the end of the experiment, the subjects reported that in pairs at an angular difference of 180°, they often could judge swiftly, before finishing the rotation, whether the figures were identical or not by using the symmetrical configuration of the figures. That is, they could do so by knowing that the figure on the right (or left) was a mirror image of that on the left (or right) against an imaginary central axis (often vertical) of each figure. And it is also possible that the subjects could often guess correctly whether the figures were identical or not even when they rotated the figures about 120°.

2. In *different* trials, it might be that the subjects always made a 120° or full 180° rotation on figures at any angular difference, inasmuch as these mean RTs were close to those for *same* pairs at an angular difference of 120° or 180° and did not vary monotonically with angular difference.

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