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Can We Imagine How Objects Look from Other Viewpoints?

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Many psychologists who study cognition believe that perception achieves object-centered representations that make it possible to extract representations of how the object would appear from differing viewpoints. Others believe we can achieve representations of how an object would appear by a process of visualization or mental rotation. We report experiments in which the subject tries to imagine how three-dimensional novel wire objects would appear from positions other than the one they are in. Subjects are unable to perform this task unless they make use of strategies that circumvent the process of visualization. It is suggested that the linear increase in time required to succeed in mental rotation tasks as a function of the angular discrepancy between the figures compared is the result of increasing difficulty rather than of the time required for rotation.

When we view an object from a particular point of view, do we know how that object looks from other viewpoints? Since at least Helmholtz's (1867–1962) time, there has been interest in this question. The prevailing assumption among psychologists who study cognition has been that we are capable of imagining how objects look from other viewpoints. Piaget and Inhelder (1967) consider it a characteristic of young children's egocentrism that they were incapable of apprehending the spatial relationships among objects from a position other than the one they were in. The implication of children's failure in their well-known three-mountain paradigm was that only upon reaching a late stage of development are we

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able to imagine how the position of the mountains would change when we look at them from a different viewpoint. It was presumed that adults can do so. Similarly Shepard and his co-workers have assumed that we are capable of imagining how objects look when they are not in the same orientation as one another (Shepard & Cooper, 1982). In his famous experiments on mental rotation the task is to decide if two drawings of three-dimensional objects represent the same object when they are depicted in orientations differing from one another with respect to the z or y axis. The question posed is not whether subjects *can* imagine the necessary rotation, but how long it takes to do so as a function of how different they are from one another in orientation. It would seem to be implicit in this research that imagining how one of these objects will look if *it* is mentally rotated is essentially the same task as imagining how it would look if one were to view it from a different position.

A closely related issue is whether or not, in looking at an object, we achieve a representation of it that transcends that of the momentary view. If we do, then it is plausible to believe that in imagination we can extract from such an object-centered representation a representation of how the object would look from any viewpoint. In their work on computational vision, Marr and Nishihara (1978) and Marr (1982) have described both observer-centered and object-centered representations, which they refer to as a "2½-D sketch" and a "3-D model description." The 3-D model is based on the intrinsic axes of an object and is independent of viewpoint, while the 2½-D sketch is essentially an egocentric perspective view which includes the depth relationships that have been provided by early visual processing such as stereopsis and motion perspective. It is argued that we achieve the object-centered description on the basis of computation from the observer-centered description. With this distinction in mind, Pinker and Finke (1980) have provided evidence that, in imagination, observers can extract a required perspective view from a stored object-centered representation. The result of this process is claimed to be an imagined viewer-centered "percept" much like the 2½-D sketch proposed by Marr and Nishihara.

However, if it is true that we do achieve object-centered representations, then another prediction follows. We ought to recognize an object in positions or orientations other than the one in which it was originally seen. In fact it is precisely this belief, that we do recognize objects in all orientations or, otherwise expressed, from all viewpoints, that has led theorists such as Marr to seek an explanation of how object-centered representations arise. But do we recognize objects seen from only one viewpoint when they are later encountered from other viewpoints?

It is a well-known fact that we often fail to recognize objects when their orientation with respect to the z axis has changed. It is true that we generally do recognize things when they remain in the same orientation in the environment and we view them from an altered orientation (Rock, 1973). Thus one might say that in such cases maintenance of observer-centered orientation is not required for recognition. Even so we would have to say that an object-centered representation must include reference to the directional coordinates of the environment. Only with objects that have clear intrinsic axes, such as the human body, can representations ignore environmental orientation. Moreover, for certain material such as handwriting and pictures of faces, the maintenance of orientation with respect to the observer *is* necessary for recognition.

However, one might want to argue that orientation with respect to the z axis is a special case and reference to it should not be invoked to challenge the more general fact that recognition occurs despite changes in the orientation of objects with respect to the other axes of space. But recently evidence to the contrary has been produced. In one study using three-dimensional novel wire objects it was shown that when, in a recognition test following earlier viewing of these objects, they are presented in an orientation rotated by 90° around the y axis, recognition drops off sharply compared to baseline trials where no change of orientation occurred (Rock, DiVita, & Barbeito, 1981). The subjects are not told that changes of orientation may occur in the test. So the experiment is concerned with spontaneous recognition rather than with mental rotation. In a subsequent study with the same objects, it was shown that merely displacing them laterally from one location relative to the observer to another—for example, from upper left to lower right—produces a sharp decline in recognition (Rock & DiVita, 1987). What these two studies have in common is the fact that a three-dimensional object of the kind used yields a drastically different retinal image of the same object as a function of its orientation or location relative to the observer. The shape of the image of the object, qualitatively speaking, becomes very different. (In this respect these experiments differ from the traditional experiments on shape constancy in which the slant of a two-dimensional shape such as a circle leads to a qualitatively similar projection.) Apparently then these are cases where the representation achieved is primarily observer-centered despite the fact that all information necessary for the achievement of an object-centered representation is available, namely, the three-dimensional relationship of the parts of the object to one another. Nonetheless, an object-centered representation does not seem to be achieved.

From these findings it is but a small step to inquire whether one can *imagine* how such an object would look from another viewpoint. If an object-centered description is not achieved, than a representation of how the object would look from another viewpoint cannot be extracted since there is nothing to extract it from. Still it is possible to maintain that even without such a representation we are capable of imagining how the object would look from a different viewpoint.

The experiments reported here look directly at the question of whether observers can imagine how objects look from other than their immediate viewpoint. We show that by and large they are unable to do so and that in cases where they respond correctly beyond chance guessing they are able to do so by employing strategies that circumvent imagining or mental rotation. Observers were shown the kind of three-dimensional novel objects just described. They were constructed from wire so that the entire object was visible to them. That is, there was no significant occlusion of one part of the figure by other parts. Complete information regarding the object's three-dimensional form was visually available.[1] In Experiment 1 the subjects' task was to look at the object from one viewpoint and then make a drawing of how they thought it looked from another viewpoint, namely, from a position 90° away from the viewing position. The object remained in view while the subject made the drawing. In Experiment 2 recognition measures were used. In Experiment 3 a number of changes were introduced, among which were the inclusion of viewpoints other than 90° and the use of three-dimensional wire objects as the test figures rather than pictures of them.

EXPERIMENT 1[2]

Method

Subjects. The subjects were 13 Rutgers University undergraduates who participated as partial fulfillment of a psychology course requirement.

Materials and viewing arrangement. The test objects initially used by Rock et al. (1981) were made by bending wire, painted orange, into curved three-dimensional novel forms, two of which were closed and two open (see Fig. 1). The average height and width was 17 and 12 cm, respectively, and each form was secured to a 25-cm stem. A stand which served as a mount for the form was placed on a table 80 cm from the subject's viewing position. Chairs were placed in left and right positions 90° from the viewing position (with the form's position treated as the point of origin). See Fig. 2.

Procedure. Subjects sat in the designated viewing position placing their head on a chin rest and were told to look at the practice form that was mounted in the stand on the table in front of them. They were then told that they would be shown other similar forms. They were instructed that their task would be, first, to imagine how the form would look if they were to move to the chair at the viewpoint 90° to the right (left) of their current one, and then to draw the form as they thought it would look from that imagined view. Once it was clear the

[1] We are assuming that the depth of these objects is perceived because they are presented in full room illumination at a near distance at which information from retinal disparity, accommodation, and convergence and possibly other depth information would be expected to be adequate. However, see Experiment 4 for a test of this assumption.

[2] Experiments 1 and 2 were first reported by Deborah Wheeler at the 1982 Meeting of the Eastern Psychological Association.

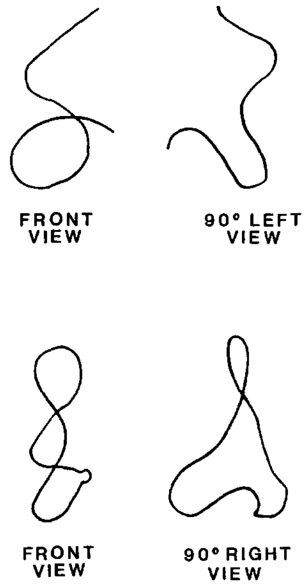

FIG. 1. Front and side views of the kind of wire objects used in the experiments. (Top) An open object; (bottom) a closed object.

the subject understood these instructions, the practice form was replaced by one of the other forms. The subjects then carried out the instructions just described; that is, they imagined how it appeared from a point 90° either to the left or right of their own and made a drawing depicting the form from that view. The object remained in view while the observer drew it. This was repeated for the other 90° view. When the two drawings made under the imagination instructions were completed, the subject made drawings of the object (while actually looking at it) from the original viewing position and from the left and right 90° positions. For the 90° views, the subject moved to the chairs positioned at those points to make the drawings. Thus each subject made two drawings of each of four objects under imagination instructions and three drawings while actually looking at the view being depicted.

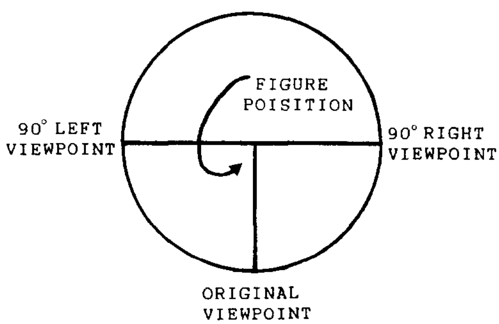

FIG. 2. A schematic diagram of the viewing arrangement in Experiments 1 and 2.

Results

The data consist of the drawings produced by the subjects while they imagined particular views of the objects and while they actually held those particular viewpoints. Examples of these drawings are shown in Fig. 3. These data were analyzed by judges in the following way. Each subject's drawings made under the imagination condition were compared to those made while actually looking at the particular view in question. This was done using the imagination condition drawings as the test items in a forced-choice similarity judgment task. The choice items were the front and left (or right) drawings of the object in question. The test and comparison items were arranged as triplets on a response sheet and 21 independent judges rated them. Twelve triplets were eliminated from the

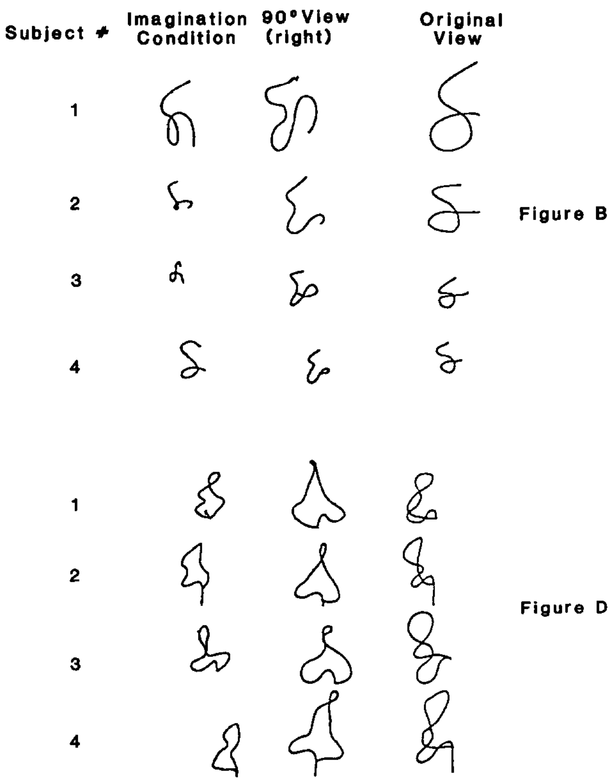

FIG. 3. Examples of drawings of the imagined appearance of the wire objects by four subjects in Experiment 1 (Column 1). The second column contains direct copies by these subjects of how the wire object looked from the 90° right position. The third column contains direct copies of how the object looked from the 0° position. Note that the drawings of the imagined appearance correspond more with how the object looked from the original (0°) position than with how the object looked from the to-be-imagined position.

analysis because the front and left (or right views) made while the subject actually held those vantage points did not sufficiently resemble the object, leaving a total of 92 triplets to be judged [(13 subjects × 4 forms × 2 views) − 12 eliminations]. All other direct drawings from a given vantage point were excellent representations of the objects' shapes seen from that position as is evident from inspection and the unanimity of these drawings across subjects (see Fig. 3, columns 2 and 3). The judges were instructed to circle the comparison item that looked most like the test item, basing their selections on the shape characteristics of the items only. They were told to ignore any size differences. In other words, they were judging whether the imagination condition drawings looked more like the actual view from that perspective or more like the view the subjects had in looking at the object but the judges did not know that this was what they were judging. Table 1 shows the percentage of time the drawing made under imagination instructions was judged to look like the view being imagined for the four forms. These ranged from 41 to 66%, the average being 55.5%. Thus, the subject's drawings under imagination instructions were not reliably judged to resemble the drawings made while the subject actually looked at that view of the object since chance performance would be 50%.

Discussion

The fact that the drawings made under imagination conditions were not judged as looking like the drawings made while actually viewing the object from that viewpoint fits with many of the subjects' comments about the task and with those of other people who informally tried this task.

TABLE 1
Results of Experiment 1

Object	Percentage of imagination drawings judged more similar to 90° drawings[a]
A	53%
B	41%
C	62%
D	66%
Overall	55.5%

[a] Based on 21 judges' decisions concerning each triplet as to whether the drawing based on imagination was more like the subjects' direct drawing from the 90° position than like the subjects' direct drawing from the 0° position. Since there were 13 subjects for both the left and right 90° viewpoints, there were 26 triplets for each of the four objects. However, 12 of the 104 triplets (13 subjects × 4 objects × 2 viewpoints) were eliminated because the direct drawings were poor representations of the object from the viewpoint in question.

Most people either voluntarily or when queried commented that they did not feel as if they knew what the object looked like from the imagined point of view. Two people with extensive drawing experience tried the task informally and both produced quite accurate drawings. However, both reported using strategies to produce the drawings. One strategy involved analyzing the form by considering one small segment at a time, drawing that segment, and then going on to the next one. The person using this strategy said that he was not guided by an imaginary experience of the object but rather had no idea of what the specified viewpoint really looked like until he had completed his drawing. The other observer said she used a strategy of translating variations of the form along a depth dimension into changes along a left–right dimension. For example, if the wire of the form was bent toward her she drew it going to the left.

One objection to the method used here might be that observers knew what the object looked like from the imagined perspective but were simply unable to reproduce it. Difficulty with drawing cannot be ruled out as a possible contributing factor but one relevant point here is that subjects were able to produce recognizable drawings of the views at which they were looking. So their difficulty in drawing the imaginary view was not simply the result of inadequate drawing skills. However, in order to eliminate any special problems associated with the use of drawing as a measure, Experiment 2 was conducted which used recognition responses.

EXPERIMENT 2A

Method

In this experiment the drawing responses were replaced by a recognition task in which the observers selected from four drawings the one that most closely resembled the object as they imagined it looked from the required viewpoint. A perception condition was added as a way of making certain that the recognition task was easily performed when there was no doubt that observers knew how the object looked from the view in question. This was particularly important given the fact that the displays were three-dimensional objects while the recognition items were two-dimensional drawings. Separate groups of observers were used for the two conditions.

Subjects. Subjects were 35 Rutgers University undergraduates who participated as partial fulfillment of a course requirement.

Materials and viewing arrangement. Three-dimensional wire objects as described in the prior experiment were used (two open and two closed). For each object, a correct recognition view was made by displaying the object in question on a video screen and then tracing it. Three false choices were made for each object by tracing the images of different objects, the guiding consideration in selecting the false choices being that they were clearly discriminable from the correct choice although maintaining their character as open or closed figures. These recognition items are shown in Fig. 4. The viewing arrangement was the same as that described in Experiment 1.

Procedure. The procedure was like that of Experiment 1 with the following changes. The drawing responses were replaced by recognition measures. After the observer looked at a test object for an unlimited time, it was covered and the observer was instructed to select

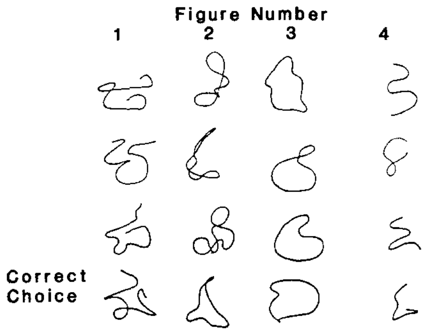

FIG. 4. Recognition choices for the four objects used in the test in Experiment 2A. The choices for each object are shown in the columns and the bottommost of these is the correct choice.

from the four recognition choices the drawing that most closely resembled the imagined perspective while in the perception condition they selected the drawing that matched the view actually seen. The recognition test for each object followed immediately the viewing of that object. The observer knew in advance what the task would be on each trial. Each observer saw all four display objects, and presentation order was varied.

Results

The data are presented in Table 2 as percentage of time that the subject selected the drawing that depicted the object from the imagined viewpoint. The correct drawing was selected in the imagination condition 50% of the time (n = 35), the range being 35 to 71%. This is greater than chance performance which with four choices would be 25%. However, even though performance is above chance, there is still a sense in which it is not very good. Since the recognition choices for an object were easily

TABLE 2
Results of Experiment 2A: Unlimited Viewing Time

	Objects	Percentage correct (N = 35)
Imagination condition	1	48%
	2	71%
	3	35%
	4	46%
		X = 50%
Perception condition	1	97%
	2	100%
	3	97%
	4	100%
		X = 98.5%

discriminable, one could argue that if the observers actually had an idea of what the object looked like from the imagined viewpoint, performance should have been much better. The perception condition provides a situation in which it is reasonable to assume that the observers actually knew what the object looked like from the viewpoint in question, and indeed performance was excellent in that condition. The correct drawing was selected 98.5% of the time. See Table 2. Thus, under conditions where there was no doubt that observers knew how the object looked they were able to recognize a two-dimensional depiction.

Discussion

Informal interviews after the experimental sessions again suggested that the use of analytic strategies was improving performance. One such strategy was the isolation of a particular feature and then basing recognition solely on it. The unlimited viewing time gave observers ample opportunity to consider various strategies if they wished and it is quite likely that these contributed to their performance. A possible control for this was to limit the viewing time and the next experiment did this.

EXPERIMENT 2B

Method

This experiment is a replication of Experiment 2 with the viewing time reduced to 4 s. This time interval was selected because it is sufficient for mental rotation tasks such as those used by Shepard and Metzler (1971) even for the 180° transformations and yet seemed short enough to limit the development of effective strategies. Both imagination and perception conditions were used.

Subjects. The subjects were 19 Rutgers University undergraduates who participated as partial fulfillment of a course requirement.

Procedure. The procedure was exactly like that of Experiment 2A except that the display was covered after 4 s viewing time. Observers were told that viewing time would be limited and given a demonstration of its duration.

Results

The results are shown in Table 3 as the percentage of time observers picked the drawing that correctly depicted the imagined view of the object. The average was 32.8% and the range was 21 to 47%. Thus performance dropped by an average of approximately 17% when viewing time was reduced to 4 s. The average of 32.8% is not significantly different from the chance expectation of 25%. Correct recognition also decreased in the perception condition but to much lesser extent. See Table 3. For the perception group, correct recognition occurred 92.5% of the time with 4 s viewing time, as compared to 98.5% that occurred with the unlimited viewing time in Experiment 2A for a difference of 6%. The reduced view-

TABLE 3
Results of Experiment 2B: Four-Second Viewing Time

	Objects	Percentage correct
Imagination condition	1	21%
	2	47%
	3	21%
	4	42%
		$\bar{X}$ = 32.8% (N = 19)
Perception condition	1	90%
	2	90%
	3	100%
	4	90%
		$\bar{X}$ = 92.5% (N = 19)

ing time had a greater impact on recognition for the imagination group than it did for the perception group.

Discussion

A final experiment was undertaken in order to address certain limitations of the preceding experiments. It might be argued that while subjects are indeed able to imagine how an object will appear from another viewpoint they are unable to extract from such a mental representation the appropriate two-dimensional projection of it. A recognition test utilizing two-dimensional line figures, however, would seem to require just this further process. Therefore, in Experiment 3 recognition was tested using three-dimensional wire objects, not drawings of them.

In Experiment 1 the object remained in view while the subjects drew it, but in the subsequent experiments it was not visible during the recognition test. It might be argued that subjects had succeeded in visualizing how the object looked from the differing viewpoint but were unable to remember it adequately in the subsequent test. Therefore, in Experiment 3 the wire object remained in view during the recognition test.

A further limitation of the preceding experiments is that only the 90° viewpoint was investigated. While this is adequate to test the issue under consideration here, visualizing capability, by including other viewpoints in Experiment 3, it is possible to throw additional light on the problem.

Finally, there is an interesting difference in the task we have given the subjects and the one typically employed in experiments on mental rotation since Shepard and Metzler's (1971) classic paper appeared. We ask subjects to imagine themselves viewing the object from a different viewpoint whereas Shepard and Metzler and others ask the subject to imagine the object rotated to a certain orientation. For research on children comparing these two tasks see Huttenlocher and Presson (1973, 1979), Piaget and Inhelder (1967, 1970), Presson (1980), and Youniss and Robertson (1970). Our intuition was that, of the two kinds of instruction, ours would be the easier for adults, but in Experiment 3 we deliberately included both kinds of instruction.

Other differences in procedure between these and the previous experiments are described below.

EXPERIMENT 3

Method

Subjects. Thirty-six Rutgers University undergraduates served as subjects. All subjects had normal vision.

Materials and viewing arrangement. The same kind of wire objects of the previous experiments were employed except that in this experiment each consisted of a curved white wire supported by a 15-cm black stem which was mounted on a circular black base not visible to subjects. The average height and width of the curved wire objects were 21 and 17 cm, respectively. The shapes of the curved objects were chosen so that each was inherently distinct from every other.

Six objects were used in the present experiment. Three of these were closed and three open. For each of these six standard objects both an identical and enantiomorph comparison object were constructed.

The objects were displayed in a viewing frame measuring 71 × 35 cm and placed on a table 180 cm from the subject's viewing position. Two objects were displayed in the viewing frame: the standard object which always appeared on the subject's right and the comparison object which appeared on the left.

Procedure. Each subject was tested under one of two conditions so that there were 18 subjects in each. In the Object-Rotation Condition subjects attempted a counterclockwise mental rotation of one of the six standard objects, a 45, 90, or 180° rotation. In the Self-Rotation Condition subjects attempted to imagine how the object would look if they moved around 45, 90, or 180° to the left of the object's actual position, thus corresponding to the method used in the previous experiments. Subjects in both conditions then compared their imagined views with the comparison object presented next to it.

There were 18 trials per subject, consisting of three blocks of 6 trials each. Within each block all six standard objects were presented in a particular orientation. Across blocks, for each subject, a 45, 90, and 180° rotation was required for each standard object and within each block two 45, 90, and 180° mental rotations were performed. Subsequent to the mental rotation of the presented standard object subjects were presented with a comparison object. Subjects then compared their imagined view of the standard object with the comparison object. Three types of comparison objects were utilized in the experiment. Specifically, comparison objects consisted of either (1) an identical object displayed in the orientation to be imagined (we call these the same or S objects), (2) an identical comparison object but displayed in one of the two alternate orientations, i.e., in an orientation other than the one to be imagined (we call these different or D objects), or (3) a mirror-image or enantiomorph comparison object displayed in the orientation to be imagined. We call these the E objects. Across blocks, for each subject, a comparison object of type S, D, and E was displayed for each object. Within each block two S, two D, and two E comparison objects were presented. However, it was not necessarily the case that, for each subject, there were an equal number of comparison objects of each type for each of the three orientations to be imagined. For open or closed objects that number was 1, 2, or 3. Across subjects order of standard objects was counterbalanced and every object was imagined in every orientation with every comparison object. Subjects were told that their task would be to compare an imagined view of one object to a real view of a second object. The two objects would be presented to them in the viewing frame, side by side. Instructions were read to subjects. Prior to the experimental trials subjects were given practice trials in which the object consisted of folded papers. When subjects demonstrated proficiency in the practice trials the experimental session began.

The standard object was then presented and always appeared on the subject's right side of the viewing frame in its 0° orientation. The left side of the frame was initially obscured by a black curtain. Above the standard object an arrow marker appeared which indicated a specific orientation of 45, 90, or 180°. Subjects were required to mentally rotate the object to the orientation indicated by the marker (Object-Rotation Condition) or to attempt to imagine how the object would look if they moved to the location specified by the marker (Self-Rotation Condition). Subjects were given 4 s in which to do this task. After the 4 s transpired the curtain on the left side of the viewing frame was opened and subjects were presented with a comparison object. It appeared in the S, D, or E form. The subject's task was to decide if the comparison object looked like their imagined view of the standard object; that is, was Object 2 on the left what Object 1 on the right looked like from its specified orientation. Subjects were to respond "same" or "different."

It was explained that Objects 1 and 2 would often be duplicates of one another but that decisions were not to be based on slight or minor differences in their construction. Also they were not to say "same" because they believed the objects were the same but only to do so if the comparison object represented the appropriate view of the standard. In other words, subjects were only to judge if Object 1, viewed from a specific orientation, looked just like Object 2. Subjects were given 2 s in which to make their decision and respond, during which time both the standard and comparison objects were displayed simultaneously.

Results

The first question to consider is the level of performance overall, i.e., across conditions, objects, orientation to be imagined, type of comparison object, subjects, and order of trials. Correct responses on trials in which the S comparison object is presented are "same" and on trials in which the D or E comparison object is presented are "different." The percentage of correct responses overall is 71. Chance performance based on guessing would be 50%. However, subjects achieved significantly more correct responses to S objects, 82% than to either of the other two kinds of comparison objects, these values being 71% to D objects and 60% to E objects (t = 2.6 and 4.5, respectively, $p < .01$ for both comparisons). Figure 5 presents the results graphically. Moreover, the high percentage of correct responses to S comparison objects is largely due to a very high level of such correct responses for the trials on which a 180° rotation was called for, a fact to be discussed below. Figure 5 presents the results graphically of S, D, and E comparison trials and a breakdown of percentage correct for these trials for the three orientations to be imagined.

As to a possible difference between the conditions in which subjects imagined themselves viewing the object from a different position (Self-Rotation) or imagined the objects rotating by an equivalent angle (Object-

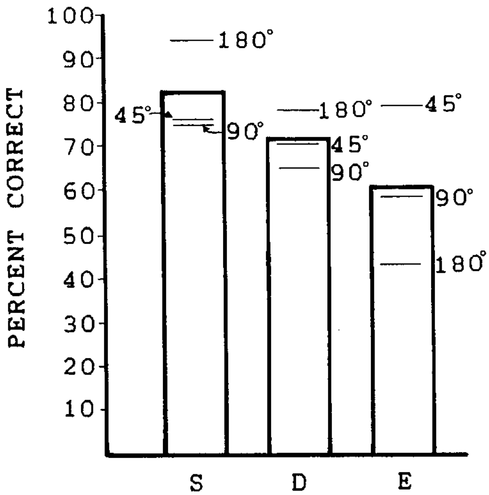

FIG. 5. The percentage correct on same (S), different (D), and enantiomorph (E) trials in Experiment 3. For each of these kinds of trials the results for trials requiring a 45, 90, or 180° change of viewpoint are given.

Rotation), there proved to be essentially none, with 72.5% correct in the former condition and 70% correct in the latter ($t = .18$, $p > 0.4$). That being the case, the data for the two instruction conditions were combined for all further comparisons and are presented graphically in Figs. 5, 6, 7, and 8.

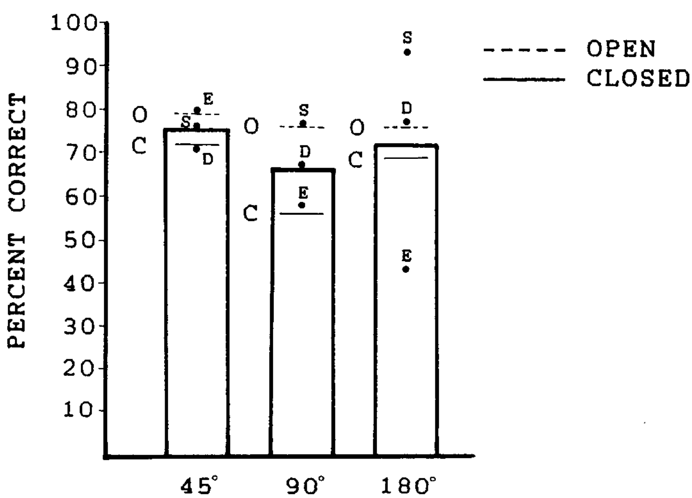

FIG. 6. The percentage correct for trials requiring 45, 90, or 180° change of viewpoint. For each of these the results for open (O), closed (C), and for S, D, and E trials are given.

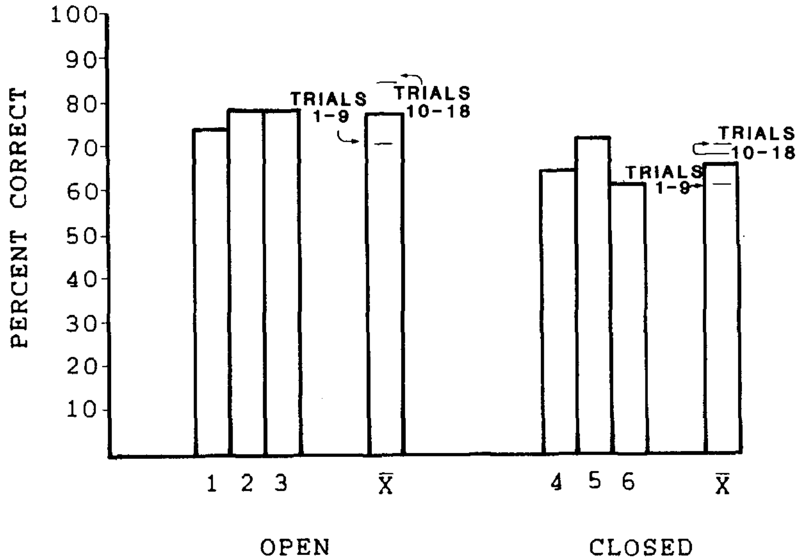

FIG. 7. The percentage correct for each object and for the means of open and closed objects. For each of these the results for the first nine trials and the second nine trials are shown.

For purposes of direct comparison with the previous experiments reported here, performance only for trials in which a 90° rotation of object or self was required should be considered. The overall percentage correct on such trials is 66 and that value is significantly lower than for the percent correct of 75 for 45° ($t = 2.24$, $p < .05$) and lower, but not significantly lower, than the percentage correct of 72 for 180° ($t = 1.2$, $p < .10$). See Fig. 6. Therefore, one might reasonably conclude that the poor performance on 90° rotation trials, albeit significantly better than chance ($X^2 = 22.7$, $p < .001$), is consistent with the poor performance of subjects in the previous experiments. Further analysis revealed that, overall, subjects do much better with the open objects than with the closed ones, these percentages being 77 and 56, respectively, for the 90° rotation trials. The former value is significantly better than chance ($X^2 = 31$, $p < .001$), but the latter value is not ($X^2 = 1.33$, $p > .20$) and this latter result is fully consistent with those of the previous two experiments.

Figure 7 shows the percentage of correct responses for the open and closed objects and for each object separately across all orientation trials. The percentage correct for open objects was 77 and for closed objects 65, and this difference is significant ($t = 4.23$, $p < .01$). Figure 8 shows the percentages of correct responses overall for trials 1 to 9 and 10 to 18. These values were 66 and 76.5, respectively, which differ significantly ($t = 3.1$, $p < .01$).

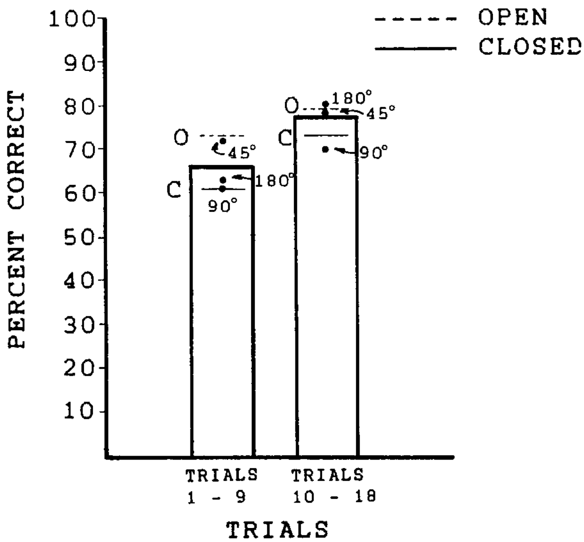

FIG. 8. The percentage correct for Trials 1 to 9 and 10 to 18. For each of these the results for open (O), closed (C), and the 45, 90, and 180° trials are shown.

Discussion

Despite the fact that overall performance is significantly better than the 50% chance level, there are various reasons for believing that subjects were not able to imagine how the wire objects would look from the viewpoint required but instead arrived at the correct responses by indirect means. We have only circumstantial evidence for this conclusion but we have a good deal of it.

Once again subjects' comments during the interview following the experiment were very revealing. By and large subjects stated that they were simply unable to form a mental picture of what the object would look like from the viewpoint required. Instead they tried to use "tricks" such as focusing attention on one part of the object, e.g., one of its ends in the case of open objects, and then figuring out where that part ought to be located in the viewpoint suggested. So, for example, if the end were in front and the task required a 90° shift in viewpoint (let us say leftward for self-rotation or counterclockwise for object-rotation) then they realized that it ought to be on the right side. Thus, if the comparison object included an end on the right side the subject was inclined to say "same". In support of this introspective data is the fact that subjects performed better with open objects than closed ones. As can be seen in Fig. 6, the difference in performance between open and closed objects seems to be greatest for 90° trials. Open objects readily provide such distinct end "landmarks," whereas usable "landmarks" have to first be extracted from the standard object and identified in the comparison view in the case of closed objects. The use of "landmarks" in mental rotation tasks has been elegantly demonstrated by Hochberg and Gellman (1977).

Another strategy subjects reported using concerned the 180° change of viewpoint. Many realized that such a change would entail a reversal of left and right. Therefore, a comparison object that conformed to this expectation was likely to be considered "same," whereas one that did not was likely to be considered "different." In support of this introspective report is the surprising finding that a 180° change of viewpoint did not lead to poorer performance (and in fact the trend is in the direction of better performance, namely, 72% correct) than did a 90° change of viewpoint, 66% correct. In light of the well-known linear function relating reaction time to degree of mental rotation obtained by Shepard and his associates and of the intuitive feeling one has about the increased difficulty of imagining how an object would look when the change of viewpoint increases from 90 to 180°, this finding is difficult to interpret in any other way than the one suggested here by introspective reports.[3] Moreover, subjects were correct on 94% of the 180° trials when the S comparison object was presented and incorrect on 43% of such trials when the E comparison object was presented. See Fig. 5. These values mean that subjects tended to say "same" on trials in which the comparison object is a left–right reversal. Therefore, they are correct on S trials and have a very high error rate on E trials.

In further support of the interpretation suggested here, that subjects employ cognitive strategies rather than draw upon a representation based on mental rotation, is the fact that performance was significantly better for the second half of the 18 trials than for the first half. (In this connection it is interesting to note that in Experiments 1, 2A, and 2B, in which only *four* trials were given, subjects were unable to draw or recognize the imagined view.) Going along with this fact are subjects' comments that they thought up strategies as the experiment proceeded. While it is true that improvement in an experimental task over trials is not an unusual

[3] It is true that the effect on recognition of varying degrees of disorientation of figures in a frontal plane is not such that 180° change leads to less recognition than 45 or 90° change. See Rock (1973). However, that is an entirely different matter. The degree of phenomenal change based on a changed assignment of directions to a figure is a function of each particular figure. For example, the maximum change one would expect for a square occurs at 45°. The effect under discussion here, however, concerns rotation about the y rather than the z axis and, more important, does not concern spontaneous effects on recognition of a change in directional assignment but rather the difficulty of imagining how an object looks as a function of how great an angular transformation has to be achieved.

finding, we find it difficult to explain why such improvement in mental rotation should be expected to occur once the subjects understand the task if what the subjects are doing is exercising a capacity which comes naturally, so to speak.

We cannot fully explain why subjects are more often correct on S trials than D or E trials. However, a good portion of the difference derives from S and E trials for the 180° rotation task as already explained. Saying "same" on the S trials and "same" on the E trials resulted in correct performance in the former case and errors in the latter case. Both tendencies may have been guided by the same strategy based on perceptual evidence of a left–right reversal.

There is one objection that can be made to the conclusion that subjects were unable to visualize how the wire objects appeared from other viewpoints. Perhaps the depth of these objects was not adequately perceived. If so, even excellent visualization would result in an incorrect mental representation that could lead to lack of recognition of these objects. It was with this problem in mind that the wire objects were deliberately placed quite near the subject in Experiments 1 and 2, namely, 80 cm away. At this near distance, with full binocular cues and ordinary room illumination, one would not expect depth perception to be inadequate. However, in Experiment 3, the wire objects were placed farther away, at 180 cm, to minimize any difference in viewpoint between the standard and comparison objects that were placed next to one another. At this distance it can be argued that with our unique wire objects, the depth of which is primarily given by binocular rather than pictorial cues, there is some falling off of phenomenal depth.

With this objection in mind a control experiment was performed in which subjects had to judge all three dimensions of the wire objects.

EXPERIMENT 4

Method

Subjects. Eight undergraduates served as subjects.

Material and viewing arrangement. Two of the open and two of the closed wire objects used in Experiment 3 were used in this experiment. They were placed at both the nearer distance used in Experiments 1 and 2 (80 cm) and at the greater distance used in Experiment 3 (180 cm). The subject viewed them with head stationary on a chin rest.

Procedure. The task was to match the width, the height, and the depth of each wire object to a wire length by snipping off these lengths from a coil of wire with a wire cutter. The subject, whose head remained on the chin rest in performing this task, placed each of the three cut lengths into small ball of clay, orthogonally to one another, thus indicating the three dimensions perceived. These were set aside and later measured by the experimenter. The subjects were told that they were to imagine a three-dimensional box into which the wire object would just fit in width, height, and depth and to cut the wire lengths to indicate each of these dimensions. There were two trials with each wire object at each distance and the data consist of the average for each subject of the two trials of each of the three dimensions judged.

Results

Since there was considerable variation in the absolute size of wire lengths selected for all three dimensions and since the question of interest concerned three-dimensional shape perception, to evaluate the adequacy of depth perception, the subject's judgments were converted to ratios, of width to depth, and of height to depth. These ratios could then be compared to the actual width-to-depth and height-to-depth ratios of the corresponding standard object. So, for example, if the wire object was 12 cm wide, 24 cm high, and 16 cm deep, the width-to-depth ratio was .75 and the height-to-depth ratio was 1.5. If depth were underperceived we would expect the mean obtained ratio of width-to-depth to be greater than .75 and the mean obtained ratio of height-to-depth also to be greater than 1.5. In fact, the subjects' obtained ratios reflected impressive accuracy in their perception of the object's dimensions (including the width-to-height ratio as well, although this was not of direct interest to the question of depth perception). Moreover, there was no evidence of any inadequacy or falling off of depth perception for either the near or far distances. Overall, of 64 obtained mean ratios (4 width-to-depth, 4 height-to-depth ratios per subject × 8 subjects), 36 were either equal to or *less than* the corresponding object dimension ratios and 28 were greater than these ratios. The mean ratios obtained for each wire object for each of the two critical comparisons (width-to-depth and height-to-depth) were extremely close to the actual ratios of these dimensions of the standard objects and did not even approach a significant departure from them. The combined mean ratio obtained for all wire objects at both distances of both width-to-depth and height-to-depth was 1.29. The mean corresponding combined ratio of the dimensions of all standard objects was 1.31.

Discussion

We conclude that the depth of the wire object was perceived veridically at both the near distance used in Experiments 1 and 2 and the greater distance use in Experiment 3. Thus poor performance in visualizing how the objects looked from other viewpoints cannot be attributed to inadequate perception of their depth.

GENERAL DISCUSSION

The first three experiments all show that subjects are unable to perform adequately on tasks bearing on their prior viewing of wire objects. Precisely what is it that they have failed to achieve? We have already ruled out in Experiment 4 the possibility that our subjects were unable to perform an accurate representation of the object in depth. It is possible that, while they have achieved such representation, they were simply unable to remember it? If so, there is no need to entertain the belief that failure in the test concerns the inability to visualize an object from another viewpoint. However, in Experiment 2 we were able to show in the perception condition that memory for the wire object in the orientation in which it had been seen was excellent and from the results of Experiment 4 we can infer that that memory was of a three- and not merely of a two-dimensional representation. Besides, in Experiment 3 there was no demand on memory at all, because the wire standard object remained in view when the comparison object was introduced.

The next possibility to consider is that subjects were unable to form a viewer-independent (or object-centered) representation of the wire object and that is why they could not extract the appropriate representation from it of how the object would look from a specified viewpoint. This may well be true but in our opinion the inference does not necessarily follow. Even if such an object-centered representation is not achieved, logically it still is possible to argue that one can imagine how an object viewed from one position would look from another. Conversely if such an object-centered representation *is* achieved it is still possible to argue that one can be unable to extract varying viewpoint-dependent representations from it. In point of fact, as pointed out earlier, research in our laboratory has indicated that object-centered representations of these wire objects seem not to be spontaneously achieved (Rock et al., 1981; Rock & DiVita, 1987).

We are, therefore, left with two possible explanations of the difficulty our subjects experienced in carrying out the task of visualization: either they could not achieve the specified viewpoint representation because they had no object-centered representation from which to extract it and such a representation is necessary in order to do so *or* they simply could not manipulate their viewpoint-dependent representation to achieve a representation differing from it. But whichever of these is true, or if both are true, the result challenges the widespread contemporary belief in the human capability of such visualization or mental rotation.

However, have we indeed made an adequate case for the conclusion that we cannot visualize or imagine what an object looks like from a viewpoint other than the one from which we see it? Since such imagining is roughly equivalent to what is meant by mental rotation, don't we already know from the seminal work of Shepard and his associates and the many variations and repetitions of this work over the last 15 years that precisely such imagining can and does occur?

Obviously we cannot prove the Null Hypothesis, that under certain conditions, or for certain objects, or for some individuals, such imagining or mental rotation cannot occur. But we can ask whether it does occur under conditions that provide a reasonable test of the currently prevailing assumption that we are capable of such mental rotation. So the question is whether the kind of object used and tasks required here are appropriate examples of the kind of imagining activity of which we are said to be capable and how these compare with the kind of object and task Shepard and his associates have employed.

We believe that if one were starting out to study this problem and no previous research had been done on it, our choice of object and methods ought to be considered perfectly appropriate, perhaps ideal. The wire objects are novel so that prior experience is ruled out. They are not overly complex. Unlike most solid objects, including Shepard's drawings of cube structures, regions in back are not occluded by regions in front.

The use of three-dimensional objects viewed binocularly at a close distance ought to be considered preferable to the use of two-dimensional drawings of three-dimensional objects. The irregularity of these wire objects precludes inference about their appearance from differing viewpoints on the basis of regularity and symmetry such as may occur with other types of figures.

One might, however, criticize the use of this type of object on the grounds that it is not representative of the type of object we typically encounter. In addition to the lack of symmetry and other regularities such as axes of elongation and distinguishable parts, they lack surfaces. The absence of surfaces means the absence of information about shading, texture, and perspective. It would be difficult to apply certain theories of object recognition to these objects, such as one recently espoused by Biederman (1987) based on the concatenation of certain volumetric parts.

There are two answers we would give to this kind of criticism. One is that there are in fact objects in the natural environment that are irregular, asymmetrical, and unfamiliar such as rocks, lumps of dirt or clay, mountains, cloud formations, and clusters of branches. Certainly such objects were not atypical in the primitive environment in which man evolved. But the more important answer is that typicality is not the issue. The issue is whether or not we have a particular cognitive capability, namely, to visualize the appearance of things from viewpoints other than the present one. Given the fact that wire objects are *perceived* veridically in three dimensions—whether they are typical percepts or not—then there is no obvious reason why the visualization capability under investigation should not occur for such objects, particularly if one believes that the mental rotation process is analog in character. If the three-dimensional representation of the wire object from the observer's viewpoint is achieved, as common sense and as our data indicate it is, then why should it not be subject to mental rotation that is based on an analog operation as much as any other kind of object? If so, then in fact the choice of this kind of object as a testing ground for the claim of mental rotation has the advantages referred to above.

As to method, it will be recalled that several were used, namely, drawing the imagined object, recognition, and a same–different task not unlike the one used by Shepard and his associates. The drawing task used in Experiment 1 should not be dismissed out of hand because of the well-known difficulty people have in drawing. Our subjects have no difficulty in making direct copies of the wire objects from the position they were in. Clearly then the difficulty in drawing the imagined orientation was not motor but one based on the inadequacy of the mental representation. In fact we believe that one of the difficulties people have in drawing, that of drawing something from memory, is precisely the inadequate mental representation of that thing.

In any event the recognition test used in Experiments 2A and 2B revealed the same fact, namely, that subjects are unable to achieve a mental representation of the wire object from a position 90° distant from the one they are in. The recognition test here is in fact a rather easy one in that the four choices are qualitatively quite distinct, representing as they do entirely different wire objects. In other words, the recognition test does not require making fine discriminations among qualitatively similar shapes.

The same–different task employed in Experiment 3 comes closest to the method of Shepard and his associates in that (1) a response of "same" or "different" was required in comparing two objects and (2) on some trials the comparison object was an isomer (mirror image or enantiomorph) of the standard. Our task differed, however, in a number of respects: (1) the comparison object was sometimes incorrect because it was the wrong view of the standard, not an isomer; (2) the comparison object was not visible during the time the subject was presumably engaging in the mental rotation (although the standard remained visible when the comparison object appeared); (3) the object was three-dimensional rather than a drawing of a three-dimensional object; (4) only 3 imagined orientations were tested rather than 10 covering 20° intervals tested by Shepard and his associates; (5) a condition was included duplicating the task we used in the first three experiments in which the subject was instructed to imagine viewing the object from a different position rather than imagine the object rotated to a corresponding position; (6) many fewer trials were run in our experiment and our subjects were not practiced in the task.

However, in our opinion, none of these methodological differences ought to be critical and in fact some, such as the use of actual objects rather than drawings of objects, ought to make the task easier or more natural. We attach particular importance to the last-mentioned item concerning practice and number of trials. If people are capable of mental rotation then it should not be necessary to provide them with a good deal of practice in an experiment designed to investigate this cognitive capacity. All that should be necessary is to make the task clear. Shepard and Metzler (1971) provided 40 such trials and the number of experimental trials was 1600 no doubt in order to reduce noise in the data and obtain clear results. It is now an established fact that familiarity with the figure and practice affect the facility with which mental rotation tasks are carried out (Bethell-Fox & Shepard, 1988; Kail, 1986; Pylyshyn, 1979). But we would argue that these are not desirable features in such research for the reason to which we alluded above, namely, that familiarity and practice enable subjects all the more to achieve correct answers on the basis of strategies that do not directly require or make use of mental rotation.

Subjects in the Shepard et al. paradigm may have arrived at correct answers on the basis of the same kind of strategies that our subjects reported using and this may have been all the more effective because of practice and multiple trials and the kind of object employed. For example, in some of their cube figures one arm at an end is distinctive by virtue of containing an end cube whose third face is visible or by virtue of containing either two or three cube components and such a "landmark" can then enable a subject to look for that same part in the comparison figure. From this subjects can infer what the orientation of the comparison object is and then finally whether or not it is the same object or an isomer of it depending upon how that part relates to the arm of the object at right angles to it. That the process does begin with the comparison of distinct parts is supported by recordings of eye fixations (Just & Carpenter, 1976). It is important to realize that the same–different method does not guarantee that the subject has achieved a mental representation for one of the objects that matches in all particulars the representation given in direct perception of the other object.

Undoubtedly the most impressive aspect of the research of Shepard and his associates on mental rotation is the finding of a progressive, linear increase in reaction time as a function of the angular discrepancy between the orientation of the two objects. This finding more than any other would seem to suggest an analog-like process in which a representation must pass through intervening orientations to arrive at a final orientation, much as would the object itself. However, it strikes us that a different interpretation of this finding is possible. The greater the difference in orientation between a perceived object and the one to be imagined, the more difficult the comparison.

We can best illustrate this argument in the case of change of orientation of a figure in a frontal plane. A tilt of 45° requires a slight shift in the region assigned as "top" and similarly with respect to "left", "right" and "bottom". We can easily imagine the vertical axis of the figure in an oblique orientation but not because it takes little time to do so. A tilt of 90°

requires substitution of, let us say, right side for top, bottom for right side and so forth. We can imagine the horizontal axis as the figure's vertical axis but it is more difficult than to substitute an oblique axis for the figure's vertical. Again this is not because of the time required. Finally, 180° rotation or inversion requires a polarity substitution with "top" becoming "bottom," "left" becoming "right," and so forth. We know that for many figures, such as faces, the task is not merely different, it is impossible. We may guess what the facial expression is or whose face it is, but we simply do not achieve a correct or adequate representation of the face when it is inverted. But according to the currently prevailing notion of mental rotation should we not achieve such a representation given an adequate amount of time?

In any event, it would not be surprising that in a same–different paradigm subjects might be able to answer correctly and yet in this case we know that they do not really achieve the representation that mental rotation is supposed to produce. It would also not be surprising if it required more time to answer correctly for an inverted face than for one tilted 90°. The greater difficulty of the task would lead the subject to spend more time on it. Further support for this interpretation derives from a finding of Pylyshyn (1979) that the difficulty of the task the subject is required to perform in relation to the mentally rotated figure systematically affects the obtained reaction time–angle of rotation relationship. Whether or not the experiment by Hochberg and Gellman (1977) on the role of "landmarks" referred to above supports the difficulty interpretation suggested here depends on how their findings are interpreted. One interpretation—the one we believe these investigators suggest—is that "landmarks" are important in *facilitating* mental rotation. They tell the subject early on in which direction and by what angle to rotate mentally one of the two figures presented. But another interpretation is that the "landmarks" make the task easier to deal with by some cognitive strategy. For example, if the figure is an elongated L and the short arm is at the top facing right in one figure and the subject readily detects that it is on the right in the other, then it ought to face down if it is part of the same figure but up if it is part of a reflected figure. According to this interpretation continuous mental rotation does not enter in at all in the process. All of these considerations suggest to us the importance of directing research more carefully at the question of the nature of or the adequacy of the representation achieved rather than merely ascertaining whether subjects can make a particular discrimination such as obverse vs reverse orientation.

If it is difficulty rather than the greater angle through which the alleged mental rotation must pass that accounts for the progressive increase in RT as a function of angular discrepancy, then the supposition that a process of progressive or continuous mental rotation occurs is called into question. Must we imagine the intervening appearances of an object in order to arrive at a representation of its appearance in the final angular orientation required? Intuitively some such process often does seem to occur but perhaps we do it in order to keep track of the various parts of the object until as a whole it has reached the orientation we are instructed to imagine.[4] But consider two examples where this intuition does not seem to hold. Suppose we view an inverted face and try to imagine how it looks upright. It seems most unlikely that we try to do this by rotating it through 180° so that it must go through a 90° orientation. More relevant to the research reported here is the following example. In Experiment 3, in one condition, subjects were asked to imagine how the object would look if they were to view it from a particular orientation (Self-Rotation Condition). Here it is unlikely that one must imagine oneself moving progressively to the position indicated. One can simply imagine oneself *in* that position. Thus, while our results failed to show a significant difference in correct performance between this and the Object-Rotation Condition there nonetheless may be important and interesting differences in processing between these conditions. Research on children suggests that there is (e.g., Huttenlocher & Presson, 1979). In our experiments reliance on strategies—and quite possibly somewhat differing strategies—may have obscured such possible differences in allowing subjects to succeed in the tasks equally well. In fact, there appear to be interesting interaction effects between these conditions and type of object, type of comparison object, order of trial, etc., that remain to be clarified. For example, for the Self-Rotation Condition there was an increase of 23% correct for 90° rotation trials from the first 9 trials to the second 9 trials, whereas for the Object-Rotation Condition there was an increase of almost 30% correct for *180°* rotation trials from Trials 1–9 to 10–18. However, the design of the experiment and the kind of data obtained preclude statistical tests of interaction. We, therefore, feel that the last word on the difference between these two methods has yet to be said.

[4] There is one reported finding that does strongly support the claim that subjects do rotate representations progressively along a trajectory, passing through intermediate positions on the way to the final orientation required (Cooper, 1976). It was shown that reaction time to respond correctly to a probe figure was very short and the same for all orientations when it was presented in exactly the orientation the subject's changing representation was expected to be in if it indeed was rotating mentally at the speed known to be required for rotation of that figure for each particular subject. When probes appeared in unexpected orientations, reaction time increased linearly with the angular difference between it and the expected orientation. This critical experiment should be repeated preferably with a large number of less practiced subjects.

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