Mental rotation

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Mental Rotation is the process of imagining an object rotated into a different orientation in space. Beginning in 1971, experiments on mental rotation have had an appreciable influence on the field of cognitive science for several reasons.

- They demonstrated that phenomena of mental imagery, which had previously seemed too subjective and qualitative for rigorous scientific study, could be investigated in an objective and quantitative way.
- They provided striking evidence for mental processes whose continuous or *analog* nature differed markedly from the discrete symbolic processes assumed in the theories of cognition prevailing at that time.
- The remarkably orderly chronometric data that emerged from these studies implied a mental process in which the intrinsic structure of an object is accurately represented in successively more rotated orientations over the kinematically simplest path.
- Mental rotation and related mental transformations, may have played crucial roles in scientific discovery (Shepard, 2004, 2008). Einstein, a master of thought experiments, noted that he "very rarely" thought in words, and that his particular ability did not lie in mathematical calculation either, but in "visualizing ... effects, consequences, and possibilities" by means of "more or less clear images which can be 'voluntarily' reproduced and combined" (see Shepard & Cooper, 1982, p. 6).

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Pre-Experimental Recognition of Such Imagined Transformations

Hermann von Helmholtz, the great 19th century physicist and physiologist, stated in 1894 that "we can clearly imagine all of the perspective images which we may expect upon viewing [an object] from this or that side, and we are immediately disturbed when such an image does not correspond to our expectations." (Shepard & Cooper, p. 1.)

Ernst Mach, whose principle of inertia was embraced by Einstein's theory of general relativity and who introduced the term *Gedanken [i.e., thought] Experiment* noted in 1894 that recognition that two objects are identical in shape is immediate when they are in the same orientation (Figure 1A), but requires an additional "intellectual act" when they are in different orientations (Figure 1B). (Shepard & Cooper, p. 8.)

Experimental Investigations of Mental Rotation

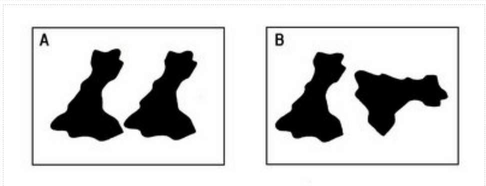

Figure 1: Pairs of objects that Ernst Mach (1886) noted can be seen as identical in shape almost immediately (A) or only after an additional "mental act" (B).

Example 1: Mental rotation of three-dimensional objects

Origin: Shepard and Metzler (1971) were the first to measure the time required to perform the "intellectual act" posited by Mach. The idea for their experiment was initially outlined in a brief memorandum that Shepard drafted on November 18, 1968, just after he - during an hypnopompic state of slowly awakening from sleep - "experienced a spontaneous kinetic image of three-dimensional structures majestically turning in space" (Shepard & Cooper 1982, pp. 7, 19-23).

Rationale: Earlier approaches to mental imagery, in which people were simply asked to describe what they imagined, afforded no objective check on the veridicality of their reports. Instead, Shepard sought objectivity: first, by ensuring that the participant's responses were classifiable as correct or incorrect; and, second, by taking the recorded reaction times of their correct responses as measures of mental processing times.

Method: Figure 2 shows examples of the pairs of (computer-generated) perspective views of asymmetric three-dimensional objects used. As soon as possible upon the appearance of a pair of such images, regardless of the portrayed orientations of the objects, the participant was to operate a right- or a left-hand lever to indicate that the objects were, respectively, identical or intrinsically different in three-dimensional shape. To prevent decisions from being based on some orientation-independent visible feature, the pairs of different-shaped objects were constructed to be enantiomorphic - that is, to differ only by a reflection in space (like a left and a right hand).

Thus, the objects in Pair A are identical except for a rotation in the picture plane, and the objects in Pair B are identical except for a rotation in depth. For pairs of both of these types, the objectively correct response is to pull the right-hand lever. In Pair C, however, neither object can be transformed into the other by any rigid rotation. For such a pair, the objectively correct response is to pull the left-hand lever.

Results: Figure 3 shows the average reaction times for correct responses to pairs that were of the same shape, plotted as a function of the angular difference in the portrayed orientations of the two objects. The results are plotted separately for pairs that differed by a rotation in the picture plane and for pairs that differed by a rotation in depth.

Implications:

The strikingly linear increase in average reaction time with angular difference in orientation is consistent with the participant's own reports that they made the decision of same or different shape by imagining one object rotated into the orientation of the other. The slope of the reaction-time function indicates that (in this task) they performed this mental rotation at an average rate of roughly 40 degrees per second.

That the average rate was approximately the same for picture-plane and depth pairs is consistent with the hypothesis that in both cases, the participants were representing the objects as rotating in three-dimensional space - even though only a picture-plane rotation corresponds to a transformation that is rigid on the surface of each retina.

Example 2: Confirmation of the analog character of mental rotation

Rationale: In order to obtain objective confirmation that the object is actually being mentally represented in successively more rotated orientations during mental rotation, Lynn A. Cooper (a former Shepard student) required participants to respond to visual test stimuli while they were performing the mental rotation (Cooper, 1976).

Method: Cooper used two-dimensional random polygons for which she had previously determined the individual participants' rates of mental rotation. (These rates were roughly 15 times greater than rates in the Shepard-Metzler experiment, probably because Cooper's participants had advance knowledge of the object and of the direction in which it was to be mentally rotated and, so, did not have to look back and forth between objects in unfamiliar orientations, as did the Shepard and Metzler participants.)

At the beginning of each trial, one of the familiar random polygons (such as that illustrated in the lower right of Figure 4B) was displayed for 2 seconds. A brief blackout signaled the participant to imagine that polygon rotating in a clockwise direction within the blank circular field. Then, at an unpredictable time and in an unpredictable orientation, either that polygon or its mirror image suddenly appeared in the circular field. As soon as possible and regardless of the orientation in which that test polygon was presented, the participant was to push a right- or left-hand button, to indicate that the test polygon was, respectively, the standard polygon initially presented or the mirror-image version of that polygon.

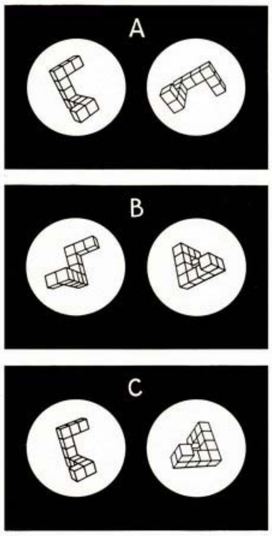

Figure 2: Examples of pairs of objects presented in the experiment by Shepard and Metzler (1971) that differ by a rotation in the picture plane (A), by a rotation in depth (B), or that are intrinsically different (specifically, enantiomorphic) in shape (C).

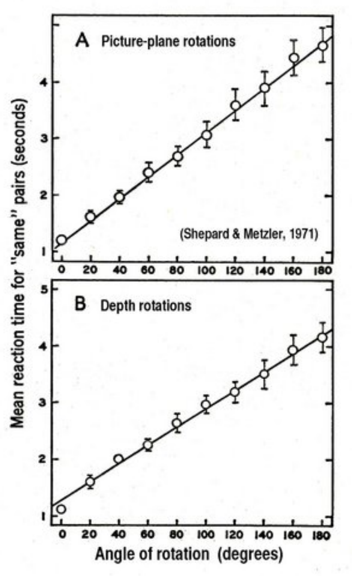

Figure 3: Times that participants in the experiment by Shepard and Metzler (1971) took to determine that two presented objects were of the same shape, when the objects differed by a rotation in the picture plane (A) and when they differed by a rotation in depth (B), plotted as a function of the angular difference in the portrayed orientations.

Results: As shown in Figure 4A, when the test polygon was presented in the orientation at which the participant was predicted to be representing the polygon at the moment of test (based on that participant's previously determined mental rotation rate), the standard vs. reflected responses were uniformly accurate and fast - averaging a little over half a second, regardless of the absolute angle of that predicted orientation.

As shown in Figure 4B, however, when the test polygon was presented in an orientation that departed from the orientation predicted for the participant's mental representation at the time of the test, the reaction time increased very linearly with that departure.

Implications:

The linear increase in reaction time with angular departure of the test polygon from the predicted orientation of the participant's representation supports the hypothesis that when there was such a departure, the participant had to carry out an additional (forward or backward) mental rotation to bring the mental representation into alignment with the test polygon to determine whether or not the shapes matched.

That the reaction times were uniformly fast when the test polygon was presented at the orientation the participant was predicted to be representing at the moment of test indicates that the internal process passed through representations of those intermediate orientations - even for orientations (shown by the unfilled circles in Figure 4A) that differed by 30 degrees from the (60-degree) orientations previously tested.

Mental rotation is thus an analog process in which something is actually rotating. What is rotating need not be anything physical. It is, more abstractly, the orientation in physical space in which an appropriate physical test stimulus, if it were presented, would permit the participant's fast and accurate match-versus-mismatch response.

Example 3: Demonstration of an analogous phenomenon of rotational apparent motion

Rationale: Mental rotation requires a voluntary cognitive effort. There is, however, a related, perceptually driven phenomenon of visual apparent motion that is automatic and effortless. An experiment by Shepard and Judd (1976) confirmed that these two types of phenomena of mental transformation obey laws of the same form.

Method: For close comparison, the stimuli were the original perspective views of three-dimensional objects used by Shepard and Metzler. But, instead of recording the time required to determine whether two such simultaneously displayed objects were of the same shape, objects that were of the same shape were presented in temporal alternation and the minimum onset-to-onset duration yielding the experience of rigid rotation was determined for each angular difference in orientation.

Results: At sufficiently slow rates of alternation, participants experienced a continuous rigid rotation of the object, back and forth, between the two alternately presented orientations. At sufficiently higher rates, the participants experienced some smaller but distinctly non-rigid motion (typically, in which the right-angled limbs in one image independently moved into non-corresponding limbs in the other image.)

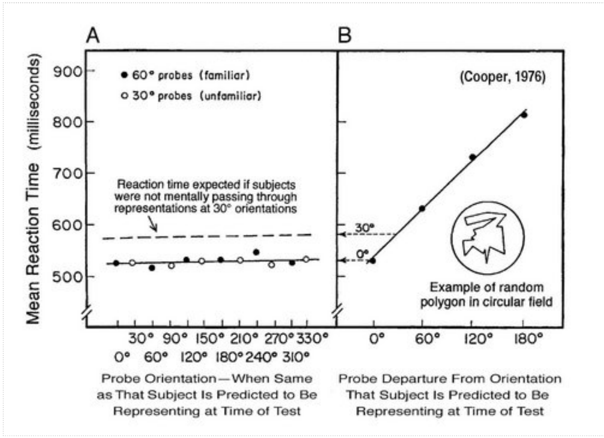

Figure 4: Results from the experiment of Cooper (1976) on mental rotation (in the plane) of random polygons with which they had become familiar. Times taken to classify a test polygon as standard or reflected when presented in the orientation the participant is predicted to be imagining at the time of the test presentation (A) and when presented in an orientation differing (from 0 to 180 degrees) from the orientation the participant is predicted to be imagining at the time of the test presentation (B).

In Figure 5 the minimum duration of each successive image that still yielded the experience of rigid rotation is plotted, as before, against the angular difference in orientations of the two presented objects. The dependence of the critical-time on angular difference is again linear and of essentially the same slope for picture-plane and depth pairs - just as Shepard and Metzler found for mental rotation (compare Figure 3 and Figure 5). The linear slopes found for rotational apparent motion correspond, however, to still faster rotational rates of about 1000 degrees per second (compared to about 40 degrees per second in the mental rotation task introduced by Metzler and Shepard, or the 600 degrees per second in the different task devised by Cooper).

Implications: Despite these differences in speed, processes of apparent rotational motion, like those of mental rotation, require times that increase linearly with the angle of the rotation and that are essentially independent of the axis of the rotation. Both processes evidently are of an analog type:

- that represents operations in three-dimensional space and is not influenced by the complexity of what these would correspond to on the two-dimensional retina, and
- that passes through representations of intermediate orientations. For apparent rotational motion, this was later confirmed, in three different ways, by Robins and Shepard (1977), by McBeath and Shepard (1989), and by Kourtzi & Shiffrar (1997).

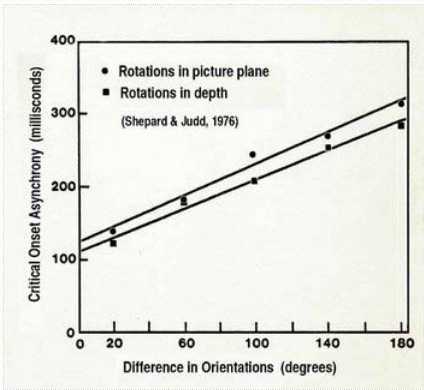

Figure 5: Minimum times between the Shepard-Metzler objects, presented in alternation, yielding the perception of a rigid rotation back and forth of a single object, as measured by Shepard and Judd (1976). (For shorter times - that is, for more rapid alternations - any motions were experienced as distinctly non-rigid.)

Neuronal mechanisms and abstract mathematical characterizations of mental rotation

The results, reviewed here, of the cognitive-behavioral studies by Shepard, Cooper, and their associates, demonstrate that highly orderly and quantitative laws of mental operations can be objectively established without depending on any knowledge of the neuronal mechanisms that carry out these mental operations in the physical brain.

Electro-neurophysiological investigations, particularly by Georgopoulos and his associates using monkeys, have however yielded evidence supporting the claims of Shepard, Cooper, et al. - that mental rotation is an analog process that sequentially passes through representations of intermediate orientations (e.g., Georgopoulos 1993, 1999; Georgopoulos, Lurito, Petrides, Schwartz, & Massey, 1989).

In a manner more akin to theoretical physics than to empirical neurophysiology, Shepard and his associates have also shown that the phenomena of mental rotation and apparent rotational motion, alike, conform with elegant group-theoretic formalisms for kinematically simplest - hence least-time - transformations, abstractly represented as geodesic paths in the curved, higher-dimensional spaces of distinguishable orientations determined by the symmetry group of the objects transformed (e.g., Carlton & Shepard, 1990a, 1990b; Shepard, 1994, 2001, 2008; Shepard & Farrell, 1985).

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Further reading

External links

- Roger Shepard's website

See also

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