Mental Rotation

Intermediate article

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Mental rotation refers to rotational transformation of an object's visual mental image. Mental rotation may indicate that, unlike the object's verbal description, the image shares some spatial and visual properties with the object itself.

INTRODUCTION

When psychological studies of mental imagery revived in the late 1960s, arguments centered upon the question of whether mental imagery should be distinguished from language as a separate system of mental representation. Although mental imagery was repeatedly shown to facilitate word retrieval, this did not convince many psychologists that mental imagery and language are different kinds of representation. Mental rotation attracted great attention because it appeared to attest that mental imagery has some spatial and visual properties that are lacking in language. (*See* **Mental Imagery, Philosophical Issues about**)

RELATION BETWEEN ANGULAR DISPARITY AND RESPONSE TIME

Mental rotation was first reported by Shepard and Metzler (1971). Participants in their experiment were shown a pair of objects like those in Figure 1(a), and asked to judge as quickly and accurately as possible whether they were the same or different. When the two objects were different, they were mirror images of each other as in Figure 1(a). Angular disparity between them was varied from 0 to 180 degrees. Response time was measured between presentation of the objects and a participant's response.

Mean response time for the 'same' pairs was found to be proportional to angular disparity (see 0–180 part of Figure 1(b)). Shepard and Metzler (1971) interpreted this finding as follows: to make mirror image discrimination, participants mentally rotated the image of one object at a constant speed until it is aligned with the other.

This interpretation triggered a lively debate as to whether an image was actually rotated or not. The most convincing evidence of rotation was provided by Cooper (1976), who estimated the speed of mental rotation (i.e. the slope of the linear function) for each participant in an experiment similar to Shepard and Metzler's (1971). In a subsequent experiment, the participant was asked to rotate the image of a presented standard object clockwise. A test object was later presented in the orientation that the standard object's image was expected to take at that very moment. The participant could not predict where the test object would be presented. Nevertheless, the results showed that the participant was able to make mirror image discrimination

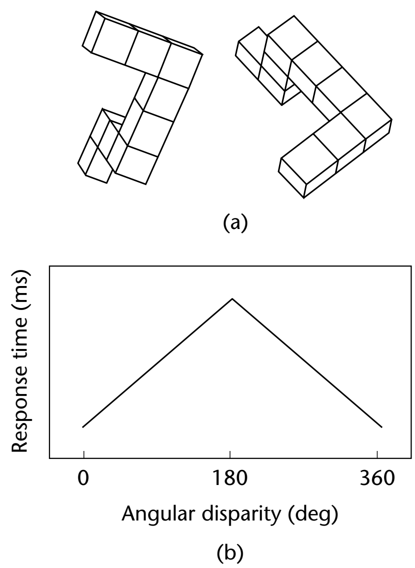

Figure 1. Materials and results in a typical mental rotation experiment: (a) an example of a 'different' pair of objects used by Shepard and Metzler (1971); (b) a schematic illustration of a typical mental rotation function.

at any angular disparity as fast as when the test and standard objects were presented in the same orientation. This strongly suggested that the image was actually present at the expected orientation. It follows that the image was actually rotated at least in that it passed through the intermediate rotational path.

Whether rotation is real or not, the systematic relation between angular disparity and response time provided strong evidence that mental imagery is different from language. In the case of language, the time to transform a sentence, for example 'The object is upright', into the sentence 'The object is tilted by X degrees' does not systematically relate to the value of X.

NON-MONOTONICITIES AT 180 DEGREES

When angular disparity exceeded 180 degrees, it was found that response time did not continue to increase monotonically but turned to decrease up to 360 degrees. In other words, it showed non-monotonicity at 180 degrees. As a result, a typical mental rotation function became an inverted V, as in Figure 1(b). This implies that it was possible to choose the shorter rotational path before starting the rotation.

The basis for identifying the shorter rotational path consists of those structural properties that are not affected by orientational change (Takano, 1989). In the case of the two objects in Figure 1(a), the human visual system detects the following structural properties irrespective of the objects' orientations: each object is composed of cubes, one end is composed of two cubes while the other end has only one, the two ends are orthogonal to each other, and so on. These orientation-free properties can be used to identify the corresponding parts between the two objects. Once the corresponding parts are identified, it is not difficult to determine the shorter rotational path.

INFLUENCES OF COMPLEXITY AND FAMILIARITY

Familiarity

It was found that more familiar objects could be rotated faster. To rotate unfamiliar objects like those in Figure 1(a) by 180 degrees, participants in Shepard and Metzler's (1971) experiment had to spend about 3000 ms. When objects were familiar alphanumeric characters, the time was reduced to 230–1200 ms.

The most dramatic demonstration was provided by Sayeki (1981) who told his participants to regard one of Shepard and Metzler's (1971) objects as a human body. In the case of Figure 1(a), the left object is a sitting person who is extending the left arm, whereas the right object is a person extending the right arm. Once an originally unfamiliar object was likened to a human body, it suddenly became a very familiar one. To rotate it by 180 degrees, Sayeki's (1981) participants needed only 180 ms.

Complexity

Early experiments found no effect of complexity on the speed of mental rotation. It turned out, however, that the reason for this absence was that participants reduced complex objects to simpler properties that were indispensable for making a same/different discrimination. When the task was changed so that the reduction was impossible, the speed of mental rotation was found to be slower for more complex objects.

It was also found that the speed of mentally rotating complex objects became faster as a result of practice (Heil *et al*., 1998). Given that intensively practised objects become familiar, this effect of practice may be essentially identical to that of familiarity.

Mental rotation seems to have some limitation in its ability to deal with complex structures. Thompson's (1980) 'Thatcher illusion' is its most impressive demonstration: a face with some modifications looks almost normal when it is inverted, whereas it looks monstrous when it is upright. It is impossible to see the monstrous face by mentally rotating the inverted one. This suggests that mental rotation does not have sufficient capacity to transform such a complex structure as a human face while holding its structural details intact.

SITUATIONS THAT REQUIRE MENTAL ROTATION

A Basic Principle

In general, mental rotation occurs when a 'different' object is a mirror image of an original, whereas it does not when a 'different' object is of other types. Takano (1989) explained this by making a distinction between orientation-bound and orientation-free structural properties.

When two figures are mirror images of each other, they differ only in orientational relation between their constituent parts. In Figure 1(a), for example, the left object's 'arm' extends to the *left* of its 'body', whereas the right object's 'arm' extends to the *right* of its 'body', if both objects are upright. This type of structural property is orientation-bound in that it is altered by a whole figure's orientational change. In Figure 1(a), in fact, the 'arm' of the right object which is not upright extends to the *left*, not *right*, of its 'body'. Therefore, it is impossible to compare orientational relations directly between two objects while they are in different orientations. To compare the orientational relations between the two objects, their orientations have to be aligned first. A common way of alignment is mental rotation.

When two objects are not mirror images of each other, there always exist structural differences that are orientation-free. Imagine, for example, that a non-mirror-image 'different' object is made by adding one more cube to the end of the left object's 'arm' in Figure 1(a). Then, it will be easy to tell whether a test object is the same or different, irrespective of its orientation. Mental rotation is not needed in this case.

Flexible Strategies

The human brain is an extremely complex and thus flexible system. Therefore, whether mental rotation is actually conducted or not sometimes differs from the above basic principle's prediction.

On the one hand, mental rotation could be conducted when it is unnecessary in principle. Suppose that you are looking for a toy. You have to discriminate it from other similar-looking objects, which could appear in any orientation for you. Although they may differ from the toy in some orientation-free properties, you cannot tell beforehand exactly what will be the differences. In such a situation, it may be wise to mentally rotate a similar-looking object to see whether it is the wanted toy. Thus, mental rotation may be conducted in natural settings as a convenient tool even if it is not indispensable. This sort of mental rotation was confirmed in an experiment, where participants failed to detect differences in orientation-free structural properties between compared objects because of their complexity. They did conduct mental rotation, though it was unnecessary in principle (Takano, 1989).

On the other hand, mental rotation may not be conducted when mirror images have to be discriminated. Mental rotation can be skipped because it is not the only way to discriminate between mirror images. If an object's form is remembered in various orientations, mirror image discrimination can be made without mental rotation (Tarr and Pinker, 1989) because the orientational relation in a presented object can be directly compared to that in the original object remembered in the same or neighboring orientation.

Another way of skipping mental rotation is to remember regularities in changing orientational relation. Suppose, for example, that part *A* is to the right of part *B* in an object. When the object is rotated by 90 degrees clockwise, *A* is below *B*; when the object is rotated by 180 degrees, *A* is to the left of *B*. If these regularities are utilized, mirror image discrimination can be made without mental rotation because the orientational relation in a presented object can be compared directly to that in the original object if the latter orientational relation is transformed adequately on the basis of these regularities (Takano, 1989).

THEORIES OF MENTAL ROTATION

Theoretical arguments about mental rotation centered upon the nature of mental representation of visual imagery. In the imagery (or analogue–propositional) debate, which continued for more than ten years, the analogue camp (e.g. Kosslyn, 1973) argued that the mental representation of a visual image is analogous to the corresponding physical object or its physical representation (e.g. a picture) with regard to some spatial and visual properties. The propositional camp (e.g. Pylyshyn, 1973) argued that the mental representation of an image is composed of propositions, a system of symbols that resembles language but is distinguished from it by different vocabulary and grammatical rules.

Mental rotation attracted a great deal of attention as the most convincing evidence for the analogue camp because mental rotation of a visual image closely resembled physical rotation of a physical object. The propositional camp showed that such properties as complexity and familiarity affected the 'speed' of mental rotation, and argued that a visual image differs from its corresponding physical object because a physical object's rotation speed is not affected by its complexity or familiarity. However, this type of criticism failed to show that the mental representation of an image must be propositions, because a representation could still be an analogue while it is different from its corresponding physical object in some respects (e.g., a picture of a person may be different from the real person in its size, material, temperature, and so on).

In the course of the imagery debate, the analogue camp was able to provide rational accounts for experimental findings presented by the propositional camp; conversely, the propositional camp was also able to provide rational accounts for experimental findings presented by the analogue camp. Anderson (1978) claimed that the debate would not be resolved by any experimental data because any behavior of an analogue system would be mimicked by a propositional system equipped with appropriate processes that deal with propositional representation, and vice versa. This claim can be considered a special case of the Duhem–Quine thesis that any core assumption (e.g. propositional mental representation of imagery) can be made consistent with any empirical data by appropriately modifying peripheral assumptions.

Although the imagery debate thus has not reached any clear-cut resolution, a variety of experimental findings presented during the debate as to mental rotation provide an invaluable empirical basis to infer exactly what spatial and visual properties are manifested by visual mental imagery, whether they are implemented by analogue or by propositional representation.

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