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Implicit transfer of motor strategies in mental rotation

Maryjane Wraga,[a,*] William L. Thompson,[b] Nathaniel M. Alpert,[c] and Stephen M. Kosslyn[b,d]

[a] *Department of Psychology, Smith College, Northampton, MA 01063, USA*
[b] *Department of Psychology, Harvard University, Cambridge, MA 02138, USA*
[c] *Department of Radiology, Massachusetts General Hospital, Boston, MA 02114, USA*
[d] *Department of Neurology, Massachusetts General Hospital, Boston, MA 02114, USA*

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Abstract

Recent research indicates that motor areas are activated in some types of mental rotation. Many of these studies have required participants to perform egocentric transformations of body parts or whole bodies; however, motor activation also has been found with nonbody objects when participants explicitly relate the objects to their hands. The current study used positron emission tomography (PET) to examine whether such egocentric motor strategies can be transferred implicitly from one type of mental rotation to another. Two groups of participants were tested. In the Hand–Object group, participants performed imaginal rotations of pictures of hands; following this, they then made similar judgments of pictures of Shepard–Metzler objects. The Object–Object group performed the rotation task for two sets of Shepard–Metzler objects only. When the second condition in each group (which always required rotating Shepard–Metzler objects) was compared, motor areas (Area 6 and M1) were found to be activated only in the Hand–Object group. These findings suggest that motor strategies can be covertly transferred to imaginal transformations of nonbody objects.

Keywords: Mental imagery; Mental rotation; Motor learning; PET

1. Introduction

Some 30 years ago Roger Shepard and colleagues first reported that participants who are asked to compare two misoriented objects mentally rotate the objects into alignment (e.g., Shepard & Metzler, 1971; Shepard & Cooper, 1982). This finding was important not only because it documented that people can transform objects in images, but also because it showed that the mental rotation process is incremental: Response times increase linearly with greater angular disparity between objects. This result suggests that participants transform objects in the mind similarly to the way objects are physically transformed, despite the fact that the physical constraints of the environment need not apply to imaginal space.

* Corresponding author. Fax: +413-585-3786.
E-mail address: mwraga@smith.edu (M. Wraga).

More recently investigators have begun using neuroimaging techniques to examine the neural underpinnings of mental rotation. One intriguing finding is that participants use motor strategies to perform some types of mental rotation, as indicated by activation in motor areas of the brain such as the premotor area (PMA) and primary motor cortex (M1). Many of these studies require participants to mentally transform body parts (e.g., Bonda, Petrides, Frey, & Evans, 1995; Ganis, Keenan, Kosslyn, & Pascual-Leone, 2000; Kosslyn, DiGirolamo, Thompson, & Alpert, 1998; Parsons et al., 1995). For example, Parsons et al. (1995) used positron emission tomography (PET) to study brain activation while participants judged whether drawings depicted left or right hands. Parsons (1987) previously had hypothesized that participants solved this task by comparing the rotated representation of their own hand to that of the stimulus. Mapping the coordinates of one body reference frame to another (i.e., hand-to-hand) is an

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egocentric transformation (Howard, 1982). When participants' brains were scanned while they performed the hand rotation task, Parsons et al. (1995) found activation of brain areas involved in motor control, specifically in premotor areas as well as the superior parietal lobule.

In another PET study Kosslyn et al. (1998) compared performance on same/different judgments of hand drawings and Shepard–Metzler (1971) cube figures. Rotation of the latter requires a mapping of object-relative reference frames rather than egocentric reference frames (Howard, 1982). Kosslyn et al. found that motor and premotor areas were activated during the hand rotation task but not the object rotation task. Further evidence for the role of motor areas in egocentric transformations was reported by Ganis et al. (2000), who used transcranial magnetic stimulation (TMS) to impair primary motor cortex transiently, which hindered participants' performance on an imaginal hand and, to a lesser extent, foot rotation task. These findings collectively suggest that mental rotation tasks involving body parts elicit motor strategies.

Motor activation also has been reported when participants mentally transform nonbody objects (e.g., Barnes et al., 2000; Carpenter, Just, Keller, Eddy, & Thulborn, 1999; Cohen et al., 1996; Lamm, Windischberger, Leodolter, Moser, & Bauer, 2001; Richter et al., 2000; Tagaris et al., 1997; Vingerhoets et al., 2001). Using functional magnetic resonance imaging (fMRI), Cohen et al. (1996) studied mental rotation of the original Shepard–Metzler figures and found premotor activation in half of their participants. More recently Kosslyn, Thompson, Wraga, and Alpert (2001) used PET to demonstrate that when participants are led to use motor strategies, motor areas are activated even when they mentally rotate nonbody objects. When participants were instructed to imagine Shepard–Metzler objects being rotated by their dominant hand (i.e., object-to-hand mapping), Kosslyn et al. found activation in contralateral M1 regions. In contrast, they found no such activation when participants imagined the objects being rotated by an external (nonbody) source (i.e., object-to-object mapping). These findings suggest that motor strategies are not defined by their reliance on mental rotation of a body-related stimulus per se, but rather may be defined as strategies that can be used in tasks requiring egocentric transformations.

In the present study we investigated whether motor strategies can be transferred *implicitly* from a task involving egocentric transformations to one that does not. Research on motor sequence learning has shown that primary and secondary motor areas are involved in implicit transfer of motor skills (Grafton, Hazeltine, & Ivry, 1995; Grafton, Hazeltine, & Ivry, 1998). In the current study, we examined whether motor strategies adopted during mental rotation of hands would carry over to mental rotations of objects, under conditions where participants received no explicit instructions on relating the objects to their hands. We hypothesized that participants can perform mental rotation in two ways, either by imagining themselves rotating the object or by imagining an external force rotating it, and that the strategy they adopt depends in part on what they have been doing immediately prior to the task.

2. Method

2.1. Participants

Sixteen right-handed males (aged 18–39 years) volunteered to take part in the study as paid participants. All participants gave written informed consent prior to the study, and all were tested in accordance with local laws and regulations as stipulated and approved by the Harvard University and Massachusetts General Hospital/Partners Institutional Review Boards.

2.2. Materials

The stimuli were identical to those used by Kosslyn et al. (1998). The object stimuli were depictions of three-dimensional, multi-armed cube figures enclosed in a circle, based on the figures originally used by Shepard and Metzler (1971). The figures were rotated in 20° increments from 20° to 180° in each of the three planes of rotation (X, frontal; Y, transverse; Z, sagittal), for a total of 27 versions. We then created a mirror-reversed version of each stimulus. The addition of normal and mirror-reversed figures at 0° resulted in a total of 56 stimuli. For the rotation condition, a vertical version of each stimulus was positioned to the left of each tilted version of the same stimulus. For the baseline condition, each stimulus of the pair appeared at the same angle of orientation, with half the pairs including mirror-reversed versions and half including identical versions. We divided the full group of stimuli in half, which resulted in two stimulus sets per condition. We administered a different stimulus set for each block, counterbalancing so that each stimulus set appeared equally often in each condition within a task. Thus, participants in the Object–Object group could not repeat the task with the same objects. Each stimulus set had equal numbers of all angles and axes of rotation, but not every angle/axis combination, which would have required the full set of 112 stimuli.

The hand stimuli consisted of two-dimensional line drawings of hands, each of which was enclosed in a circle. We created four finger configurations: (a) all five fingers raised; (b) thumb, index finger, and middle finger raised with ring and little finger folded; (c) thumb, index finger, and little finger raised with middle