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Frontostriatal circuits are necessary for visuomotor transformation: Mental rotation in Parkinson's disease

Melissa M. Amick[a], Haline E. Schendan[a,b,d,*], Giorgio Ganis[c,d,e], Alice Cronin-Golomb[a]

[a] *Department of Psychology, Boston University, 648 Beacon Street, 2nd Floor, Boston, MA 02215, USA*
[b] *Department of Psychology, Tufts University, The Psychology Building, 490 Boston Avenue, Medford, MA 02155, USA*
[c] *Department of Psychology, Harvard University, Cambridge, MA 02138, USA*
[d] *Massachusetts General Hospital, Martinos Center, Charlestown, MA 02129, USA*
[e] *Department of Radiology, Harvard Medical School, Boston, MA 02115, USA*

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Abstract

The mental rotation of objects requires visuospatial functions mediated by the parietal lobes, whereas the mental rotation of hands also engages frontal motor-system processes. Nondemented patients with Parkinson's disease (PD), a frontostriatal disorder, were predicted to be impaired on mentally rotating hands. Side of PD motor symptom onset was investigated because the left motor cortices likely have a causal role in hand mental rotation. The prediction was that patients with right-side onset (RPD, greater left-hemisphere dysfunction) would commit more errors rotating hands than patients with left-side onset (LPD). Fifteen LPD, 12 RPD, and 13 normal control adults (NC) made same/different judgments about pairs of rotated objects or hands. There were no group differences with objects. When rotating hands, RPD, but not LPD, made more errors than the NC group. A control experiment evaluated whether visual field of presentation explained differences between PD subgroups. In the first experiment (1A), the hand to be mentally rotated was presented in the right visual field, but here (1B) it was presented in the left visual field. Only the LPD group made more errors than the NC group. The evidence suggests a double dissociation for the RPD and LPD groups between tasks differing in visual-field presentation. The findings indicate that hemifield location of a to-be-rotated hand stimulus can cause the hemispheric frontoparietal networks to be differentially engaged. Moreover, frontostriatal motor systems and the parietal lobes play a necessary role during the mental rotation of hands, which requires integrating visuospatial cognition with motor imagery.

Keywords: Visual spatial; Parietal cortex; Motor imagery; Visual object; Hemispheric laterality; Basal ganglia

1. Introduction

Diverse visuospatial functions are impaired in Parkinson's disease (PD), including route walking, angle size estimation, left–right decisions, and visuospatial closure (reviewed in Cronin-Golomb and Amick (2001)). There is currently no consensus, however, as to whether or not PD patients are impaired on mental rotation tasks. Some studies have reported spared mental rotation abilities in PD patients (Boller et al., 1984; Duncombe, Bradshaw, Iansek, & Phillips, 1994; Raskin et al., 1990). Other studies that instead documented impaired performance considered whether different stimulus types may engage different cognitive operations on mental rotation tasks (Dominey, Decety, Broussolle, Chazot, & Jeannerod, 1995; Lee, Harris, & Atkinson, 1998). In particular, mental rotation of objects invokes object-centered transformations, whereas mental rotation of hands invokes viewer-centered transformations. Each mode of mental transformation is associated with a distinct network of brain regions. These networks are likely affected differentially by the neuropathology of PD.

During the mental rotation of objects, the coordinate system is object-centered; objects are rotated in space irrespective of the viewer's position in the environment (Cronin-Golomb & Amick, 2001; Ogden, 1990). In the

* Corresponding author. Tel.: +1 617 627 2143; fax: +1 617 627 3181.
E-mail address: Haline_E.Schendan@tufts.edu (H.E. Schendan).

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typical experimental design, two objects appear in different orientations and are either identical to each other ("same" objects) or left–right mirror images of each other ("different" objects). Response time to make "same" or "different" judgments has been found to increase linearly as the difference in orientation between the two objects increases. The linear relation between angular disparity and response time and error rate is interpreted as evidence that observers imagine the object moving through space along the same continuous trajectory as if they were physically rotating the object into the upright position (Cooper & Shepard, 1975).

Behavioral and neuroimaging studies have shown that posterior parietal cortices, especially in the right hemisphere, are engaged during the successful execution of the mental rotation of objects. Behavioral studies of object mental rotation support a unique role for the right parietal lobe (reviewed in Corballis (1997)). Neuroimaging studies with a parametric design reveal a linear increase in activation of the intraparietal sulcus (IPS) as the degree of rotation is increased. The IPS may be responsible for the scaling of mental rotation task performance with angular disparity (Carpenter, Just, Keller, Eddy, & Thulborn, 1999; Harris et al., 2000; Podzebenko, Egan, & Watson, 2002). Neuroimaging findings of lateralization are more mixed but similar to behavioral studies in favoring right-hemisphere dominance. Specifically, some neuroimaging studies reveal lateralized activity in the superior and inferior parts of the right parietal lobe (Harris et al., 2000; Vingerhoets et al., 2001), whereas others report instead bilateral posterior parietal activation (Carpenter et al., 1999; Cohen et al., 1996; Kosslyn, DiGirolamo, Thompson, & Alpert, 1998; Podzebenko et al., 2002; Richter et al., 2000; Richter, Ugurbil, Georgopoulos, & Kim, 1997). Some studies reporting bilateral parietal activation, however, do support a right-hemisphere advantage for this task, finding more extensive activation in the right than left hemisphere (Carpenter et al., 1999; Podzebenko et al., 2002).

By contrast, the mental rotation of hands may be performed using a different strategy of viewer-centered transformation, wherein viewers consider their own spatial coordinates with respect to other objects in the environment (Cronin-Golomb & Amick, 2001; Ogden, 1990). During this cognitive operation, viewers are thought to access and then manipulate a mental representation of their body in space (Kosslyn et al., 1998).

In contrast to the right-hemisphere advantage for object-centered transformations, regions in the left hemisphere appear to be necessary for viewer-centered transformations, as shown in studies of patients with lateralized brain damage or artificially induced transient dysfunction. For example, autotopagnosia, the disorientation of personal space, and right–left disorientation are two neuropsychological disorders that occur in patients with left posterior parietal-lobe lesions (De Renzi, 1982; Semmes, Weinstein, Ghent, & Teuber, 1963; Sirigu, Grafman, Bressler, & Sunderland, 1991). Parsons, Gabrieli, Phelps, and Gazzaniga (1998) examined the mental rotation of left and right hands projected to either the left or right hemisphere in two callosotomy patients and a control group, and observed a left hemisphere advantage. The patients were accurate only when mentally rotating the hand processed routinely by that hemisphere, demonstrating a double dissociation, but all participants tended to be more accurate when targets were presented to the left relative to the right hemisphere. These findings were taken as evidence that the left hemisphere has representations of both hands, whereas the right hemisphere has representations only of the contralateral left hand. Ganis, Keenan, Kosslyn, and Pascual-Leone (2000) found that applying transcranial magnetic stimulation to the hand region of the left primary motor cortex impairs performance for the mental rotation of images of hands, and more so than for the mental rotation of images of feet. Critically for the present study, these findings also indicate that the mental rotation of hands draws upon the same cortical regions necessary for overt movement.

In studies comparing object-centered and viewer-centered transformations directly, differences have been found in behavioral hemispheric dominance and in neural activity within hemispheres. Specifically, Tomasino, Toraldo, and Rumiati (2003) found a double dissociation of performance on object and hand mental rotation in patients with left- versus right-hemisphere lesions. Patients with left-hemisphere lesions are impaired at mentally rotating hands but not objects, whereas patients with right-hemisphere lesions show the opposite pattern. In a neuroimaging study, Kosslyn et al. (1998) had participants perform a mental rotation task with Shepard and Metzler (1971) objects or hands. Mental rotation of objects elicited bilateral activation in superior and inferior parietal areas, whereas the mental rotation of hands elicited activation in left parietal and left frontal regions centered on primary motor, premotor, and supplementary motor areas. Taken altogether, convergent findings indicate that object-centered transformations require primarily the IPS of the right hemisphere, whereas viewer-centered transformations require primarily the motor cortex of the left hemisphere.

These two main cortical regions for mental rotation of objects and hands are likely disrupted by the neuropathology of PD. Consider that the loss of dopamine-producing cells in the substantia nigra results in dysregulation of the striatum and consequently in dysfunction of multiple circuits connecting the basal ganglia with motor and cognitive cortical regions (Middleton & Strick, 2000a, 2000b). Neurons of the substantia nigra and the globus pallidus, the basal ganglia output nucleus, terminate in non-overlapping prefrontal regions (Middleton & Strick, 2000a). This connectivity pattern suggests that the prefrontal cortex may be functionally deafferented in PD due to reduced dopamine availability in the basal ganglia. Critically for mental rotation, the prefrontal and posterior parietal cortices are densely interconnected and share zones of termination within the striatum. Further, both regions are part of a large neural circuit that is specialized for spatially guided behavior, and this circuit includes the head of the caudate nucleus (Selemon & Goldman-Rakic, 1988)