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Mental rotation of letters, body parts and scenes during whole-body tilt: Role of a body-centered versus a gravitational reference frame

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ABSTRACT

It is known that in mental-rotation tasks, subjects mentally transform the displayed material until it appears "upright" and then make a judgment. Here we evaluate, by using three typical mental rotation tasks with different degrees of embodiment, whether "upright" is coded to a gravitational or egocentric reference frame, or a combination of both. Observers stood erect or were whole-body tilted by 60°, with their left ear down. In either posture, they saw stimuli presented at different orientation angles in their frontal plane: in condition LETTER, they judged whether the stimuli were normal or mirror-reversed letters, in condition HAND whether they represented a left or a right hand, and in condition SCENE whether a weapon laid left or right in front of a displayed person. Data confirm that reaction times are modulated by stimulus orientation angle, and the modulation curve in LETTER and HAND differs from that in SCENE. More importantly, during 60° body tilt, the modulation curve shifted 12° away from the gravitational towards the egocentric vertical reference; this shift was comparable in all three conditions and independent of the degree of embodiment. We conclude that mental rotation in all conditions relied on a similar spatial reference, which seems to be a weighted average of the gravitational and the egocentric vertical, with a higher weight given to the former.

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1. Introduction

When humans are asked to judge objects presented in their frontal plane at different orientations, their reaction times increase consistently with the angle between the displayed and the canonical "upright" orientation of those objects; this suggests that objects are mentally rotated into the upright before a judgment is made (Cooper & Shepard, 1973; Shepard & Metzler, 1971). In another paradigm, participants are asked to judge the location of objects in front of an avatar displayed at different orientations with respect to their own body. In this case, reaction times increase with the angle between the avatar and the own body, which again suggests that mental rotation took place (Ratcliff, 1979; Semmes, Weinstein, Ghent, & Teuber, 1963; Zacks, Rypma, Gabrieli, Tversky, & Glover, 1999). However, several lines of evidence suggest that the underlying processes differ between the two paradigms: the speed of mental rotation is not the same (Kessler & Thomson, 2010; Kozhevnikov, Motes, Rasch, & Blajenkova, 2006;), clinical deficits are dissociated (Fiorio et al., 2007; Ratcliff, 1979; Semmes et al., 1963) and neural activation patterns are different (Thomas, Dalecki, & Abeln, 2013; Wraga, Shephard, Church, Inati, & Kosslyn, 2005; Zacks et al., 1999). These discrepancies have been interpreted as evidence that in the former paradigm, objects are mentally rotated with respect to the own *stationary body* while in the latter paradigm, the own body is mentally rotated with respect to the *stationary scene* (Jola & Mast, 2005; Kessler & Thomson, 2010).

When objects are mentally rotated, they could be judged as "upright" relative to the own body (egocentric reference), or relative to the gravitational vertical (gravicentric reference). To distinguish between these alternatives, some studies compared subjects' performance in an upright posture with that in a head-tilted or whole body-tilted posture, and found that displayed objects were mentally rotated into an orientation that was in-between the egocentric and the gravitational vertical (Corballis, Nagourney, Shetzer, & Stefanatos, 1978; Friedman & Hall, 1996; McMullen & Jolicoeur, 1992). It therefore appears that the spatial reference for mental rotation of extrinsic objects is formed by combining egocentric and gravitational cues.

The present study expands this work by evaluating the spatial reference for mental rotation not of extrinsic objects, but rather of one's own body. Since the behavioral and neuronal correlates for these two mental transformations differ (see above), it is conceivable that the spatial reference differs as well. Two earlier studies asked subjects to judge the identity of visual landscapes (Gaunet & Berthoz, 2000) or hand drawings (Sekiyama, 1982), and observed a predominance of the egocentric reference; however, it is unclear whether subjects in those studies mentally rotated the displayed material or their own body, and the spatial reference for own-body rotation therefore remains unclear. Moreover, mental rotation stimuli differ in their level of embodiment, which is likely to be low for external objects, higher for human hands and highest for scenes containing an avatar (Jola & Mast, 2005; Kessler & Thomson, 2010; Wraga et al., 2005). The latter type of stimulus is therefore most likely to induce mental rotation of one's own body, which is why we selected it for our study.

To compare mental rotation of the own body with that of extrinsic objects, we included a letter rotation task. We also included a third popular variant, the hand rotation task. All three tasks were administered to the same subjects in the same experimental session, to quantify differences between tasks unconfounded by interindividual variability or by fluctuations of mood, fatigue, food intake, etc.; serial-order effects were controlled by counterbalancing the order of stimuli and of body postures. By using a letter rotation, hand rotation and own body rotation task we were also able to compare whether the reference frame for 'upright' judgments differs between different degrees of embodiment. Furthermore, we decided to increase the statistical power of our data by using a sample size of $n = 24$, while $n = 10$ was the typical used sample size in the previous studies on mental rotation with body tilt. The main aim of the present study was therefore to elucidate the effects of whole-body tilt on mental rotation of three common stimuli (external objects, body parts, whole body), to find out whether the reference frame for "upright" judgments differs between tasks.