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Mental rotation and the motor system: Embodiment head over heels☆

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ABSTRACT

We examined whether body parts attached to abstract stimuli automatically force embodiment in a mental rotation task. In Experiment 1, standard cube combinations reflecting a human pose were added with (1) body parts on anatomically possible locations, (2) body parts on anatomically impossible locations, (3) colored end cubes, and (4) simple end cubes. Participants ($N = 30$) had to decide whether two simultaneously presented stimuli, rotated in the picture plane, were identical or not. They were fastest and made less errors in the possible-body condition, but were slowest and least accurate in the impossible-body condition. A second experiment ($N = 32$) replicated the results and ruled out that the poor performance in the impossible-body condition was due to the specific stimulus material. The findings of both experiments suggest that body parts automatically trigger embodiment, even when it is counterproductive and dramatically impairs performance, as in the impossible-body condition. It can furthermore be concluded that body parts cannot be used flexibly for spatial orientation in mental rotation tasks, compared to colored end cubes. Thus, embodiment appears to be a strong and inflexible mechanism that may, under certain conditions, even impede performance.

1. Introduction

The mental transformation of pictures of body parts appears to follow the same rules as an equivalent actual movement of the depicted limb (Parsons, 1987, 1994). This raises the question of why this mental transformation follows physiological constraints. The same is true for mental rotation (Shepard & Metzler, 1971), where mental imagery seems to obey physical constraints: The linear relationship between the angular disparity of two visual stimuli and the reaction time (RT) necessary to decide whether these stimuli are identical or not suggests that humans perform an analog mental transformation of the stimuli. This mental transformation adheres to certain rules of the physical world.[1] The connection between mental and physical processes traces back to the assumption that kinetic imagery is powered by the motor system. As our motor system is optimized to steer our bodily interaction with the physical world, our mental transformations are therefore bound to bodily and earthly restrictions (for an overview see Gibbs, 2007; Prinz, 1990).

Especially for mental rotation the impact of the motor system on imagery processes had been proposed early on (e.g., Sekiyama, 1982). This supposition was soon confirmed by measurements of the cerebral blood flow during mental rotation tasks indicating the involvement of motor regions in mental rotation processes (Deutsch, Bourbon, Papanicolaou, & Eisenberg, 1988). Moreover, Sayeki (1981) found that the mental rotation of block configurations was facilitated when a human head was attached to a proper position, implying that the "body analogy" supported mental imagery. According to Wohlschläger and Wohlschläger (1998; Wohlschläger, 2001), mental rotation and motor processing (or motor planning) are essentially one and the same thing as mental rotation can be conceived as covert action. This assumption has been substantiated by their findings of interferences between mental and manual rotation. Participants solved mental rotation tasks faster when they performed a compatible manual rotation (i.e., rotating a knob along the shortest path to bring two objects into alignment) compared to an incompatible manual rotation. Similar effects of compatible and incompatible actions on mental rotation were found when participants manually rotated a joystick (Wexler, Kosslyn, & Berthoz, 1998) and when children rotated a hand crank (Frick, Daum, Walser, & Mast, 2009).

However, these interpretations are contestable as there are also indications of a separation between the motor system and mental rotation under certain conditions (e.g., Kosslyn, Thompson, Wraga, & Alpert,

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[1] In contrast to the current scientific consensus, it would also be conceivable that mental transformations happen in the abstract and are therefore unconstrained by outside analogs (for an overview see Tye, 2000).

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2001; Sack, Lindner, & Linden, 2007). Reviewing the literature, Kosslyn et al. (2001) found that a substantial number of neuroimaging studies reported no activation of motor areas when participants were completing mental rotation tasks. To solve this conundrum, Kosslyn et al. (2001) designed the following experiment: Before participants completed mental rotation tasks in a PET scanner, they were shown an exemplary Shepard and Metzler (1971) cube combination (S-M cube). For half of the participants this S-M cube combination was rotated by a machine, while the other half were asked to rotate the same combination by using their own hands. In the following mental rotation tasks, Kosslyn et al. found activation in the motor cortex only among those participants who had previously rotated the cube combination by hand.

Furthermore, when trying to replicate the behavioral effects of manual rotation on mental rotation (Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998), Sack et al. (2007) found this effect only when participants rotated pictures of hands. For all other objects (e.g., S-M cubes or pictures of carrots) no such effect was discernable.

These findings point to the fact that the impact of motor processes on mental rotation depends on the task context, and, in our opinion, warrant two interpretations: Either, when confronted or primed with body stimuli, humans' mental rotation processes *forcefully* and *automatically* turn to *embodied* mental transformations. Or, when handling mental rotation, humans have a repertoire of cognitive strategies available. Embodied cognition or degrees thereof are only a part of these strategies. When solving mental rotation tasks, *cognitive flexibility* allows for choosing the most adaptive strategy.

A recent study by Amorim, Isableu, and Jarraya (2006) is of particular interest in this context and for our present research: Amorim et al. extended the study of Sayeki (1981) by examining whether stimuli that resembled human bodies would enhance the mental rotation performance. They hypothesized that body-like stimuli would be processed and mentally rotated in a holistic way rather than piecemeal like abstract stimuli (Hall & Friedman, 1994). Accordingly, Amorim et al. expected that the holistic mental rotation of body-like stimuli would be faster and less error prone (cf. Khooshabeh, Hegarty, & Shipley, 2013). This was confirmed by the data. The authors concluded that body analogy of the stimuli activates a human body schema that could be used to track the spatial transformations of body-like stimuli (cf. Alexander & Evardone, 2008). More specifically, participants might project their own body axes (i.e., head-feet, left-right, front-back) onto the body-like stimuli (spatial embodiment). Simultaneously, the observed posture of the body-like stimuli might be mentally emulated by the brain's motor centers (motoric embodiment). It is assumed that this emulation is facilitated by the so-called mirror neurons. They do not only discharge if an individual executes an action but also if the individual observes somebody else executing the same action (e.g., Gallese, Fadiga, Fogassi, & Rizzolatti, 1996). Spatial and motoric embodiment should support the comparison of rotated body-like stimuli.

The aim of the present study was to examine if body stimuli (that have to be mentally rotated) force automatic embodiment or if the human mind can process body stimuli in a more flexible and adaptive way. Therefore, we adapted the paradigm of Amorim et al. (2006) and developed additional conditions. In all conditions, S-M cube configurations served as basic figures. While these pure configurations were shown in one condition, in a second condition heads, feet, and hands were added to the appropriate places allowing for an easy projection of the human body. These two conditions would suffice to replicate the findings by Amorim et al. (2006). However, in a third condition, we added body parts to S-M cubes at places that were incompatible with human anatomy and thus prevented a projection of the body. In a fourth condition, we added colored cubes to the S-M cube configurations. These modifications served to test the hypothesis of whether mental rotation of body-like stimuli is facilitated only because body parts provide cues that might be used for spatial orientation independently of embodiment.

On the one hand, we expected that participants would profit greatly from the body compatible stimuli (lower RT and higher hit rate than for standard S-M cubes). Moreover, if they were be able to process the stimuli in a flexible and adaptive way, they could use the body parts of the body incompatible stimuli as orientation markers similar to the colored cubes (lower RT and higher hit rate compared to standard S-M cubes but similar to the colored cubes). On the other hand, if participants were compelled to project their body onto the stimuli with attached body parts, they would also profit from the body compatible stimuli, but the processing would be obstructed by the incompatibly placed body parts (higher RT and lower hit rates than for standard S-M cubes and colored S-M cubes), because the projection and thereby the embodiment would be dysfunctional in the latter case. Thus, in both cases we expected to replicate the findings by Amorim et al. (2006), but the critical distinction comes from the participants' reaction to the stimuli incompatible with the human body.

2. Experiment 1

2.1. Method

2.1.1. Participants

A total of 30 individuals (mean age: 25 years, $SD = 6$ years, min age $= 18$ years, max age $= 48$ years; 10 males, 20 females) participated in this experiment. With the exception of three individuals, all were right handed. Participants were not aware of the purpose of the study and had not partaken in a similar study before. They participated on a voluntary basis and received credit points for their course of studies.

2.1.2. Materials

The stimulus material consisted of four different types of 3D figures: (1) the standard S-M cube combinations (standard S-M), (2) the cube combinations with the end cubes colored (colored S-M), (3) the cube combinations with body parts attached in anatomically possible places (possible-body), and (4) the cube combinations with body parts in anatomically impossible places (impossible-body). Google SketchUp was used for preparing two basic figures, fitting body parts and coloring cubes, creating the nine different angles of rotation (0°, 45°, 90°, 135°, 175°, 185°, 225°, 270°, and 315°), creating the respective mirror images, and converting the 3DS-files into 947 × 947 pixel jpg-files. This resulted in 144 quasi 3D stimuli (4 [conditions] * 2 [basic figures] * 9 [angles] * 2 [mirror images]). Pictures of all different types of stimuli can be found in Fig. 1A-D. Stimuli were presented on an HP Compaq 6820 s laptop computer (17″, 1440 × 900 pixel). E-Prime software was used for presentation and data collection.

2.1.3. Procedure

Stimuli were presented as pairs of the same type side by side. The left stimulus was always presented at 0°, while the right stimulus was always the same or the mirror image of the left stimuli presented at 0°, 45°, 90°, 135°, 175°, 185°, 225°, 270°, or 315° of rotation (in the picture plane).[2] All 288 possible combinations were presented in a random order. There was a short break after 144 trials. All trials were preceded by a fixation cross in the middle of the screen for 1 s and ended after the first key press.

As in the classical mental rotation task (cf. Shepard & Metzler, 1971), participants were asked whether the presented stimuli were congruent or incongruent. They reacted by pressing either the blue marked “f” key or the yellow marked “l” key on the laptop's keyboard - for half of the participants blue meant “same” and yellow “different” and for the other half the other way round.

[2] We aimed for an unequivocal shortest rotation path in all conditions. Therefore, there was no 180° rotation but a 175° and a 185° rotation instead (Krüger, Kaiser, Mahler, Bartels, & Krist, in press).