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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).

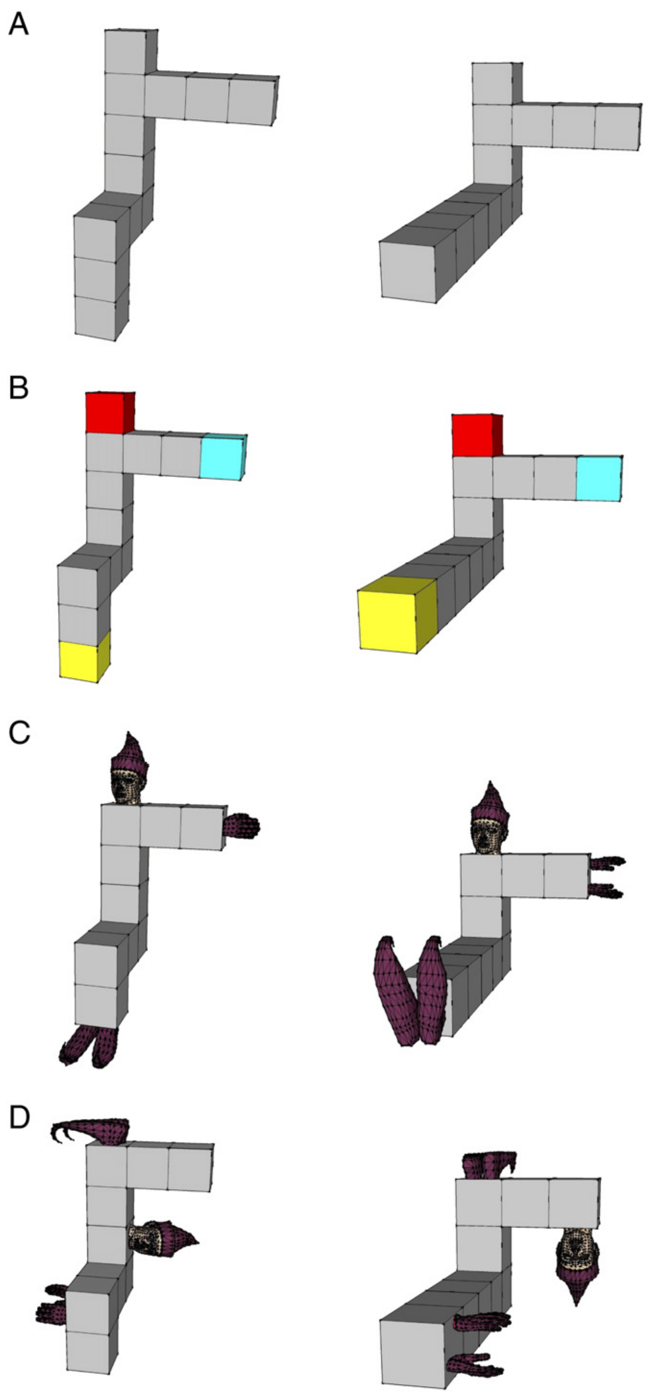

Fig. 1. Pictures of the stimuli: (A) *standard* S-M cubes, (B) *colored* S-M cubes with colored end cubes, (C) *possible-body* S-M cubes with body parts in anatomically possible locations, and (D) *impossible-body* S-M cubes with body parts in anatomically impossible locations.

2.2. Results

Only correct responses to identical pair trials were considered in the analysis of the RTs (cf. Amorim et al., 2006). Trials with RTs smaller than 300 ms or RTs larger than three standard deviations above the mean were excluded (43 trials). Mean RTs per angle were computed by aggregating across those trials, for which the shortest rotation path between stimulus and target was the same (e.g., 45° and 315°). In addition, trials including the two basic figures in either the original or mirrored version were aggregated.[3] One mean RT of a single participant was missing due to the selection of the data and was thus replaced by the mean of the group in the corresponding condition. The mean accuracy was calculated as mean proportion of correct reactions to the aggregated trials. Preliminary analyses revealed no interactions between the variables sex, condition, and angle with regard to the mean RTs and the mean accuracy, $F < 1$. Sex was thus omitted from the following analyses, supposing that the results would apply for both males and females in a similar manner.

2.2.1. RTs

An ANOVA with repeated measures on the within-subjects factors angle and condition revealed main effects of angle, $F(1.97, 57.14) = 98.5$,[4] $\eta^2 = .28$,[5] condition, $F(1.39, 40.33) = 127.00$, $\eta^2 = .37$, and an interaction between angle and condition, $F(3.97, 115.14) = 11.60$, $\eta^2 = .05$, $ps < .001$ (see Fig. 2). For the angles, a linear trend was highly significant, $F(1, 29) = 153.68$, $p < .001$, $r^2 = .98$,[6] implying a proportional increase of reaction times with larger rotation angles typical for mental rotation. In addition, a significant quadratic trend, indicated the increase of RTs becoming flatter at greater angles, $F(1, 29) = 8.08$, $p = .008$, $r^2 = .015$, which might be due to the fact that the last rotation step (i.e., from 135° to 175°) was slightly shorter than the other rotation steps that were equidistant. Each condition showed a linear trend ($ps < .0001$).

However, the slope was significantly steeper for the impossible-body condition as compared to each other condition ($ps < .0001$), indicating a larger increase of RTs for larger rotation angles in the impossible-body condition in relation to the other conditions. Moreover, the slope for the colored S-M was steeper than for the possible-body condition, $F(1, 29) = 4.18$, $p < .05$, whereas the slopes for the possible-body condition and standard S-M did not differ, $F < 1$. The quadratic trend was only significant for the impossible-body condition, $F(1, 29) = 6.66$, $p < .02$, and the colored S-M condition, $F(1, 29) = 7.14$, $p < .02$, but did not differ significantly (i.e., a similar additional non-linear trend was visible in both conditions), $F(1, 29) = 1.14$, $p > .29$. In addition, pairwise post-hoc comparisons (Tukey's HSD test) revealed significant differences between the mean RTs, averaged across all angles, between all stimulus conditions, $ps \leq .05$, except between standard S-M ($M = 1762$ ms, $SD = 403$ ms) and colored S-M ($M = 1684$ ms, $SD = 388$ ms), $p = .75$. Mean RTs were smallest in the possible-body condition ($M = 1476$ ms, $SD = 228$ ms) and largest in the impossible-body condition ($M = 2854$ ms, $SD = 790$ ms).

To uncover differences in the visual encoding and discrimination of the stimuli - independent of the rotation - RTs were analyzed only for those cases, in which both stimuli were presented in an upright position (i.e., 0°). An ANOVA with repeated measures on the variable condition revealed a significant main effect, $F(3, 27) = 20.74$, $p < .001$, $\eta^2 = .46$. Post-hoc comparisons (Tukey's HSD) specified that it took significantly longer to discriminate the upright stimuli in the impossible-body condition ($M = 1572$ ms, $SD = 415$ ms) compared to all other conditions (possible-body: $M = 1028$ ms, $SD = 180$ ms; standard S-M: $M = 1241$ ms, $SD = 487$ ms; colored S-M: $M = 1061$ ms, $SD = 311$ ms), $ps < .05$.

[3] Preliminary analyses revealed that neither the mean reaction times nor the mean accuracy differed significantly between the two figures and the presentation (i.e., original vs. mirrored). The dependent measures were therefore collapsed across the two figures, mirrored and not mirrored, for the following analyses.

[4] Greenhouse-Geisser is reported if sphericity could not be assumed.

[5] Eta-squared values were computed (rather than partial eta-squared values) as $\eta^2 = SS_{\text{effect}}/SS_{\text{total}}$ so that the sum of eta-squared values would not be greater than 100% of the explained variance, which might be the case with partial eta-squared values (Ferguson, 2009; Levine & Hullett, 2002).

[6] For trend analysis, the η^2 value of each trend corresponds to the r^2 of the fit to the mean values.

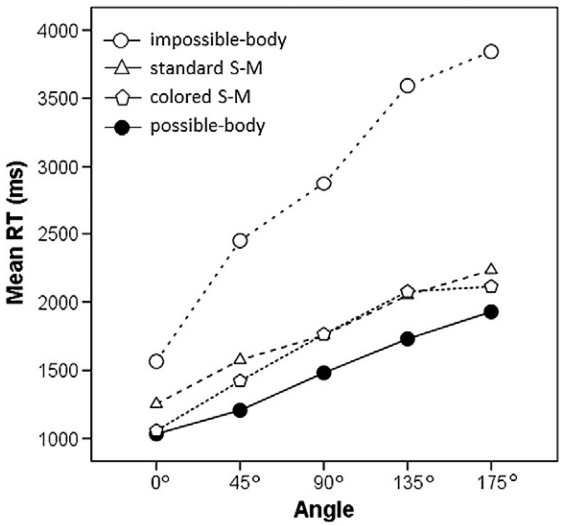

Fig. 2. Mean RT as a function of angle of rotation for the different conditions (Exp. 1).

2.2.2. Accuracy

An ANOVA with repeated measures revealed, similar to the RTs, main effects of angle, $F(3.02, 87.63) = 24.95$, $p < .001$, $\eta^2 = .13$, condition, $F(1.64, 47.66) = 20.51$, $p < .001$, $\eta^2 = .11$, and an interaction between angle and condition, $F(7.51, 217.68) = 2.93$, $p < .005$, $\eta^2 = .04$ (see Fig. 3). Furthermore, pairwise post-hoc comparisons (Tukey's HSD test) showed that the impossible-body condition ($M = .84$, $SD = .14$) was the least accurate, averaged across all angles, compared to all other conditions ($ps \leq .001$). The mean accuracy of the other conditions did not differ, $ps > .26$ (possible-body condition: $M = .94$, $SD = .06$; colored cubes condition: $M = .94$, $SD = .05$; standard S-M cubes: $M = .92$, $SD = .07$). For angles, a linear trend became highly significant, $F(1, 29) = 57.58$, $p < .001$, $r^2 = .98$, with no significant quadratic trend, $F < 1$, indicating a proportional increase of errors with rotation angle typical for mental rotation.

Each condition showed a linear trend ($ps < .004$), however the slope was significantly greater for the impossible-body condition as compared to all other conditions ($ps < .008$). The slopes of the other conditions did not differ from each other, $ps > .25$.

2.3. Discussion

Experiment 1 replicated the positive effect of stimuli resembling the human figure (i.e., possible-body condition) on mental rotation speed (cf. Amorim et al., 2006). Additional analyses of the reaction times revealed that this effect was not due to a better discrimination of these stimuli in the upright position compared to more abstract stimuli, but that it emerged in fact due to a faster mental rotation process, as reflected by the mean reaction times averaged across all angles. Body parts forming an anatomically impossible figure (i.e., impossible-body condition) had a negative effect on mental rotation speed, which goes beyond the poorer visual discriminability of these stimuli, and also impaired the mental rotation accuracy. The colored S-M cubes did not seem to have a major impact. However, at this point, it cannot be ruled out that the poor performance in the impossible-body condition was due to the specific design of the stimuli as body parts were attached to different locations of the basic S-M figures (in comparison with the other conditions, see Fig. 1). This amounts to more turns and angles, enhancing the stimulus complexity, which, in turn, might have led to longer RTs in the mental rotation of the impossible-body stimuli (e.g., Bryden, George, & Inch, 1990; see also Metzler & Shepard, 1974). To rule out this alternative explanation, a second experiment was conducted. In Experiment 2, new impossible-body stimuli were introduced. These new stimuli had different body parts located at the same locations as the possible-body stimuli.

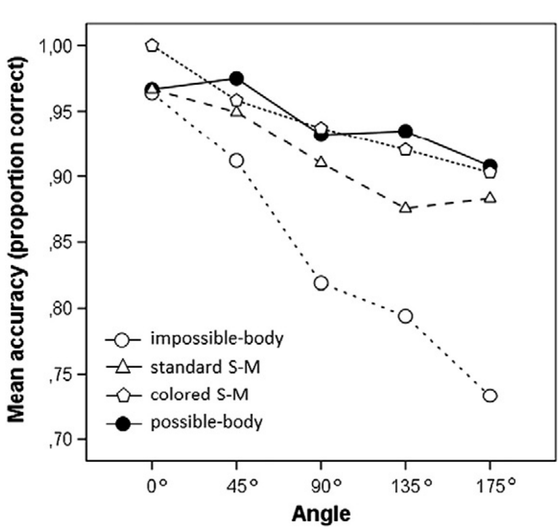

Fig. 3. Mean accuracy as a function of angle of rotation for the different conditions (Exp. 1).

3. Experiment 2

The aim of Experiment 2 was to examine whether the observed negative effect of the impossible-body condition in Experiment 1 was due to the incompatibility of the stimulus material with an anatomically correct human body or due to stimulus complexity.

3.1. Method

3.1.1. Participants

A total of 32 individuals (mean age: 23 years, $SD = 5$ years, min age = 18 years, max age = 46 years; 16 males, 16 females) participated in this experiment. With the exception of two 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.

3.1.2. Materials

The same standard S-M (Fig. 1A) and possible-body (Fig. 1C) stimuli as in Experiment 1 were used. New impossible-body stimuli were created. They had their specific features (body parts) at the same locations as the possible-body stimuli to enhance the comparability across the different conditions, but still depicted anatomically impossible bodies (Fig. 4).

Stimuli were presented on a Fujitsu Siemens Amilo PI 1556 laptop computer (15.4″, 1280 × 800 pixel). E-Prime software was used for presentation and data collection.

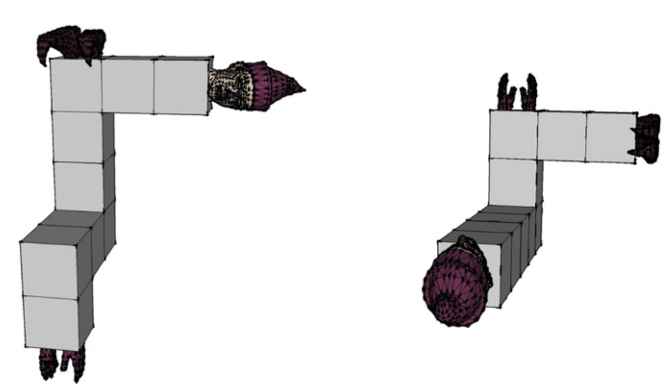

Fig. 4. Pictures of the extra stimuli for Experiment 2: *impossible-body* S-M cubes with body parts in anatomically impossible locations.

3.1.3. Procedure

The procedure was the same as in Experiment 2 except for the following changes: There were only the three conditions (1) standard S-M, (2) possible-body, and (3) impossible-body, resulting in 216 trials and the participants reacted by pressing one of two unmarked hand switches (one for each hand).

3.2. Results

The preparation and analysis of the data followed the same principles as in Experiment 1. Sixty-five trials were outliers according to the previously mentioned criteria and had to be excluded. Preliminary analyses revealed only a significant interaction between sex and angles with regard to the mean RTs, $F(2.26, 67.88) = 3.98$, $p = .019$. The descriptive data suggest a stronger increase of the mean reaction times with larger angles for women compared to men. However, as there was neither an interaction between sex and condition with regard to the mean RTs nor any interactions between sex, angle, and condition concerning the mean accuracy (*ps* > .20), sex was excluded from the following analyses.

3.2.1. RTs

An ANOVA with repeated measures on the within-subjects factorsangle and condition revealed main effects of angle, $F(2.13, 66.14) = 91.24$, $\eta^2 = .47$, condition, $F(2, 62) = 85.59$, $\eta^2 = .18$, and an interaction between angle and condition, $F(5.64, 174.68) = 4.64$, $\eta^2 = .02$, *ps* < .001 (see Fig. 5). For the angles, a linear trend was highly significant, $F(1, 31) = 137.92$, $p < .001$, $r^2 = .96$, implying a proportional increase of reaction times with larger rotation angles typical for mental rotation. In addition, a significant quadratic trend, $F(1, 31) = 24.38$, $p < .001$, $r^2 = .03$, indicates the increase of RTs becoming flatter at greater angles. As in Experiment 1, this might be due to the fact that the last rotation step (i.e., from 135° to 175°) was slightly shorter than the other rotation steps that were equidistant. Each condition showed a linear trend (*ps* < .00001), whereas a quadratic trend was evidenced only for the standard S-M ($p < .01$) and the impossible-body condition ($p < .001$).

However, the linear slope was significantly larger for the impossible-body condition as compared to the possible-body condition, $F(1, 31) = 41.12$, $p < .00001$, and also marginally larger than in the standard S-M condition, $F(1, 31) = 3.10$, $p = .088$, indicating a larger increase of RTs for larger rotation angles in the impossible body condition compared to the two other conditions. Moreover, the slope for the standard S-M condition was larger than for the possible-body condition, $F(1, 31) = 15.78$, $p < .001$. The quadratic trend was only significant for the impossible-body condition, $F(1, 31) = 14.06$, $p < .001$, and for the standard S-M condition, $F(1, 31) = 11.15$, $p < .01$, but did not differ significantly, $F < 1$.

In addition, pairwise post-hoc comparisons (Tukey's HSD) revealed significant differences between the mean RTs of all stimulus conditions averaged across angles, *ps* < .001. The mean reaction times were smallest in the possible-body condition ($M = 1469$ ms, $SD = 634$ ms), significantly larger in the standard S-M condition ($M = 1724$ ms, $SD = 843$ ms), and largest in the impossible-body condition ($M = 2196$ ms, $SD = 962$ ms).

An additional ANOVA including only the stimuli in the upright position (i.e., 0°) revealed a main effect of condition, $F(1.45, 45.03) = 15.16$, $p < .001$, $\eta^2 = .33$. Post-hoc comparisons (Tukey's HSD) indicated that mean RTs were shortest in the possible-body condition ($M = 927$ ms, $SD = 216$ ms), significantly longer in the S-M condition ($M = 1053$ ms, $SD = 253$ ms), and longest in the impossible-body condition ($M = 1305$ ms, $SD = 512$ ms), *ps* < .05.

3.2.2. Accuracy

An ANOVA with repeated measures revealed, similar to the RTs, main effects of angle, $F(3.31, 102.52) = 19.69$, $p < .001$, $\eta^2 = .13$, condition, $F(2, 62) = 3.36$, $p = .041$, $\eta^2 = .02$, and an interaction between angle and condition, $F(5.90, 182.96) = 2.31$, $p = .037$, $\eta^2 = .03$ (see Fig. 6). Furthermore, pairwise post-hoc comparisons (Tukey's HSD) showed that the possible-body condition ($M = .95$, $SD = .06$) was marginally more accurate than the impossible-body condition ($M = .91$, $SD = .08$), $p = .053$, but did not differ from the S-M condition ($M = .92$, $SD = .06$), $p = .10$. The accuracy in the impossible-body condition did not differ from the accuracy in the S-M condition ($p > .94$). For angles, a linear trend became highly significant, $F(1, 31) = 49.58$, $p < .001$, $r^2 = .81$, in addition to a smaller, cubic trend, $F(1, 31) = 25.22$, $p < .001$, $r^2 = .18$.

Each condition showed a linear trend (*ps* < .01), however the slope for the possible-body condition was marginally shallower as compared to impossible-body condition, $F(1, 31) = 2.90$, $p = .05$, whereas the other slopes did not differ, *ps* > .10. Only the impossible-body condition and the standard S-M condition showed cubic trends, with $F(1, 31) = 6.99$, $p = .013$ and $F(1, 31) = 16.20$, $p = .0004$, respectively, that did not differ significantly, $F(1, 31) = 1.98$, $p = .17$.

3.3. Discussion

The results of Experiment 2 largely replicated the findings of Experiment 1: The mental rotation of possible-body stimuli was facilitated in terms of smaller reaction times, whereas the mental rotation of impossible-body stimuli was hampered. Apart from the fact that the visual encoding and discrimination of the stimuli in the impossible-body condition took longer than in the other conditions, the rotation

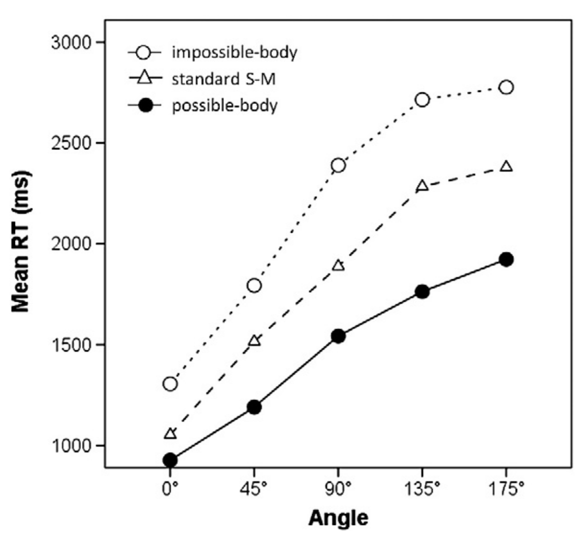

Fig. 5. Mean RT as a function of angle of rotation for the different conditions (Exp. 2).

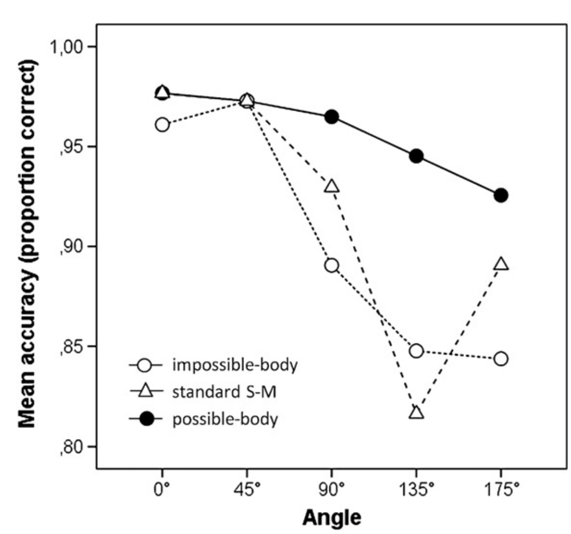

Fig. 6. Mean accuracy as a function of angle of rotation for the different conditions (Exp. 2).

speed was also significantly slower, as indicated by the slopes. Compared to Experiment 1, the effects were only marginally significant with regard to the accuracy. This might suggest that the participants tried to minimize their errors in each condition, but, nevertheless, at a cost of larger reaction times in the impossible-body condition.

4. General Discussion

The aim of the present study was to investigate whether body parts attached to cube combinations would automatically force embodiment – and thus improve mental rotation performance if body parts were attached to anatomically possible locations, but impair performance if their placement on anatomically impossible locations hampered embodiment. Alternatively, if body parts are processed flexibly, they might provide additional cues for spatial orientation – similar to the colored cubes – even in the impossible-body condition. As a result, the mental rotation of impossible-body stimuli should be improved compared to that of pure S-M cube combinations. As expected, participants profited greatly from the body parts placed in anatomically possible locations. They reacted distinctively faster than in any other condition – which cannot solely be explained by a better discrimination of possible-body stimuli per se (see Exp. 2). This superiority of body parts placed on anatomically possible locations clearly supersedes the effect of colored end cubes, indicating that an embodiment of the stimulus material can facilitate mental rotation beyond the mere addition of orientation markers.

By contrast, the body parts placed in anatomically impossible locations dramatically disrupted mental rotation performance. Reaction times and errors skyrocketed, suggesting that participants were unable to prevent a dysfunctional embodiment of the stimulus material. Obviously, they were lacking the cognitive flexibility necessary to simply ignore the attached body parts and to process the stimuli like standard S-M cubes.

Comparing the performance for standard and colored S-M cubes in Experiment 1, the effect of additional orientation markers appeared to be negligible. Differences in RTs and accuracy were only descriptive. The standard and colored S-M cubes neither seemed to help nor perturb spatial embodiment in any way.

Overall, the results of both experiments suggest that participants embodied the stimuli automatically when body parts were involved - head over heel for better or worse. These findings are in accordance with the theoretical approach by Amorim et al. (2006): Projecting the human body axes onto the stimulus material at hand (spatial embodiment) and using motor resources for processing the stimuli (motoric embodiment) work fine for body parts placed on anatomically possible locations, but clearly raise difficulties when body parts are placed anatomically incorrectly.

Attempts to bring the impossible-body stimuli into alignment with the human body (spatial embodiment) were necessarily unsuccessful. Thus, in accordance with the model of Amorim et al., the impediment of spatial embodiment (and not of motoric embodiment) by confronting participants with body-impossible stimuli interferes with mental rotation, while allowing for spatial embodiment by means of body-possible stimuli supports mental rotation. This is indicated by generally larger mean RTs and specifically by the larger RT at 0° for the impossible-body stimuli compared with the body-possible stimuli.

Moreover, the lower rotation speed in the impossible-body condition compared to the possible-body condition, which was signified by the slope differences, suggests an unsuccessful requisition of motor resources (in terms of common coding, Prinz, 1990) for the mental rotation of the impossible-body stimuli (motoric embodiment). The lack of slope differences between the more abstract standard S-M cubes and the possible-body stimuli in Experiment 1 is more plausibly explained by the usage of motor resources for processing the mental transformation in both conditions than the persistent exclusion of such resources (cf. Kosslyn et al., 2001).

In future research, body stimuli that are more or less in alignment with the observer (e.g., facing away from or facing the observer) might be used to test whether the observer's ability to adopt the depicted pose of the stimuli influences RTs (cf. Parsons, 1987). This should also give insight into the question, whether participants projected *a human body* or *their own body* upon the stimuli. Furthermore, one might collect introspective reports of the participants to unravel their strategies in the mental rotation of body-like and abstract stimuli.

4.1. Conclusion

The present findings provide further support for the importance of motor processes in mental imagery (Gibbs, 2007; Prinz, 1990) by highlighting how mental rotation can be hampered if stimuli are involved that are incompatible with the human body. This is complementing studies that showed the benefits of embodiment and mental rotation (e.g., Amorim et al., 2006). However, we should not hastily accept more radical theories of embodiment (e.g., Gibbs, 2007): It is entirely possible that participants – after wasting cognitive resources on an unsuccessful attempt to bring the anatomically impossible stimuli into alignment with the human body – switched to covert action as if rotating the malformed stimuli by hand (cf. Wohlschläger, 2001). But, it seems as likely that after embodiment failed them, participants turned to a non-embodied analog mental transformation (cf. Kosslyn et al., 2001).

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