In: Acta Psychologica, 2014, Volume 145, S. 104-110, EISSN 0001-6918; https://doi.org/10.1016/j.actpsy.2013.11.004

Mental Rotation and the Motor System:

Embodiment Head Over Heels

Markus Krüger, Michel-Ange Amorim, Mirjam Ebersbach

Abstract

We examined whether body parts attached to abstract stimuli automatically force embodiment in a mental rotation task. 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) were fastest to decide whether two rotated stimuli were identical or not and made less errors in the possible-body condition, but slowest and least accurate in the impossible-body condition. The results 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.

Keywords: mental rotation, embodiment, mental transformation, embodied cognition

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 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 analogue mental transformation of the stimuli – a mental simulation that adheres to certain rules of the physical world, although it would also be conceivable, that mental transformations happen in the abstract and are therefore unconstrained by outside analogues (for an overview see Tyre, 2000). 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 if a human head was attached at 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 covered 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 (e.g., rotating a knob along the shortest path to bring two objects into alignment) compared to an incompatible manual rotation (cf. Frick, Daum, Walser, & Mast, 2009; Wexler, Kosslyn, & Berthoz, 1998).

However, these findings are contestable. Reviewing the literature, Kosslyn, Thompson, Wraga, and Alpert (2001) found that in a substantial number of neuroimaging studies no activation of motor areas was reported 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, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998), Sack, Lindner, and Linden (2007) did find 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, which was assumed for abstract stimuli (Hall & Friedman, 1994). Accordingly, Amorim et al. expected that the mental rotation of body-like stimuli would be faster and less error prone. These assumptions were confirmed by the data. The authors concluded that body analogy of the stimuli would activate a human body schema that could be used to track the spatial transformations of the 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 centres (motoric embodiment). It is assumed that this emulation is facilitated by the so-called mirror neurons that do not only discharge if an individual executes an action but also if the individual observes somebody else executing an 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 if participants were to process the stimuli in a flexible and adaptive way, they would profit greatly from the body compatible stimuli (lower RT and higher hit rate than for standard S-M cubes), but would use the incompatibly placed body parts as orientation markers similar as 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 processing would be obstructed by the incompatibly placed body parts (higher RT and lower hit rates than for standard S-M cubes), because the projection and thereby the embodiment would be dysfunctional in the latter case.

Method

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.

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 anatomical possible places (possible-body), and (4) the cube combinations with body parts in anatomical 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. Examples of the four different types of stimuli can be found in Fig. 1a-d. Stimuli were presented on an HP Compaq 6820s laptop computer (17”, 1440 × 900 pixel). E-Prime software was used for presentation and data collection.

Procedure

Stimuli were presented in 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). 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 second 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 answered 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.

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. 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.

RTs

An ANOVA with repeated measures on the within-subjects factors angle and condition revealed main effects of angle, $F(1.97, 57.14) = 98.5$[1], $\eta^2 = .28$[2], condition, $F(1.39, 40.33) = 127$, $\eta^2 = .37$, and an interaction between angle and condition, $F(3.97, 115.14) = 11.6$, $\eta^2 = .05$, *p*s < .001 (see Figure 2). For the angles, a linear trend was highly significant, $F(1, 29) = 153.68$, $p < .001$, $r^2 = .98$[3], implying a proportional increase of reaction times with larger rotation angles typical for mental rotation. In addition, a significant quadratic trend, $F(1, 29) = 8.08$, $p = .008$, $r^2 = .015$, indicates the increase of RTs becoming flatter at greater angles, 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 (*p*s < .0001).

However, the slope was significantly larger for the impossible-body condition as compared to each other condition (*p*s < .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 larger 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 colored S-M, $F(1, 29) = 7.14$, $p < .02$, but did not differ significantly, $F(1, 29) = 1.14$, $p > .29$.

---

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

[2] 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).

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

In addition, pairwise post-hoc comparisons (Tukey's HSD test) revealed significant differences between all stimulus conditions, *p*s $\leq .05$, except of 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).

Accuracy

An ANOVA with repeated measures revealed, similar as for 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 Figure 3). Furthermore, pairwise post-hoc comparisons (Tukey's HSD test) showed that the impossible-body condition (*M* = .84, *SD* = .14) was the least accurate compared to all other conditions (*p*s $\leq .001$), and that the mean accuracy of the other conditions did not differ between each other, *p*s > .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 (*p*s < .004), however the slope was significantly greater for the impossible-body condition as compared to all other conditions (*p*s < .008), whereas the slopes of the other conditions did not differ between each other, *p*s > .25.

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 as 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 of the other conditions and made less mistakes than in the S-M and in the impossible-body condition. 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 anatomical 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. Additionally, the analysis of the slopes – especially for response accuracy - suggested that the stimuli in the impossible-body condition were rotated in a more piecemeal fashion, in contrast to a more holistic fashion in the other conditions (Amorim et al., 2006; Metzler & Shepard, 1974).

Comparing the performance for standard and colored S-M cubes, the effect of additional orientation markers appeared to be negligible. Differences in RTs were only descriptive and only the hit rate was significantly better for colored than for standard S-M cubes. However, this latter finding is qualified by hit rates being close to ceiling in both, the colored S-M and the possible-body condition anyway.

Overall, the results indicate 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. However, it remains unclear, what exactly led to this drop in performance. As we know that motor resources can be activated for the mental rotation (in terms of common coding, Prinz, 1990) of the more abstract standard S-M cubes (e.g., Kosslyn et al., 2001), there is no compelling reason why participants should not have used motor resources for processing the mental transformation of the impossible-body stimuli (motoric embodiment), too. In contrast, attempts to bring the impossible-body stimuli into alignment with the human body (spatial embodiment) were necessarily unsuccessful. The standard and colored S-M cubes neither help nor perturb spatial embodiment. Thus, in alignment 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.

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 show 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 analogue mental transformation.

References

Alexander, G. M., & Evardone, M. (2008). Blocks and bodies: Sex differences in a novel version of the mental rotation test. *Hormones and Behavior, 53*(1), 177-184.

Amorim, M.-A, Isableu, B., & Jarraya, M. (2006). Embodied spatial transformations: "Body analogy" for the mental rotation of objects. *Journal of Experimental Psychology: General, 135*, 327-347.

Deutsch, G., Bourbon, W. T., Papanicolaou, A., & Eisenberg, H. (1988). Visuospatial tasks compared via activation of regional cerebral blood flow. *Neuropsychologia, 26*(3), 445-452.

Ferguson, C. J. (2009). An effect size primer: A guide for clinicians and researchers. *Professional Psychology: Research and Practice*, *40*, 532-538.

Frick, A., Daum, M. M., Walser, S., & Mast, F. W. (2009). Motor processes in children's mental rotation. *Journal of Cognition and Development*, *10*, 18-40.

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain, 119*(2), 593-609.

Gibbs, R. W. (2007). *Embodiment and cognitive science*. New York: Cambridge University Press.

Hall, D. L., & Friedman, A. (1994). Shape discriminations of three-dimensional objects depend on the number and location of bends. *Perception & Psychophysics, 56,* 288–300.

Kosslyn, S. M., Thompson, W. L., Wraga, M., & Alpert, N. M. (2001). Imagining rotation by endogenous versus exogenous forces: Distinct neural mechanisms. *Neuroreport, 12*, 2519-2525.

Levine, T., & Hullett, C. (2002). Eta squared, partial eta squared and misreporting of effect size in communication research. *Human Communication Research, 28,* 612–625.

Metzler, J., & Shepard, R. N. (1974). Transformational studies of the internal representation of three-dimensional objects. In R. Solso (Ed.), *Theories in cognitive psychology: The Loyola Symposium* (pp. 147–201). Hillsdale, NJ: Erlbaum.

Parsons, L. M. (1987). Imagined spatial transformations of one´s hands and feet. *Cognitive Psychology*, *19*, 178-241.

Parsons, L. M. (1994). Temporal and kinematic properties of motor behavior reflected in mentally simulated action. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(4), 709-730.

Prinz, W. (1990). A common coding approach to perception and action. In O. Neumann & W. Prinz (Eds.), *Relationships between perception and action* (pp. 167-201). Heidelberg: Springer.

Tye, M. (2000). *The imagery debate.* Cambridge, MA: MIT Press.

Sack, A. T., Lindner, M., & Linden. D. E. J. (2007). Object- and directions-specific interference between manual and mental rotation. *Perception & Psychophysics, 69*(8), 1435-1449.

Sayeki, Y. (1981). “Body analogy” and the cognition of rotated figures. *Quarterly Newsletter of the Laboratory of Comparative Human Cognition, 3*, 36–40.

Sekiyama, K. (1982). Kinesthetic aspects of mental representation in the identification of left and right hands. *Perception & Psychophysics*, *32*, 89-95.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, *171*, 701-703.

Wexler, M., Kosslyn, S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition, 68*, 77-94.

Wohlschläger, A. (2001). Mental object rotation and the planning of hand movements. *Perception & Psychophysics, 63*, 709-718.

Wohlschläger, A., & Wohlschläger, A. (1998). Mental and manual rotation. *Journal of experimental psychology: Human perception and performance*, *24*(2), 397-412.

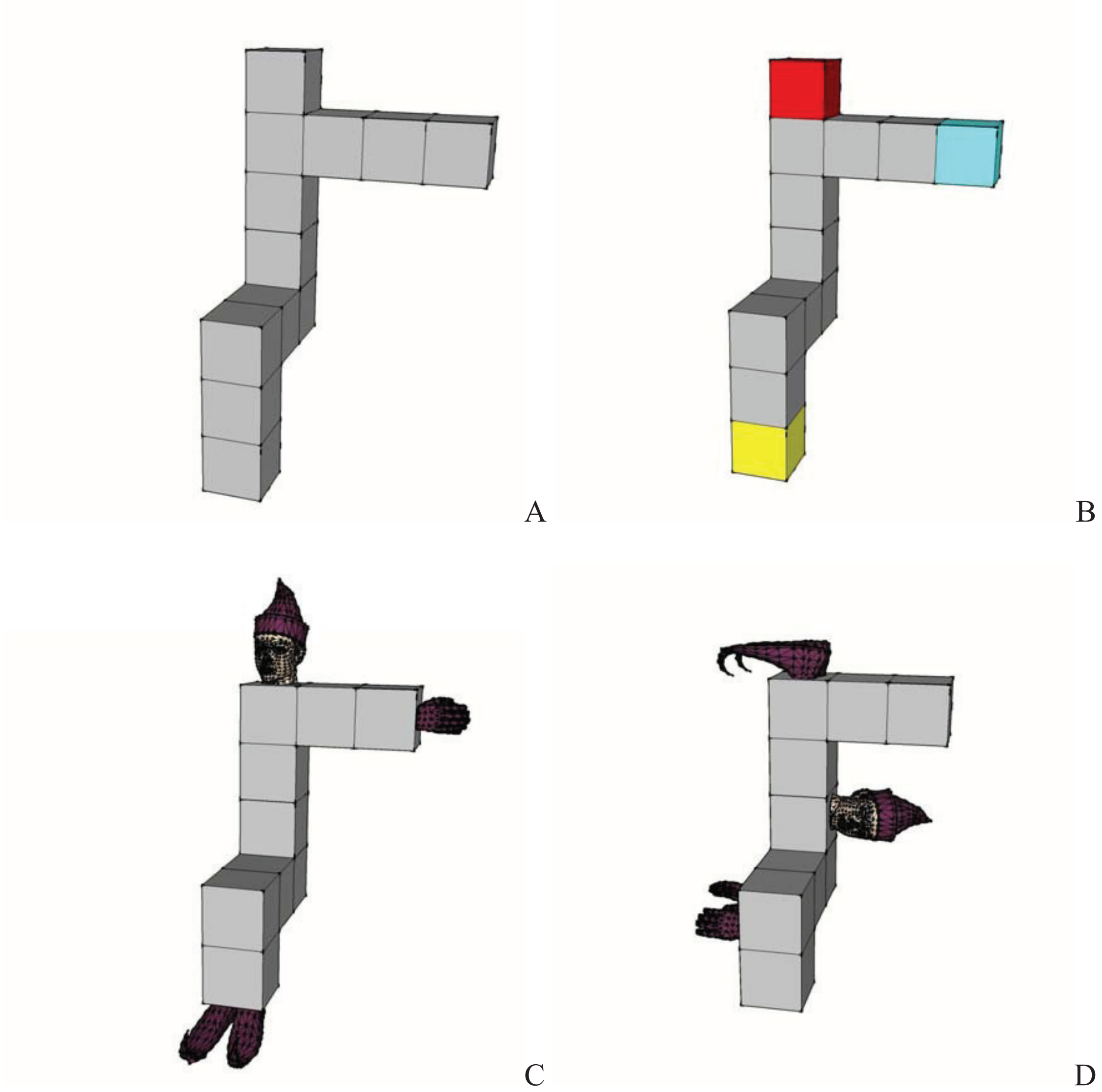

Figure 1. Examples of the stimuli: (A) *standard* S-M cubes, (B) *colored* S-M cubes with colored end cubes, (C) *possible-body* S-M cubes with body parts in anatomically possible locations, and (D) *impossible-body* S-M cubes with body parts in anatomically impossible locations.

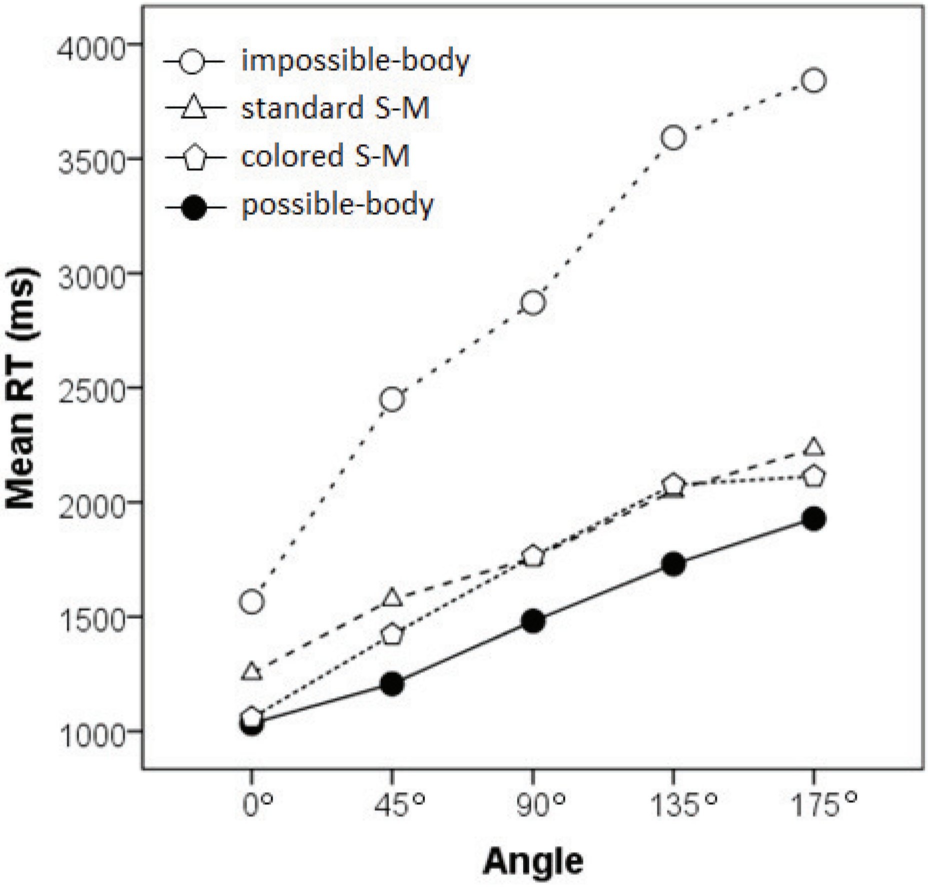

Figure 2. Mean RT as a function of angle of rotation for the different conditions.

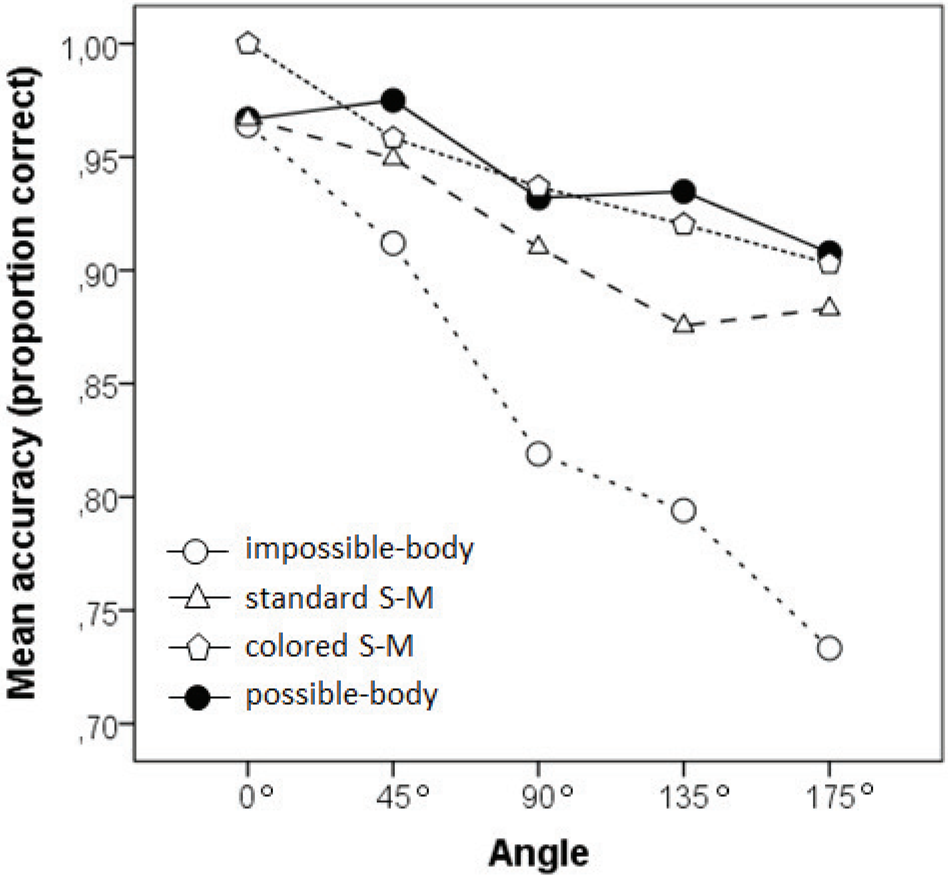

Figure 3. Mean accuracy as a function of angle of rotation for the different conditions.