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## Mental rotation and the human body: Children's inflexible use of embodiment mirrors that of adults --Manuscript Draft--

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Mental rotation and the human body:

Children's inflexible use of embodiment mirrors that of adults

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## Statement of Contribution

*What is already known on this subject?*

- In mental rotation, adults perform better when rotating anatomically possible stimuli as compared to rotating standard cube combinations.
- Performance is worse when rotating anatomically impossible stimuli.

*What does this story add?*

- The present study shows that children's mental transformations mirror those of adults in these respects.
- In case of the anatomically impossible stimuli, this highlights an inflexible use of embodiment in both age groups.
- This is in line with the Piagetian assumption of imagery being based on sensorimotor processes.

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### **Abstract**

Adults' mental rotation performance with body-like stimuli is enhanced if these stimuli are anatomically compatible with a human body, but decreased by anatomically incompatible stimuli. In the present study, we investigated these effects for kindergartners and first-graders: When asked to mentally rotate cube configurations attached with human body parts in an anatomically compatible way, allowing for the projection of a human body, children performed better than with pure cube combinations. In contrast, when body parts were attached in an anatomically incompatible way, disallowing the projection of a human body, children performed worse than with pure combinations. This experiment is of particular interest against the background of two different theoretical approaches concerning imagery and the motor system in development: One assumes an integration of motor processes and imagery over time that enables older children and adults to requisition motor resources for imagery processes, while the other postulates that imagery stems from sensorimotor processes in the first place and is disentangled from it over time. The finding that children of the two tested age-groups show exactly the same effects as adults when mentally rotating anatomically compatible and incompatible stimuli is interpreted in favor of the latter approach.

**Keywords:** mental rotation, mental transformation, embodiment, imagery, motor imagery, Piaget, spatial skills

### **Mental rotation and the human body:**

#### **Children's inflexible use of embodiment mirrors that of adults**

When comparing adults' performance in mental rotation tasks using standard cube combinations as stimuli (see Fig. 1, left) with tasks that necessitate rotating human figures, adults are clearly better when dealing with the latter (Amorim, Isableu, & Jarraya, 2006; for mental rotation see Shepard & Metzler, 1971). This effect persists when the human figures are incomplete and mainly constructed of cubes, but with some of these cubes replaced with body parts (i.e., head, feet, and hands) and therewith allow to project a complete human body upon the stimulus material (see Fig. 1, middle). However, when these replaced cubes do not allow for a projection of the human body, because the body parts are placed in an anatomically incompatible way (see Fig. 1, right), the effect is reversed (Krüger, Amorim, & Ebersbach, 2014; see also Amorim, Isableu, & Jarraya, 2006). There is a clear hierarchy comparing the effect of these three types of stimuli. Adults perform best (i.e., faster and more often correctly) when mentally rotating the anatomically possible stimuli than when rotating the standard cube combinations and worst when presented with the anatomically impossible stimuli. The latter indicates a remarkable inflexibility when solving tasks that involve the mental transformation of stimuli containing parts of the human body. This is astonishing, as one might expect adults to be more flexible when mentally transforming the anatomically impossible stimuli: They should just ignore the body parts or use them for orientation in a more abstract manner. Apparently, this is not possible and embodiment (here: the inclusion of motor processes, body representations, and motor resources in mental transformations, see Gibbs, 2005; cf. Wilson, 2002) is forced upon the mental transformation by an inevitable projection of the human body on the stimulus material.

The goal of the present study was to test whether effects of anatomically possible stimuli enhancing mental rotation and of anatomically impossible stimuli impeding it (see also Krüger, Amorim et al., 2014) can be obtained in children, too. This is of particular

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theoretical interest, as empirical studies indicate a growing influence of the projection of the human body on mental rotation with age (e.g., Conson, Mazzearella, & Trojano, 2013; Krüger & Krist, 2009a; Krüger & Krist 2009b), while other studies suggest a decrease (e.g., Funk, Brugger, & Wilkening, 2005; Sekiyama, Kinoshita, & Soshi, 2014).

According to Parsons (1987, 1994; see also Sekiyama, 1982), adults' mental rotation of hands follows the actual movement capabilities of hands. That means that the actual movement constraints of the human body are reflected in the mental transformations of body parts. Among children, findings indicate that the influence of these constraints on mental transformations are more stable in older children than in younger ones (Krüger & Krist, 2009a, 2009b): While the reflections of these constraints in primary-school children closely resemble those of adults, they are inconsistent in kindergartners. In one study (Krüger & Krist, 2009a), kindergartners did only display such effects of biomechanical constraints on mental rotation for the right hand but not for the left hand, while in another study (Krüger & Krist, 2009b), the occurrence of an effect depended on kindergartners' own hand posture. A similar trend was reported by Conson et al. (2013). They tested the influence of actual movement constraints on the mental rotation of hands, too, but with adolescents of different age groups. They found a reliable effect of such constraints in 14-15-year-olds and in 17-18-year-olds, but not in the younger 11-12-year-olds. While an overall trend to more stable effects of movement constraints in older participants within studies can be seen, considering the different age ranges tested for these three mentioned studies, data seem to be inconsistent (see Discussion).

Nevertheless, these trends can be interpreted as evidence for motor imagery and motor control being integrated over development to achieve synergies for imagery tasks like mental rotation (see Caeyenberghs et al., 2009; Jeannerod, 2001).

Other studies, however, suggest a different development. Funk et al. (2005), for instance, asked 5 to 6 years old children and adults to mentally rotate pictures of hands.

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Children reacted faster when their own hands matched the perspective of the depicted hands: Reaction times were shorter when stimulus hands were shown from a palmar perspective and children's hands rested palms-up than when the stimulus hands were presented from a dorsal perspective and vice versa. In adults, in contrast, effects of their own hand posture emerged only when stimulus hands were presented from a dorsal perspective but not when they were presented from a palmar perspective. According to Funk et al. (2005), this indicates a decreasing contribution of motor processes on mental imagery with age.

This follows the Piagetian view, that imagery and other higher cognitive functions are based on sensorimotor processes ontogenetically. Thus, younger children rely more on motor processes for imagery than older children and adults.

A slightly different approach is taken by Sekiyama et al. (2014). They tested children and adults with a hand rotation task, too. In their sample, 6-year-olds were largely unable to keep their hands still during the test and had to be excluded from data analysis. A measurable influence of actual movement constraints on the mental transformations of hands declined with age for the remaining age groups: The effect was stronger in 7-year-olds than in 8-year-olds and in turn stronger in 8-year-olds than in 9-year-olds – the same holds for 10-year-olds and adults, although the motor effect was hardly discernable. According to Sekiyama et al., this established a clear order of underlying functions: Six-year-olds perform overt action, while older children rely on motor imagery, and the oldest children and adults use visuo-motor imagery.

### **The present research**

In the present experiment, we compared children's mental rotation of *pure standard cube combinations*, similar to those used by Shepard and Metzler (1971), with the mental rotation of cube combinations with body parts attached (Amorim et al., 2006). The body parts were attached in a way that allowed for the successful projection of a human body (*anatomically possible*) or disallowed such a projection (*anatomically impossible*). Previous findings showed



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that in adults the attachment of body parts led to specific embodiment effects: Anatomically possible stimuli enhanced mental rotation performance, while anatomically impossible stimuli impeded the performance compared to the pure cube stimuli (Krüger, Amorim et al., 2014).

The goal was to investigate whether these specific embodiment effects on mental rotation are already present in children. Generally, to quantify the extent of embodiment as effect sizes and compare it between different age groups seems methodologically debatable to us, because different levels of performance between age groups imply different population means and variance (see Cohen, 1977). Therefore, we were looking for qualitative changes, that is, whether an effect of embodiment is already present or not in a specified age group. More specifically, we examined whether children show benefits of a projection of the human body onto the anatomically possible stimuli and/or the inflexible processing of anatomically impossible stimuli, as previously reported for adults (e.g., Krüger, Amorim et al., 2014). A lack of such effects in children would strongly support the idea that imagery functions become integrated with age, because the benefits of a projection of the human body onto the anatomically possible stimuli and the inflexible processing of anatomically impossible stimuli, would have been acquired through development. In turn, the Piagetian view that imagery is based on sensorimotor processes would be hard to reconcile with such effects lacking among children (see also Ebersbach & Krüger, 2016).

### **Method**

#### **Participants**

Only kindergartners older than 5 years were included in this study, as younger children cannot reliably solve standard mental rotation tasks – even those adapted for children (Estes, 1998). To test for possible differences between kindergartners and school children, as reported in previous mental rotation studies (e.g., Krüger & Krist, 2009a, 2009b), first-graders were included additionally. The tested kindergartners were not enrolled in any preschool education program.

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A total of 66 children was recruited for this study. However, six children did not finish the experiment due to non-compliance and had to be excluded. Of the remaining 60 children, 30 were kindergartners ( $M = 71$  months,  $SD = 4$ ,  $min = 65$ ,  $max = 79$ ; 16 girls, 14 boys) and 30 were first-graders ( $M = 86$  months,  $SD = 3$ ,  $min = 80$ ,  $max = 93$ ; 15 girls, 15 boys). All children were right-handed (handedness was determined by asking children to write their own name). They participated with the consent of their parents and could end cooperation anytime on their own behalf. Participation was rewarded with sweets. All children were tested in a separate room in their school or kindergarten by the same female experimenter.

### Materials

Usually, mental rotation in children is tested by means of 2D stimuli to reduce complexity and task demands – in contrast to the quasi 3D stimuli, used for adults (e.g., Marmor, 1975). However, there is a recent example that at least first-graders can cope with quasi 3D stimuli in a mental rotation task if presented with cubes with differently colored surfaces (Lütke & Lange-Küttner, 2015). Therefore, quasi 3D stimuli were used in the current experiment to enhance comparability with the findings in adults (Krüger, Amorim et al., 2014). Test stimuli consisted of pictures of cube combinations, either pure or with body parts attached (Fig. 1). When attached, body parts were replacing cubes to keep the different stimuli comparable. Body parts were placed at positions that allowed or disallowed the projection of anatomically possible body postures. There were four basic cube combinations. All pictures were rotated from their baseline ( $0^\circ$ ) by  $5^\circ$ ,  $45^\circ$ ,  $90^\circ$ ,  $135^\circ$ ,  $175^\circ$ ,  $185^\circ$ ,  $225^\circ$ ,  $270^\circ$ ,  $315^\circ$ , and  $355^\circ$ . Mirror-images were created of each of these pictures. This resulted in 3 (condition: pure, anatomically possible, anatomically impossible) x 4 (basic cube combinations) x 10 (angles of rotation) and 2 (mirror-images) = 240 pictures. For training purposes, an additional cube combination with colored cubes was created and rotated and mirrored as the actual test stimuli (Fig. 2).

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All stimuli were presented on a Samsung RC 530 Laptop (15.6", 1366 x 768 pixels) connected with an external keyboard. The external keyboard had all keys removed but the "0/ins" key at the right and "alt" key at the left. The empty keys were covered with cardboard while the remaining right key was painted red and the remaining left key was painted yellow. E-Prime software was used for presentation and the measurement of reaction times (RT) and accuracy (ACC).

### **Procedure**

Participants were presented with two pictures at a time (Fig. 3). The left picture was the target presented at 0°. The right picture was in half of the trials identical to the target picture and in the other half of the trials it was a mirror image of the target picture always rotated between 5° to 355°. Both pictures were matched for condition (pure, anatomically possible, anatomically impossible). Participants were asked to press the red button with their right hand if the pictures were the same and to press the yellow button with their left hand if the pictures were different. When they pressed the correct button, a smiley appeared on the screen and a pleasant tune was played. But when the wrong button was pressed, a frowny appeared and an unpleasant tune was played. After every trial, the experimenter had to trigger the next trial manually.

For training, children were presented with eight training trials with the colored cube combinations. The first two trials were handled by the experimenter. Both trials were "same" trials. In the first trial, the experimenter demonstrated the correct solution. To defuse children's fear and surprise of making mistakes, she deliberately pressed the wrong button in the second trial. Then children were allowed to solve the six remaining training trials by themselves. In half of the training trials, "same" was the correct answer. During the training, children were allowed to ask questions and request additional information.

Then the actual test started. Children were informed to remain silent and concentrate on the test. No questions were allowed nor further information was given. If children were

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becoming agitated, a short break was allowed. After every 60 trials, a regular break was scheduled. The actual test consisted of 3 (condition: pure, anatomically possible, anatomically impossible) x 4 (basic combinations) x 10 (angles of rotation: 5°, 45°, 90°, 135°, 175°, 185°, 225°, 270°, 315°, & 355°) x 2 (mirror-images) = 240 trials. All trials were presented in a random order.

### Results

All children solved the tasks reliably above chance on an individual level (i.e., more than 133 correct answers out of 240, Binomial distribution,  $p < .05$ ). Therefore, it was assumed that all participants were able to handle the task in a meaningful way and were therefore included in the final analysis.

### Accuracy

For the analysis of the accuracy (ACC), the number of correct reactions was converted into percent. Data were aggregated across the four different basic cube combinations and across the trials where the shortest rotation path to the upright position of the target was the same (e.g., 175° and 185°; for further consideration of the data aggregation, see Appendix A). Aggregated data were submitted to a 3 (conditions: pure, anatomically possible, anatomically impossible) x 5 (angles of rotation: 5°, 45°, 90°, 135°, 175°) x 2 (age group: kindergartners, first-graders) ANOVA.

This ANOVA yielded main effects for condition,  $F(2, 116) = 32.62, p < .001, \eta^2 = .36$ , angle of rotation,  $F(4, 232) = 39.35, p < .001, \eta^2 = .40$ , and age,  $F(1, 58) = 7.60, p = .008, \eta^2 = .12$ . Unsurprisingly, first-graders were more often correct ( $M = 87.6\%$ ,  $SD = 9$ ) than kindergartners ( $M = 79.7\%$ ,  $SD = 13$ ).

Comparing performance for the different conditions, planned  $t$ -tests revealed that children performed better when they rotated the anatomically possible stimuli ( $M = 88.6\%$ ,  $SD = 13$ ), as compared to the pure cube stimuli ( $M = 81.0\%$ ,  $SD = 11$ ),  $t(59) = 7.04, p < .001$ ,

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$d = 0.62$ , but there was no reliable difference between the pure and the anatomically impossible stimuli ( $M = 81.3\%$ ,  $SD = 11$ ),  $t(59) = 0.30$ ,  $p = .77$ .

Although descriptively ACC was not strictly proportional to the angle of rotation (participants were better at  $175^\circ$  than at  $135^\circ$  rotations), the relationship between the two variables yielded a significant linear trend,  $F(1, 48) = 61.34$ ,  $p < .001$ ,  $\eta^2 = .51$ , which explained more variance than a quadratic one,  $F(1, 48) = 35.98$ ,  $p < .001$ ,  $\eta^2 = .38$ .<sup>1</sup>

Furthermore, the factors condition, angle of rotation, and age were involved in a number of interactions, not easily to disentangle: There were interactions between condition and angle of rotation,  $F(8, 464) = 2.89$ ,  $p = .004$ ,  $\eta^2 = .05$ , age and angle of rotation,  $F(4, 232) = 3.83$ ,  $p = .005$ ,  $\eta^2 = .06$ , as well as condition, age, and angle of rotation,  $F(8, 464) = 2.05$ ,  $p = .039$ ,  $\eta^2 = .03$ . These interactions might be a result of the afore mentioned irregularity concerning the  $135^\circ$  and  $175^\circ$  trials, because – for first-graders in the pure cubes condition – the relationship between angle of rotation and ACC was better described by a quadratic function, but in all other cases as linear (see Table 1).

Importantly, there was no significant interaction between the factors condition and age,  $F(2, 116) = 1.54$ ,  $p = .22$ ,  $\eta^2 = .03$ , suggesting similar effects of the stimulus conditions in both age groups.

### **Reaction times**

Only reaction times (RTs) for correct reactions were considered. Additionally, RTs for the trials including mirror-images were excluded (see Shepard & Metzler, 1971). RTs were aggregated in the same way as the ACC and aggregated data were submitted to a 3 (conditions: pure, anatomically possible, anatomically impossible) x 5 (angles of rotation:  $5^\circ$ ,  $45^\circ$ ,  $90^\circ$ ,  $135^\circ$ ,  $175^\circ$ ) x 2 (age group: kindergartners, first-graders) ANOVA.

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<sup>1</sup>  $\eta^2$  is taken as an indicator for explained variance here.

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There were main effects for condition,  $F(2, 116) = 21.92, p < .001, \eta^2 = .27$ , angle of rotation,  $F(4, 232) = 62.95, p < .001, \eta^2 = .52$ , and age,  $F(1, 58) = 5.56, p = .011, \eta^2 = .09$ . Indeed, first-graders were faster ( $M = 5248$  ms,  $SD = 1480$ ) than kindergartners ( $M = 6410$  ms,  $SD = 2257$ ). As there was no significant interaction between condition and age, again similar effects of the stimulus conditions in both age groups can be assumed. In addition, there was no interaction between condition and angle of rotation,  $ps > .20$ .

Planned  $t$ -tests revealed performance differences between the different conditions (see Fig. 1): Children were faster in rotating the anatomically possible stimuli ( $M = 5318$  ms,  $SD = 1949$ ) than rotating the pure stimuli ( $M = 5708$  ms,  $SD = 2219$ ),  $t(59) = 2.11, p = .02, d = 0.19$ , and they were faster rotating the pure stimuli than rotating the anatomically impossible stimuli ( $M = 6460$  ms,  $SD = 2205$ ),  $t(59) = 4.72, p < .001, d = 0.34$ .

As can be expected in a mental rotation task, RT increased with angles of rotation (Fig. 4). This description is in line with a significant linear trend,  $F(1, 58) = 125.81, p < .001, \eta^2 = .68$ , and a significant quadratic trend,  $F(1, 58) = 41.04, p < .001, \eta^2 = .41$ . However, as with the ACC, the fit of the linear trend was better.

### Discussion

All children performed above chance on an individual level, which could not have been taken for granted, as the task was not simplified for children's use. Instead, task demands were exactly the same as in the original task for adults (Krüger, Amorim et al., 2014). Generally, the first graders performed more accurately and faster than kindergartners, suggesting that a quantitative development takes place in this relatively short time period of 15 months. An approximate linear trend between rotation disparity and both ACC and RT, as typical for mental rotation, was revealed. This indicates that children relied on analog mental transformations to solve the tasks (Shepard & Metzler, 1971).

Children in both age groups showed both effects of embodiment: For one thing, they benefitted from anatomically possible stimuli, as they were faster rotating them and made less

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mistakes as compared to the pure cube combinations. For another thing, they were inflexible in the use of anatomically impossible stimuli, as they were distinctively slower in rotating them – compared to anatomically possible stimuli and even to pure cube combinations. There were no indications for qualitative differences between the age groups concerning embodiment effects as both emerged in both age groups. This finding that children showed the same embodiment effects as adults is in line with the Piagetian assumption of imagery being based on sensorimotor processes, developing quite early (Funk et al., 2005; see also Sekiyama et al., 2014).

However, one might argue that the tested children were already too old for such a conclusion to be drawn. Potentially, younger children, if tested in the same way, might show no such effect of embodiment. Such a claim cannot be easily disapproved at the moment, because children younger than five years of age cannot reliably be tested with classical mental rotation paradigms (Estes, 1998; see Davis, 2015, for an overview). However, future studies with new paradigms may resolve this issue. For example, a recent paradigm suggested that the relation between angle disparity and RT can be demonstrated already in 3-year-olds (Krüger, Kaiser, Mahler, Bartels, & Krist, 2014). Such paradigms should be adapted to examine potential effects of anatomically possible and impossible stimuli on mental rotation in even younger children.

Furthermore, another interpretation has to be mentioned. There is also the possibility that motor imagery and motor control are functionally the same and provide the basis for all imagery processes – and that they cannot be disentangled at all (Gibbs, 2005; Prinz, 1990). The present finding of no qualitative change between adults and children is in line with such a theoretical approach, too.

Another aspect that should be considered in future studies are the apparent inconsistencies in the reported effects of embodiment on mental rotation. This becomes obvious with the mental rotation of hands. Children's mental rotation of hands were used to

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argue for and against a Piagetian approach (e.g., Funk et al., 2005, vs. Conson et al., 2013). Furthermore, studies that report evidence for a more stable embodiment with age do so for completely different age groups (e.g., Krüger & Krist, 2009: kindergartners and primary school children; Conson et al., 2013: adolescents). Therefore, these findings are hard to reconcile. Conson et al. (2013) and Sekiyama et al. (2014) pointed out that differences in the conceptualization of the mental rotation tasks might be responsible for these inconsistencies. All hand rotation tasks mentioned were in essence laterality tasks (Conson et al., 2013; Funk et al., 2005; Sekiyama et al., 2014). That means that participants were presented with one picture of a hand and were asked to indicate whether it was a left or a right hand. To our knowledge, only one different task was used: One large hand was presented with two small comparison hands and participants were asked to indicate the small hand that was identical with the large one (Krüger & Krist, 2009a, 2009b). Indeed, different task types could influence the results, but cannot explain the diametrically opposed divergences between the findings by Conson et al. (2013) and Sekiyama et al. (2014) for the essentially same hand mental rotation task with overlapping age groups. In our opinion these inconsistencies only highlight the need for the implementation of new approaches as we did with our present study.

### **Conclusions**

The occurrence of embodiment effects in children in the present study mirrored that of adults in the original study, using the same tasks (Krüger et al., 2014). It seems especially noteworthy to us, that the performance decline with anatomically impossibly placed body parts was as dominant in children as in adults, because it emphasizes the inflexible use of embodiment in both age groups.



**References**

- 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.
- Caeyenberghs, K., Wilson, P. H., van Roon, D., Swinnen, S. P., & Smits-Engelsman, B. C. M. (2009). Increasing convergence between imagined and executed movement across development: Evidence for the emergence of movement representations. *Developmental Science*, *12*(3), 474-483.
- Cohen, J. (1977). *Statistical power analysis for the behavioral sciences*. New York: Academic Press.
- Conson, M., Mazzarella, E., & Trojano, L. (2013). Developmental changes of the biomechanical effect in motor imagery. *Experimental Brain Research*, *226*, 441-449.
- Davis, B. (2015). *Spatial reasoning in the early years: Principles, assertions, and speculations*. London: Routledge.
- Ebersbach, M., & Krüger, M. (2016). View makes a difference: Presenting human figures from the back or front affects mental spatial transformations of children and adults. *Spatial Cognition and Computation*, *16*(3), 173-191.
- Estes, D. (1998). Young children's awareness of their mental activity. The case of mental rotation. *Child Development*, *69*(5), 1345-1360.
- Funk, M., Brugger, P., & Wilkening, F. (2005). Motor processes in children's imagery: The case of mental rotation of hands. *Developmental Science*, *8*, 402-408.
- Gibbs, R. W. (2005). *Embodiment and cognitive science*. New York: Cambridge University Press.
- Jeannerod, M. (2001). Neural simulation of action: A unifying mechanism for motor cognition. *NeuroImage*, *14*(1), 103-109.

## CHILDREN'S EMBODIMENT

- Krüger, M., Amorim, M.-A., & Ebersbach, M. (2014). Mental rotation and the motor system: Embodiment head over heels. *Acta Psychologica, 145*, 104-110.
- Krüger, M., Kaiser, M., Mahler, K., Bartels, W., & Krist, H. (2014). Analogue mental transformations in three-year-olds: Introducing a new mental rotation paradigm suitable for young children. *Infant and Child Development, 23*, 123-138.
- Krüger, M., & Krist, H. (2009a). Imagery and motor processes - when are they connected? The mental transformation of body parts in development. *Journal of Cognition and Development, 10*, 239-261.
- Krüger, M., & Krist, H. (2009b). Verknüpfung von Vorstellung und Motorik in der Entwicklung: Die mentale Transformation bei Darstellungen von Händen [Integration of imagery and motor processes in development: Mental transformation with pictures of hands]. *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie, 41*, 198-206.
- Liesefeld, H. R., & Zimmer, H. D. (2011). The advantage of mentally rotating clockwise. *Brain and Cognition, 75*, 101-110.
- Lütke, N., & Lange-Küttner, C. (2015). Keeping it in three dimensions: Measuring the development of mental rotation in children with the rotated colour cube test (RCCT). *International Journal of Developmental Science, 9*, 95-114.
- Marmor, G. S. (1975). Development of kinetic images: When does the child first represent movement in mental images? *Cognitive Psychology, 7*, 548-559.
- 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.

## CHILDREN'S EMBODIMENT

- 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.
- Sekiyama, K. (1982). Kinesthetic aspects of mental representations in the identification of left and right hands. *Perception & Psychophysics*, 32(2), 89-95.
- Sekiyama, K., Kinoshita, T., & Soshi, T. (2014). Strong biomechanical constraints on young children's mental imagery of hands. *Royal Society Open Science*, 1(4), 140118.
- Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, 171, 701-703.
- Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin and Review*, 9(4), 625-636.

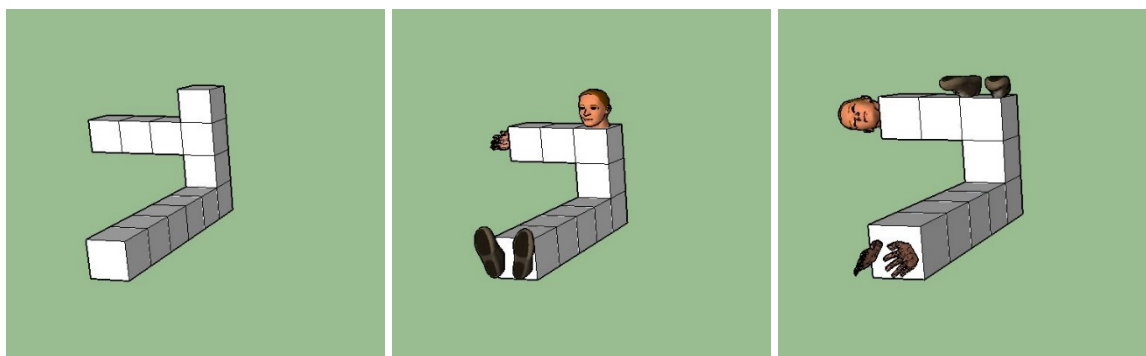
## CHILDREN'S EMBODIMENT

**Table 1**

*Indicators of fit of a linear and quadratic model ( $\eta^2$ ), describing the relationship between ACC and angle, separately for each condition and age group.*

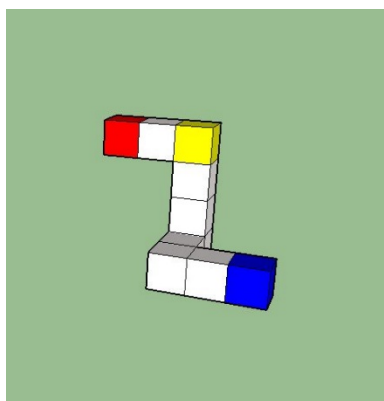
Age Group	Condition					
	Pure		Anatomically Possible		Anatomically Impossible	
	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic
Kindergartners	.55	.49	.48	.05	.38	.31
First-Graders	.32	.42	.21	.05	.45	.14

## CHILDREN'S EMBODIMENT

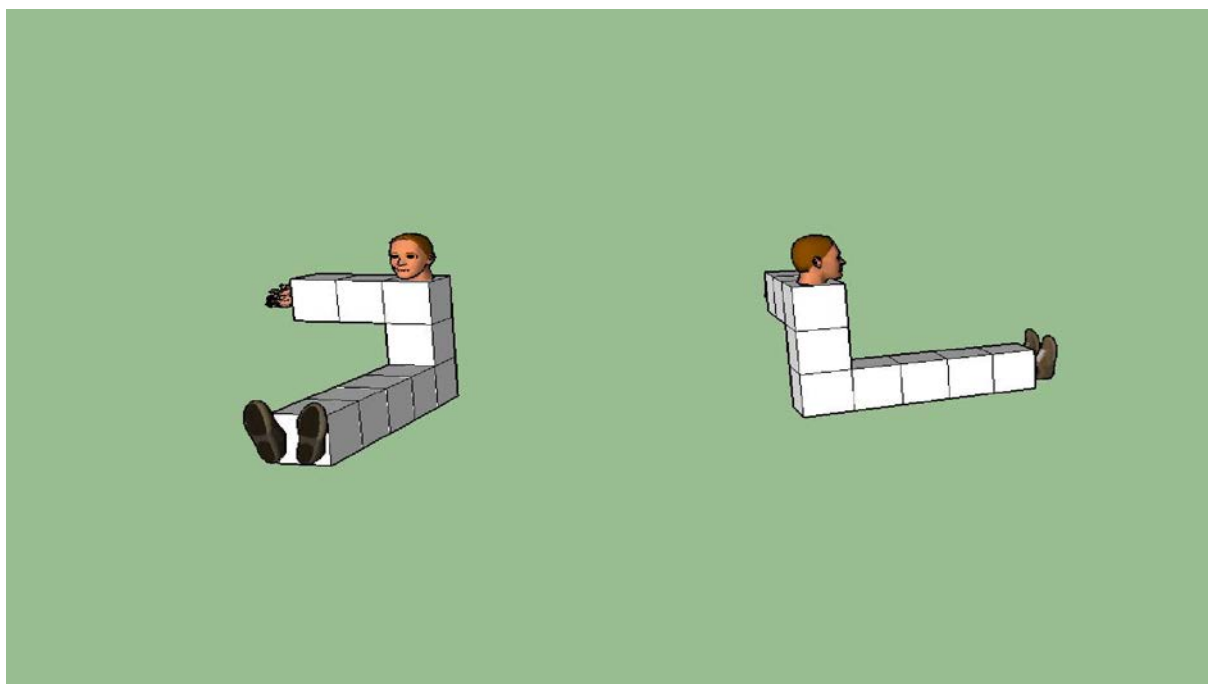


*Figure 1.* Examples of the basic cube combinations pure and with attachments (left: pure cubes, middle: anatomically possible, right: anatomically impossible).

## CHILDREN'S EMBODIMENT



*Figure 2.* Baseline ( $0^\circ$ ) stimulus used for training.



*Figure 3.* An example of the trials as seen by the participants. In this case the right picture is the mirror-image of the left one rotated by  $135^\circ$ . The correct answer would be “different” expressed by pressing the yellow key.

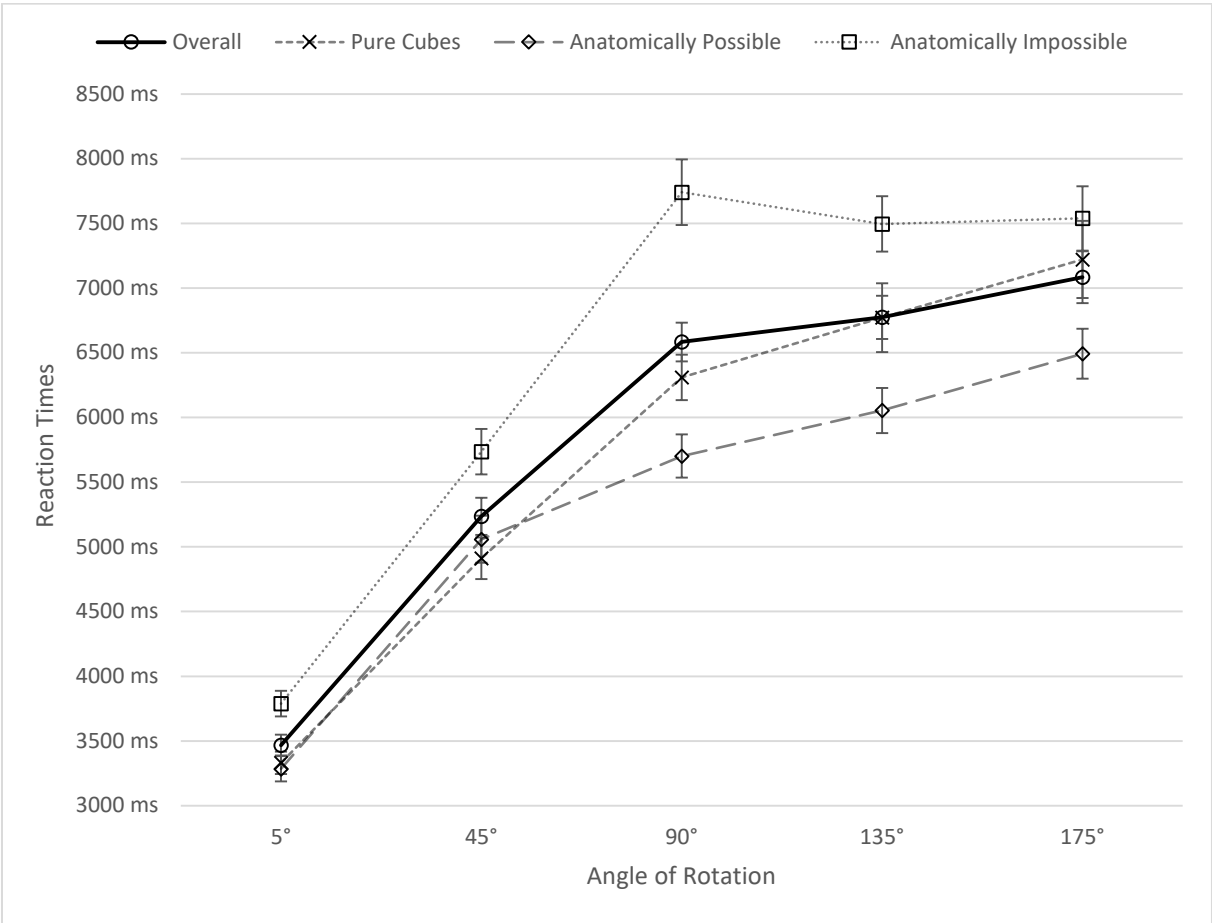


Figure 4. Mean RT (and SE) as function of angle of rotation overall and for the three different conditions.



**Appendix A**

This way of data aggregation was implemented along with the description of mental rotation by Shepard & Metzler (1971), assuming the same, shortest possible rotation path (e.g., 90° and 270°). Still, one might wonder whether the stimuli used in the current experiment changed participants' solving strategies as compared to the rotation of classical cubes only. Therefore, it was tested whether the same results could be obtained, when angles were not collapsed. Testing this for the ACC with an ANOVA with 10 angles instead of 5 yielded the same significant effects and interactions (all  $ps < .01$ ), but only a marginal interaction for condition, age, and angle of rotation ( $p = .068$ ).

Furthermore, one might wonder, whether children's ACC was different for the assumed rotation directions (i.e., clockwise and counter-clockwise; see Liesefeld & Zimmer, 2002). To test this, ACC was compared for the assumed clockwise rotation (185°-355°) and the assumed counter-clockwise rotation (5°-175°). Actually, children performed better with the counter-clockwise rotation ( $M = 86\%$  correct,  $SD = 11\%$ ) than with the clockwise rotation ( $M = 81\%$  correct,  $SD = 13\%$ ),  $t(59) = 5.14$ ,  $p < .001$ ,  $d = 0.42$ . This tendency is also visible for the RT. Children were faster when rotating counter-clockwise ( $M = 4890$  ms,  $SD = 1037$ ), than when rotating clockwise ( $M = 5089$  ms,  $SD = 1091$ ),  $t(59) = 3.12$ ,  $p = .003$ ,  $d = 0.19$ . To exclude the possibility, that this difference was due to kinesthetic properties of the stimuli fitted with body parts, performances were compared considering the pure cube combinations only. The effect is present here, too, with better performance with the counter-clockwise rotation ( $M = 85\%$  correct,  $SD = 14\%$ ) than with the clockwise rotation ( $M = 77\%$  correct,  $SD = 16\%$ ),  $t(59) = 4.60$ ,  $p < .001$ ,  $d = 0.53$ .