Running head: MENTAL TRANSFORMATION OF BODY PARTS

Imagery and Motor Processes – When are They Connected?
The Mental Rotation of Body Parts in Development

Markus Krüger and Horst Krist
Ernst-Moritz-Arndt-Universität Greifswald, Greifswald, Germany

Author Note

Markus Krüger and Horst Krist, Institut für Psychologie, Ernst-Moritz-Arndt-Universität Greifswald.

We wish to thank Marlen Kaiser for assistance in data collection.

Correspondence should be sent to Markus Krüger, Institut für Psychologie, Entwicklungspsychologie und Pädagogische Psychologie, Franz-Mehring-Str. 47, 17487 Greifswald, Germany.

Phone: ++49-3834-863780

Fax: ++49-3834-863763

E-mail: markuskr@uni-greifswald.de

This is not the copy of record. The final version is published in the *Journal of Cognition and Development*:

Krüger, M., & Krist, H. (2009). Imagery and Motor Processes - When are They Connected? The mental Transformation of Body Parts in Development. *Journal of Cognition and Development, 10*(4), 239-261.

Abstract

Motor influences on the mental transformation of body parts have been observed in both, children and adults. Previous findings indicated that these influences were more pronounced in children than in adults, suggesting a stronger link between motor processes and imagery in children. The present series of two experiments casts doubt on the general validity of such an interpretation. Kindergartners' (aged 5-6 years), first graders' (aged 7 years) and adults' performance in the mental rotation of pictures of body parts was monitored for influences of internal representations of motor constraints (motor effect). In both experiments evidence for mental rotation was obtained for each group. Unexpectedly, kindergarten boys made significantly more errors than kindergarten girls. A motor effect was only found in the second experiment, where it was least pronounced in the youngest age group. Our results suggest that mental transformations of body parts do not necessarily involve motor processes and that embodiment may become stronger with development rather than weaker with certain tasks.

Keywords: mental rotation, mental transformation, motor imagery, embodied cognition, sex differences, gender effects

Imagery and Motor Processes – When are They Connected?

The Mental Rotation of Body Parts in Development

From a developmental perspective, the present research focuses on the connection between imagery and the motor system. Before presenting and discussing a series of two experiments, in which a novel mental rotation paradigm was used, we will briefly review theory and research on the development of mental transformations before dealing with research concerning motor influences on mental rotation.

Modern experimental research on mental imagery was initiated by a seminal paper published by Shepard and Metzler (1971) almost four decades ago. In the paradigmatic mental rotation task introduced by these authors, two pictures were presented showing 3D combinations of joined cubes from different perspectives and participants had to decide whether the depicted objects were congruent or not. Shepard and Metzler (1971) found that the time needed for a decision rose linearly with the angular difference between the depicted configurations. The widely accepted interpretation of this finding was that participants solved the task by mentally rotating the objects from one perspective into the other.

In a mental rotation task, the linear relationship between angle of rotation and reaction time (RT) can therefore be viewed as evidence for mental rotation actually being employed by the participants. Based on this rationale, developmental researchers adapted the mental rotation task for studies with children. Using pictures of panda bears rotated in the picture plane instead of combinations of cubes rotated in 3D, Marmor (1975) first demonstrated mental rotation in children as young as five years. She found that, after some familiarization and training trials, 5-year-old children could solve the task satisfyingly, and she also observed a linear reaction time pattern. From these findings Marmor concluded that the ability to perform mental transformations is present at a younger age than Piaget's theory would predict. According to Piaget (1954; Piaget & Inhelder, 1967), preoperational children (i.e., children younger than 6 or 7 years) should not be capable of performing mental transformations of any kind.

Even more important than the question at which average age children can solve specific problems is the question how they get there. Fundamental for Piaget’s theory is the assumption that mental representations and their transformations emerge from the sensorimotor system. Mental transformations including imagery are thus conceived as internalized actions. This is in accordance with newer theories of modality-specific representations (e.g., Gallese & Lakoff, 2005; Gibbs, 2006): Mental representations and their transformations are not only constructed and controlled by central amodal executive functions but also by specific modal functions connected to sensory and action systems. Hence, according to this view, mental representations comprise a distributed network of different modules residing in different areas of the brain. In the case of the motor system this network consists of prefrontal executive areas and parts of sensorimotor, premotor, and motor areas. The processing of a representation in such a motor assisted network is called motor cognition, embodied cognition, or, in short, embodiment. Embodiment is not limited to movement planning and related functions but also compasses abstract thoughts and conceptual representations (cf. Wilson, 2002).

Regarding mental rotation, there is strong evidence indicating the involvement of motor resources. Deutsch, Bourbon, Papanicolaou, and Eisenberg (1988) showed that solving mental rotation problems leads to a measurable higher cerebral blood flow in areas of the brain associated with motor processes. Kosslyn (1995) interpreted the link between mental rotation and motor processes as a consequence of the fact that both share resources used for movement planning. According to Kosslyn (1995) and Kosslyn, Ganis and Thompson (2001), processes of movement planning are involved in mental rotation up to the extent that one imagines manipulating objects with one’s hands.

Whatever the exact reason for the link may be, there is converging evidence for its existence. One line of evidence concerns similarities between the movement of body parts and the mental transformation of body parts. Parsons (1987, 1994) found a strong correlation between the time needed to move a body part and the time needed to imagine its movement. When participants were assigned to identify pictures of left and right hands, their reaction times depended on the position of their own hands, the comfort of the shown postures and the awkwardness to bring their own hands into the displayed positions. Reaction times increased with the amount of disparity between the shown pictures and the participants' hands as well as with the discomfort of the shown postures and the awkwardness of the hypothetically required movement.

In a more recent paper, Amorim, Isableu & Jarraya (2006) demonstrated a connection between the mental rotation of body stimuli and the paradigm of embodied cognition. They found that the extension or replacement of the classical cube combinations with body stimuli can facilitate mental rotation in terms of a reduction in reaction times and particularly in error rates. A prerequisite for this facilitation was that the presented stimuli depicted postures that were in accordance with the human physique. According to Amorim et al. (2006), body stimuli alleviated the encoding of the material as well as participants' ability to project their body image onto the goal stimuli (embodiment).

Another line of evidence concerns interferences between motor processes and mental rotation. When carrying out a manual action like rotating a knob or a joystick while solving a mental rotation problem, adults finish the task faster if the manual rotation is compatible with the mental rotation and slower if it is incompatible (Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998). Wohlschläger (2001) also found this effect when participants were only asked to prepare for a manual rotation and therefore concluded that mental rotation may be construed as imagined or covert action.

Using this paradigm, Sack, Lindner, and Linden (2007) combined actual manual and mental rotation of specific stimuli like hands. While the above mentioned manual effect on the reaction times (RT) was shown for the mental rotation of photographs of hands, the effect could not be replicated for cube combinations.

It is noteworthy in this context, that the verifiability of motor correlated brain activities during mental rotation appears to depend on the strategy used by the subjects to solve the problem: Kosslyn, Thompson, Wraga, and Alpert (2001) induced different solution strategies by showing their participants either a hand rotating a cube combination or a cube combination rotating by itself. When they were later asked to solve mental rotation problems in an fMRT scanner, significant motor cortex activation occurred only in the hand rotating group.

Referring to Kosslyn, Thompson, et al. (2001), Sack et al. (2007) assume that different cues might induce different strategies to solve a mental rotation problem. Clearly, pictures of hands are more likely to induce the use of motor resources than abstract combinations of cubes, an interpretation which is consistent with the findings of Amorim et al. (2006).

From a developmental perspective, motor influences on imagery have as yet only been addressed in a couple of experiments. In one of these experiments, the interference between motor processes and mental rotation (as in Wexler et al., 1998, and Wohlschläger & Wohlschläger, 1998) was observed in children. Frick, Daum, Walser, and Mast (2009) asked 5-year-olds, 8-year-olds, 11-year-olds, and adults to judge whether 2D jigsaw puzzle pieces matched a notch below. These pieces were presented at different angles, hence it was expected that the participants would perform mental rotation to assess whether the pieces were potential mates for the notches. This assumption was confirmed, as the reaction times increased with the angle of rotation. While working on these tasks, participants had to spin a hand crank. It turned out that the 5-year-olds and the 8-year-olds made their decisions faster when the spinning of the wheel matched the assumed path of the mental rotation rather than the other way round. This effect did neither occur in the 11-year-olds nor in the adults. This result suggests a stronger link between imagery and motor processes in younger children but might also result from a lack of sufficient task demands for the older participants.

In a further developmental study, Funk, Brugger, and Wilkening (2005) confirmed Parsons' (1987, 1994) findings: Six-year-old children, when asked to identify rotated pictures of left and right hands, showed the expected pattern of being able to answer faster when the posture of their own hand matched that of the displayed hand. For example, when their own hands were placed palm down on the keyboard, they were faster identifying hands shown from a *dorsal* perspective (i.e., palms averted) than from a *palmar* perspective (i.e., palms up) and vice versa. Funk et al. (2005) also found that the reaction times tended to depend on the hypothetical movement required to bring the hands into the displayed position. As these effects found by Funk et al. (2005) were stronger in children than in adults, the authors concluded that the connection between motor and imagery processes was also stronger in children than in adults.

This interpretation is not only consistent with the traditional Piagetian view that mental transformations evolve from sensorimotor processes, but also with modern versions of it claiming that cognition originates from embodied actions and experiences (e.g, Gibbs, 2008) or is grounded in perception and action (e.g., Daum, Sommerville, & Prinz, in press).

A major aim of the present research was to shed further light on this fundamental issue of theories of cognitive development. Exploring a modified mental rotation paradigm with children and adults, we also aimed at relating our developmental data with those from recent cognitive psychology research.

The first experiment was designed to test our novel mental rotation paradigm: Instead of left-right judgments as employed by Parsons (1987, 1994) and Funk et al. (2005), comparison pictures were used in this experiment. These were placed in the lower left and right corner of the presentation screen, corresponding with right-oriented and left-oriented stimuli or body parts (e.g., right hand displayed on the right side). Hence, the placement of the stimuli material was more suitable for children and the overall design was closer to the original work of Shepard and Metzler (1971). Additionally, a particular problem encountered by Funk et al. (2005) was avoided: When shown the stimuli in the 180° rotation (upside down), children's error rate surpassed all expectation. This problem was probably caused by children's tendency to reinterpret instructions. For example, when children were asked during the practice period whether a car would move to the left or to the right, many of them saw no reason why it should not move in the direction in which it was heading even if shown in an upside down position (i.e., driving along the ceiling).

Furthermore, the method should allow for a direct comparison between the mental transformation of body parts and other objects. Parsons (1987, 1994) claimed that the observed effects in the mental transformation of body stimuli were specific to these objects as they only occurred in the mental rotation of hands and feet. However, he did not include images of non-body stimuli in his experiments. Similarly, Funk et al. (2005) used pictures of non-body objects (cars) in training trials only. Therefore, we assessed the mental rotation of body and non-body objects using a within-subject design. This not only allowed for the detection of possible motor influences as well as age differences in the processing of body and non-body stimuli, but also served the purpose of examining the novel research method. If this method is suitable for children, the typical linear relation between RT and angular disparity should occur in children as well as in adults, at least as far as non-body stimuli are concerned. For body stimuli, we expected the typical RT pattern to be affected by motor constraints (motor effect).

As we obtained such a linear RT trend but no motor effect in Experiment 1, a second experiment was run, in which we tried to provoke a motor effect and to compare it across different age groups. Furthermore, the method used in the first experiment was improved in several respects. As a result, the anticipated motor effect appeared in all age groups, although it was found to be the least pronounced in the youngest age group.

Experiment 1

In the first experiment, we compared the mental rotation of body stimuli (pictures of hands) with the mental rotation of non-body stimuli (pictures of cars) in kindergartners and adults.

Our first objective was a replication of the motor effect in the mental rotation of body parts based on biomechanical constraints of the wrist in the palms-down position (Parsons, 1994). While an inwards rotation is restrained and uncomfortable, an outwards rotation is less restrained and more comfortable (cf., Putz & Pabst, 1993). Accordingly, it was expected that the influence of these constraints on imagery (motor effect) would reveal itself in different RT curves for inwards and outwards rotations in the mental rotation of hands. A corresponding effect was, of course, not expected for the mental rotation of cars. There were two specific indicators for the presence of a motor effect that will be considered in turn.

The first indicator would be a three-way interaction effect of object, angle of rotation, and orientation (left- vs. right-oriented) on RT. Motor constraints are different for the (clockwise or counter-clockwise) rotation of left and right hands, while there is no such asymmetry for non-body stimuli such as cars (see above). Therefore, an interaction of angle of rotation and orientation would be expected for hands but not for cars.

The second indicator would be an interaction effect of object (hand vs. car) and angle of rotation on RT, provided RT are averaged over homologous hand rotations (e.g., left hand 90° counter-clockwise and right hand 90° clockwise). The reason is that the displayed hand postures and required movements differ in comfort and awkwardness while the influence of biomechanical constraints is equivalent for homologous movement of the left and right hand. Again, no such interaction should occur with the mental rotation of cars.

Our second objective in Experiment 1 was to evaluate the claim that the link between sensorimotor and imagery processes becomes weaker in the course of development. Evidence for such a developmental trend may be obtained qualitatively or quantitatively, that is, a motor effect could either be present in younger but not in older age groups (cf. Frick et al, 2009) or become less pronounced with development (cf. Funk et al., 2005).

Furthermore, the results of the experiment should give information on the general validity of our mental rotation paradigm. If participants use mental rotation to solve the tasks, their RT should increase linearly with the presumed angle of rotation, at least as far as non-body stimuli are concerned. Because it seemed possible that using the hands as effectors for the key-press response may affect the response strategy (but see Parsons, 1994), participants were asked to respond by pressing foot pedals, that is, by using effectors not related to the stimulus material.

Method

Participants. Twelve boys (mean age: 5 years 9 months, *SD* = 7 months) and 12 girls (mean age: 5 years 10 months, *SD* = 6 months) were accepted for the analysis. Their age ranged from 5 years and 0 months to 6 years and 11 months. They were recruited from three kindergartens in Greifswald, Germany. All children participated on a voluntary basis and with the consent of their parents. They were rewarded for their participation with a certificate. Initially 28 children participated, but 4 children had to be replaced because they felt too weak to operate the switches or were unable to stay focused on the task.

Twenty-four university students (12 male, 12 female) constituted our adult group. They volunteered for the experiment or participated in the course of their studies. Their age ranged from 20 to 34 years (mean age: 26 years, *SD* = 5 years). One student had to be replaced because he lacked sufficient skill in the German language.

None of the participants was aware of the purpose of the experiment nor had anyone of them partaken in any similar study before.

Materials. The stimulus material consisted of a digital photograph of a 7-year-old boy's hand and hand-painted pictures of child-oriented objects (clown, man with or without neck tie, teddy bear, bear, and car). The drawings were digitalized with a scanner. All the pictures were modified with Adobe Photoshop to eliminate background contexts, shadows, or irregularities. Furthermore, they were scaled to the same format (2000x2000 pixels, JPEG). Laterally reversed versions (mirror images) of each picture were created and rotated into eight different angles (0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°). In the following, the image and its mirror image will be referred to as pictures in different orientations; the right-oriented picture meaning, for example, the right hand or the car facing to the right.

Stimuli were presented on a 15.4” laptop computer monitor like in Figure 1: a big picture (380x380 pixels) in the middle and two small comparison pictures (160x160 pixels) in the lower left and lower right on a black background (800x600 pixels). The software Presentation from Neurobehavioral Systems was used for stimulus presentation and data acquisition. Responses were given via two F-Pro pedals connected via USB.

Insert Figure 1 about here

Procedure. Each child was tested individually in a separate room of the kindergarten; adults were tested in a university laboratory. The participants were seated in front of the monitor. The height of the chair was arranged for each participant in such a way that the foot pedals could be reached comfortably. Participants were given the opportunity to try out the pedals. Then they were instructed to press the left/right pedal whenever the picture in the lower left/right was identical to the big one in the middle. If a correct answer was given, the color of the background changed from black to green and a flourish of trumpets rang out, otherwise the background color changed from black to red and a slightly annoying buzzing sound was presented.

The experiment was divided into a training phase and an experimental phase. Training consisted of 32 trials. In the first eight trials different motifs were used for the left and right comparison picture, and the big picture was presented in an upright position. On the ninth and tenth trial, mirror-inverted images of the same motifs were presented as comparison pictures. From the eleventh trial onwards the big image in the middle was rotated.

The experimental trials were allocated in two blocks. They consisted of 32 trials each. One block was composed of pictures of cars. The comparison picture on the lower right was always the car with its front pointing to the right, and the comparison picture on the lower left was its mirror-image. The central picture was presented at all eight angles of rotation and in both orientations (left and right) twice (see above). The order of presentation was assigned at random. The other block was alike, except that pictures of hands were used instead of car pictures. The comparison picture in the lower right was that of a right hand, and on the lower left a left hand was depicted. Half of the participants were tested with the cars first, the other half with the hands first. In total, participants completed 64 experimental trials involving two object types displayed in two orientations and at eight angles of rotation; each combination of object, orientation, and angle was presented twice.

Participants could not see their hands during the experiment as they were instructed to place their hands palm down in a container covered with a curtain. They were asked not to move their hands during the experiment. Testing was always carried out by the same male experimenter.

Results

Error scores. While the children committed 15.17 out of 64 possible errors on average (max = 37, *SD* = 13.75), the mean number of errors was 1.29 errors for the adults (max = 6, *SD* = 1.63). This corresponded to an error rate of 2.0% for the adults and 23.7% for the children. Strikingly, boys committed 23.74 errors on average (max = 37, *SD* = 11.73, error rate = 73.1%), while girls committed 6.58 errors on average (max = 35, *SD* = 9.85, error rate = 10.3%), $t(22) = 3.882$, $p < .01$, $d = 1.59$. No further analyses of the error scores were conducted because of the insufficient data level. The high error rate in boys was unprecedented and had therefore not been considered in the design.

Reaction times. The obtained RT were averaged over each pair of trials (per combination of object, orientation, and angle of rotation) and submitted to a 2 (Object: car vs.

hand) x 2 (Orientation: left vs. right) x 8 (Angle of Rotation) x 2 (Sex) x 2 (Age) ANOVA with repeated measures on the first three variables. All RT data were included regardless of the correctness of the respective answer (see below).

There were significant main effects for age, $F(1, 44) = 52.94$, $p < .001$, $\eta^2 = .54$, object, $F(1, 44) = 11.728$, $p < .01$, $\eta^2 = .21$, orientation, $F(1, 44) = 4.98$, $p < .05$, $\eta^2 = .10$, and angle of rotation, $F(7, 308) = 12.79$, $p < .001$, $\eta^2 = .23$. The adults ($M = 1129$ ms, $SD = 254$) were, as a group, faster than the children ($M = 3922$ ms, $SD = 1874$). Participants were generally faster processing the images of cars ($M = 2144$ ms, $SD = 1500$) than the images of hands ($M = 2907$ ms, $SD = 2697$). They responded slightly faster when confronted with right-oriented stimuli ($M = 2458$ ms, $SD = 1881$) than with left-oriented stimuli ($M = 2593$ ms, $SD = 2010$). The angle of rotation effect was more complex and put to further analysis as explained below.

A set of interactions involving the variable age was found: An interaction with the variable object reflected that the children were especially slow when dealing with the images of hands, $F(1, 44) = 6.64$, $p < .05$, $\eta^2 = .13$, while a significant interaction with the variable orientation, $F(1, 44) = 5.828$, $p < .05$, $\eta^2 = .12$, was due to the fact that children responded faster to right-oriented stimuli while adults were slightly faster with left-oriented stimuli.

There was no significant interaction between sex and age, $F(1, 44) = 1.412$, $p = .24$, $\eta^2 = .03$, although girls ($M = 4352$ ms, $SD = 2248$) were slightly slower than boys ($M = 3492$ ms, $SD = 1373$), but there was a significant three-way interaction of age, object, and sex, $F(1, 44) = 5.494$, $p < .05$, $\eta^2 = .11$. To disentangle this interaction, two additional 2 (Object) x 2 (Sex) ANOVAs with repeated measures on the first variable were conducted on children's mean reaction times for the two age groups separately. While there was no significant interaction of object and sex in the adult sample, $F(1, 22) = 3.42$, $p = .08$, $\eta^2 = .13$, girls exhibited a stronger object effect than boys and were particularly slow with pictures of hands, $F(1, 22) = 4.57$, $p = .044$, $\eta^2 = .17$.

Regarding a possible motor effect, there were no significant interactions between object and angle, $F(7, 308) = 1.065$, $p = .39$, $\eta^2 = .02$, object and orientation, $F < 1$, or between object, orientation, and angle of rotation, $F < 1$. Even when data were collapsed over homologous rotations of the left and right hand, there was no significant interaction between object and angle of rotation, $F(7, 308) = 1.07$, $p = .38$, $\eta^2 = .02$.

Further analysis of the variable angle of rotation. Because of a significant interaction between angle of rotation and age, $F(7, 308) = 3.87$, $p < .001$, $\eta^2 = .08$, the data of the two age groups were analyzed separately for polynomial trends of the reaction time curves as a function of rotation angle. For this purpose, we merged the nine different rotations into five (0°, 45°, 90°, 135°, and 180°), combining those with the same angle of rotation in terms of the shortest path. Two 5 (Angle of Rotation) x 2 (Sex) ANOVAs with repeated measures on the first variable were computed. The two resulting curves can be seen in Figure 2. For the children, there was a significant linear trend only, $F(1, 22) = 40.46$, $p < .001$, $\eta^2 = .65$. For the adults, there was not only a significant linear trend, $F(1, 22) = 192.79$, $p < .001$, $\eta^2 = .90$, but also a significant quadratic trend, $F(1, 22) = 28.66$, $p < .001$, $\eta^2 = .57$.

To estimate the speed of the presumed mental rotation, we took the reciprocal value of the slope of each straight line obtained by linear regression. The derived velocity for the children was 113°/s ($B = 8.86$ ms, $r^2 = .96$) and for the adults 288°/s ($B = 3.48$ ms, $r^2 = .92$).

Inclusion of the error score (median split: high vs. low error rate) as a between-subject variable in the analysis of the RT did not yield any significant effects of the error score (all $p > .20$).

Insert Figure 2 about here

Discussion

The results showed that the participants were the slower to respond the greater the rotation of the central image. In other words, the reaction time rose monotonously with the angle of rotation (along the shortest path). There was, however, not a strictly linear function in the adults. The mental rotation of adult participants seemed to become slower with increasing angle (see Figure 2). As expected, the measured rotation speed of 113°/s for the 5- to 6-year-old children was located between the 67°/s for the 5-year-olds and the 167°/s for the 8-year-olds in Marmor's (1975) study. For the rotation speed of the adults of 288°/s, there were no reference values available for similar 2D mental rotation tasks. Compared with about 60°/s in the 3D task from Shepard & Metzler (1971), the participants in the present experiment were faster, as would be expected for a simpler task (Bauer & Jolicoeur, 1996; Shepard & Metzler, 1988). Therefore it appears justified to assume that our participants also used mental rotation to solve the present tasks.

Yet, there was no motor effect on imagery. Participants responded more slowly to hands than to cars; and this effect was especially distinct in children. The reaction time difference concerning hands and cars can, however, easily be explained by attributes of the stimulus material other than the body versus non-body distinction. For example, figural complexity was not controlled for, and it is conceivable that drawings of cars are encoded faster than realistic pictures of hands.

In any case, in order to infer a motor effect on the mental rotation of hands, more complex reaction time patterns are needed. In the present experiment no such pattern was found.

One possible reason why no motor effect was found could be that it was too weak to be discernible. The constrained inwards rotation of the hand in the palms-down posture can be quite easily compensated for by recruiting more mechanical degrees of freedom, especially in the shoulder, while one's hand remains in view. As a consequence, the motor effect on mental imagery might have been too subtle in the present experiment to be demonstrable.

Noticeable was the high error rate of the boys. It appears to run counter to the well-accepted fact of a male superiority in spatial skills, even in childhood (for an overview, see Voyer, Voyer, & Bryden, 1995). As there was no significant age by sex interaction concerning reaction times, indicating that boys were not generally faster in solving the task than girls, a speed-accuracy trade-off seems implausible. However, girls were particularly slow with pictures of hands (significant interaction between age, sex, and object). This might indicate a more cautious approach in girls with more difficult tasks.

Clearly, the results of Experiment 1 demanded further research. As the research method by and large proved suitable for investigating mental rotation in both age groups, we decided to retain it but also to improve it in certain respects.

For one thing, the absence of a motor effect on the mental rotation of hands needed clarification. Although the particular effect we were looking for had not been observed in children yet, it should have appeared at least in adults (Parsons, 1987, 1994). Moreover, an appraisal of the issue of developmental changes in the strength or quality of motor influences on imagery is impossible without the manifestation of a motor-related effect in the first place.

For another thing, the direction of the sex difference in kindergartners was contrary to the established finding of a male superiority in mental rotation tasks and therefore had to be replicated. Therefore the following experiment was designed to allow for a more detailed analysis of the error scores.

On the whole, error rates were higher than expected from the results of previous studies (Marmor, 1975; Funk et al., 2005). The reason for this might be that, in these previous studies, a far more extensive training was conducted and more participants were excluded before the test. Because of the high error rate observed in Experiment 1, all participants were included in the analysis of the RT (cf. Kosslyn, Digirolamo, Thompson, & Alpert, 1998). This somewhat dissatisfying approach was rectified in Experiment 2.

Experiment 2

The first aim of Experiment 2 was to provoke a motor effect as observed by Parsons (1987, 1994) in his paradigmatic experiments. Therefore the pictures displayed in the experimental trials showed hands in a palms-up (palmar) rather than a palms- down (dorsal) position. As the reader can verify by himself or herself it is not only less awkward to rotate one's hands inwards from a palms-up position than from a palms-down position but, in contrast to a palms-down position, it is also hardly possible to rotate one's hands outwards (for more than a few degrees) from a palms-up position. Attempts to utilize additional biomechanical degrees of freedom (in the shoulder joint) tend to move the hands out of the visual field. To further increase the likelihood of a motor effect, the possible influence of the mental rotation of pictures of non-body stimuli on the mental rotation of pictures of body stimuli was eliminated by presenting pictures of hands throughout the training and experimental trials.

To test whether the effector system influences the motor effect, different response modalities (hands vs. feet) were implemented. This was done to assess the possibility that the absence of a motor effect in Experiment 1 was due to the fact that feet served as input effectors, even though results obtained by Parsons (1994) cast doubt on this hypothesis.

Moreover, the number of angles of rotation was reduced from eight to four in favor of a higher iteration rate of each stimulus. This had the additional benefit of allowing for a more detailed error analysis matching the analysis of the RT and making it better comparable to other research.

To shed more light on the unusual sex difference observed in Experiment 1, an additional age group (7-year-old children) was included in the design of Experiment 2.

In light of the high error rates observed in Experiment 1, only participants who performed above chance were included for RT analyses in the present experiment. Children who performed below chance were replaced.

Method

Participants. Ninety-one children participated in the experiment. Forty-three kindergartners (20 boys, mean age: 6 years 0 months, *SD* = 6 months, and 23 girls, mean age: 6 years 0 months, *SD* = 5 months) were recruited from kindergartens in Greifswald, Germany. Forty-eight first-graders (22 boys, mean age: 7 years 1 month, *SD* = 3 months, and 26 girls, mean age: 7 years 2 months, *SD* = 4 months) were recruited from primary schools in Greifswald, Germany. All children participated on a voluntary basis and with the consent of their parents. They were rewarded for their participation with a certificate.

Thirteen additional children were examined but not included in the final sample: Four kindergartners were excluded, because they received the wrong training; one kindergartner discontinued the experiment complaining of aches; two failed to watch the screen during the experiment; two data sets were lost due to an equipment failure; two first-graders were excluded because it turned out that they had already participated in Experiment 1; and another two were excluded because they talked constantly during the experimental trials.

Forty university students (20 male, 20 female, mean age: 23 years, *SD* = 2 years) constituted the adult group. They volunteered for the experiment or participated in the course of their studies.

None of the participants was aware of the purpose of the experiment or had partaken in similar studies.

Materials. The stimulus material was similar to that used in Experiment 1. The pictures of non-body stimuli were discarded or, for the training, replaced by pictures of the same 7-year-old boy's hand viewed from palmar (palms up) and his pointing hand viewed from dorsal (palms averted). There were four different rotation angles (0°, 90°, 180°, and 270°). In addition to the foot pedals two F-Pro hand switches were employed.

Procedure. The procedure was similar to that in Experiment 1 except for the minor changes listed below.

The total number of trials was reduced to two blocks of 32 trials, where the first block was training only. For adults, it consisted of pictures of the hand from the dorsal view. All four rotation angles and their corresponding mirror images were shown four times in random order. The second block was identical except that the hand was shown from a palmar view.

As a consequence of a pilot study which showed that younger children had problems to understand what we wanted them to do, the children received a different training than the adults. We modified the training in such a way that it more closely resembled that of Experiment 1 and was less dependent on verbal instructions. Therefore, the first ten trials were replaced by special trials where the comparison pictures were clearly discriminable: They always showed different motifs (the hand from the dorsal view and the pointing hand). All participants were presented with the same number of trials in the training.

Half of the participants answered per foot using the pedal, the other half answered per hand switch. This difference constituted the between-subject variable response. All participants were tested by the same female experimenter.

Results

Error scores. As the adults rarely made any errors at all, error rates were only analyzed for the children. A 2 (Orientation) x 4 (Angle of Rotation) x 2 (Sex) x 2 (Age) x 2 (Response) ANOVA with repeated measures on the first two variables was conducted. There was a significant effect regarding the variable angle of rotation, $F(3, 249) = 9.74$, $p < .001$, $\eta^2 = .11$, indicating that the children erred most often with the angle of 180° ($M = 1.93$ (out of 8), $SD = 2.11$) and least often with the angle of 0° ($M = 0.93$, $SD = 1.62$). The angles of 90° and 270° resulted in an average error score of $M = 1.44$, $SD = 1.78$, and $M = 1.52$, $SD = 1.78$, respectively. There was also a significant effect of response, $F(1, 83) = 7.015$, $p < .01$, $\eta^2 = .08$: More errors occurred with the hand switch ($M = 7.26$ (out of 32), $SD = 6.34$, error rate = 22.7%) than with the foot pedal ($M = 4.36$, $SD = 5.56$, error rate = 17.4%). There was also a significant age effect, $F(1, 83) = 10.20$, $p < .05$, $\eta^2 = .11$, as the kindergartners made more errors ($M = 7.6$, $SD = 6.71$, error rate = 23.8%) than the first-graders ($M = 4.23$, $SD = 5.08$, error rate = 13.2%).

There was no significant main effect for sex, $F(1, 83) = 1.37$, $p = .25$, $\eta^2 = .02$, but there was a significant interaction of sex with age, $F(1, 83) = 7.65$, $p < .01$, $\eta^2 = .09$. Planned *t*-tests revealed, that while the female kindergartners made less errors ($M = 5.61$, $SD = 6.18$, error rate = 17.5%) than the male kindergartners ($M = 9.9$, $SD = 6.69$, error rate = 31%), $t(41) = 2.185$, $p < .05$, $d = 0.67$, female first-graders tended to make more errors than male first-graders ($M = 5.15$, $SD = 6$, error rate = 16.1% for girls, and $M = 3.14$, $SD = 3.56$, error rate = 9.8% for boys), but the latter difference was not statistically reliable, $t(46) = -1.383$, $p > .10$, $d = 0.41$.

There was no significant interaction between orientation and angle of rotation, $F < 1$, but between orientation, angle of rotation, and age, $F(3, 249) = 4.57$, $p < .01$, $\eta^2 = .05$. The error patterns of the kindergartners and first-graders resembled those for the reaction times (see below).

Reaction times. Mean reaction times were submitted to a 2 (Orientation) x 4 (Angle of Rotation) x 2 (Sex) x 3 (Age) x 2 (Response) ANOVA with repeated measures on the first two variables. Only the reaction times of those participants were included in the analysis whose number of correct responses was above chance (22 or more out of 32 trials, $p < .05$) according to a binomial distribution (with $p = .50$, for each trial). According to this criterion, 17 kindergartners (12 boys and 5 girls) and 8 first-graders (1 boy and 7 girls) had to be excluded. (Note, however, that the major RT results described below remained the same when all participants were included in a supplementary ANOVA. In particular, results concerning the motor effect were not affected by the inclusion or exclusion of below-chance performers.)

As in Experiment 1, there were significant main effects of angle of rotation, $F(3, 282) = 23.34$, $p < .001$, $\eta^2 = .20$, and age, $F(2, 94) = 48.20$, $p < .001$, $\eta^2 = .51$, as well as an interaction of angle of rotation and age, $F(6, 282) = 2.94$, $p < .01$, $\eta^2 = .06$. Post-hoc *t*-tests using Bonferroni's Adjusted Criterion ($\alpha = .0125$, for four tests) indicated no difference between the children groups (kindergartners: $M = 3690$ ms, $SD = 1394$, first-graders: $M = 3732$ ms, $SD = 1457$), $t(64) = -0.12$, $p > .90$, $d = 0.03$. The adult group ($M = 1388$ ms, $SD = 343$) was faster than both children groups combined, $t(104) = -3.21$, $p < .001$, $d = 2.20$.

The reaction times for the different angles of rotation resembled those of Experiment 1 (see Figure 3). There were significant polynomial trends reflecting the typical RT pattern of mental rotation: For the kindergartners, there was a significant linear, $F(1, 24) = 13.24$, $p = .001$, $\eta^2 = .36$, and a significant quadratic trend, $F(1, 24) = 7.65$, $p = .011$, $\eta^2 = .24$; the same trends were significant for the first-graders, $F(1, 38) = 21.38$, $p < .001$, $\eta^2 = .36$ (linear), $F(1, 38) = 11.72$, $p = .001$, $\eta^2 = .24$ (quadratic); and for the adults, $F(1, 38) = 51.27$, $p < .001$, $\eta^2 = .57$ (linear), $F(1, 38) = 58.86$, $p < .001$, $\eta^2 = .61$ (quadratic). The average speed of mental rotation was calculated in the same way as in Experiment 1 and amounted to 111°/s for the kindergartners ($B = 9.3$ ms, $r^2 = .99$ for the corresponding linear regression line), 93°/s for the first-graders ($B = 10.78$ ms, $r^2 = .91$), and 235°/s for the adults ($B = 4.256$ ms, $r^2 = .89$).

There was a significant main effect for orientation, $F(1, 94) = 5.21$, $p < .05$, $\eta^2 = .05$, favoring images of right hands ($M = 2747$ ms, $SD = 1600$) over images of left hands ($M = 2928$ ms, $SD = 1771$). This main effect was qualified by the following interactions.

In contrast to Experiment 1, there was a significant interaction of orientation and angle of rotation indicating a motor effect, $F(3, 282) = 10.21$, $p < .001$, $\eta^2 = .10$. As predicted, the participants were faster to rotate inwards (left hand 90°, right hand 270°) than outwards (left hand 270°, right hand 90°) (see Table 1). An additional three-way interaction of orientation, angle of rotation, and age, $F(6, 282) = 4.197$, $p < .001$, $\eta^2 = .08$, indicated that the pattern of the orientation by angle interaction differed between the age groups.

Planned contrasts comparing reaction times for inward and outward rotations for each age group separately yielded significant differences in kindergartners ($p < .01$), first-graders ($p < .001$), and adults ($p < .01$). As can be seen in Table 1, differences in the kindergartners were proportionally small for the left hand. Two post-hoc *t*-tests, analyzing the kindergartners' reaction times for left and right hands separately, showed that the reaction time difference between inward and outward rotations was significant ($\alpha = .0125$, according to Bonferroni's Adjusted Criterion) for the right hand, $t(25) = 2.578$, $p < .01$, $d = 0.37$, but not for the left hand, $t(25) = -1.23$, $p > .10$, $d = 0.2$.

There were no significant main effects of sex or response on the reaction times and no further interactions concerning these variables, all $F < 1$. Contrary to Experiment 1, kindergarten girls ($M = 3822$ ms, $SD = 1927$) tended to be even slightly faster than kindergarten boys ($M = 3931$ ms, $SD = 2006$) on average.

Insert Figure 3 about here

Discussion

Both, reaction times and error scores increased with angle of rotation (along the shortest path). As in Experiment 1, this indicates that the participants used mental rotation to solve the task. Unsurprisingly, older participants were generally faster and made fewer mistakes than younger ones. The mean rotation speeds were 93°/s, 111°/s, and 235°/s, for kindergartners, first-graders, and adults, respectively. These figures agree well with those obtained in Experiment 1 (113°/s for kindergartners, 288°/s for adults).

More importantly, and in contrast to Experiment 1, the predicted motor effect now appeared: The interaction between angle of rotation and orientation was attributed to the anticipated motor influence on imagery. The observation that it took participants longer to mentally rotate palmar images of hands 90° outwards than 90° inwards may be due to the fact that most of them chose not to rotate along the shortest path but in the most convenient way according to the restrictions of their own body. Yet, it seems that not all participants did it that way – or at least not always – because the more convenient but longer path would be to rotate about 270° inwards (to end 90° outwards) and therefore it should have taken them longer than to rotate about 180°. As can be seen in Table 1, this was clearly not the case. Alternatively, it is also conceivable that participants tended to choose the shortest path when mentally rotating. In this case, the reaction time pattern indicating a motor effect could result from differences regarding the awkwardness and/or movement time required for inward versus outward rotations.

Most interesting, from a developmental perspective, is the observation that the motor effect was not so distinct in the kindergartners. In this age group, the motor effect could only be demonstrated for pictures of the right hand. It is possible that everyday experience in using the dominant (right) hand led to this result as well as to the faster reactions for right than for left hands found in all age groups. In any case, there was no indication of a particular strong link between sensorimotor and imagery processes in kindergartners, rather the contrary appeared to be true.

The only effect of the response device was a main effect on the error rate unrelated to the motor effect.

The sex effect concerning kindergartners' error scores observed in Experiment 1 was replicated in the second experiment. Again, this effect manifested itself only in the error rates but not in the reaction times, confirming that a speed-accuracy trade-off was not involved. The female superiority was restricted to the kindergartners.

General Discussion

While in Experiment 1 no motor effect was discernible, it was clearly established in Experiment 2. In contrast to previous findings, qualitative differences indicated a less robust connection between motor and imagery processes in children than in adults. Furthermore, the unexpected sex difference favoring kindergarten girls found in Experiment 1 was replicated in Experiment 2. In both experiments, we obtained evidence that participants used mental rotation with our task paradigm.

Before discussing the involvement of motor processes in imagery and their role in development, the unexpected sex difference will be considered.

The observed sex difference is remarkable because it only manifested itself in the error scores of the youngest age group and had no clear counterpart in the RT. Male participants typically outperform female participants in spatial tasks, especially in mental rotation, even in childhood (cf. Voyer, Voyer, & Bryden, 1995). Yet, spatial abilities have many facets, and a general superiority of males over the lifespan cannot be taken for granted (for an overview, see Kimura, 1999). In infant studies on perception and cognition, girls sometimes exhibit more advanced capabilities than boys (e.g., Kavŝek, 2003). Yet, on the other hand, in two recently published studies (Mash, Arterberry, & Bornstein, 2008; Moore, & Johnson, 2008), only male infants exhibited looking-time behavior that the authors interpret as an indication for mental rotation.

More relevant in the present context is a sex difference detected by Ingram (1975): Girls about 5 years of age were better able to reproduce hand postures than boys of the same age. Therefore, it might be that the elevated error scores that we observed in boys did not result from a lack in spatial skills, but from difficulties in correctly encoding the stimulus material. This would also explain why no sex differences were found regarding the RT. Probably, boys and girls tended to use similar mental rotation strategies as indicated by similar RT curves, but their representations of the stimuli appeared to be insufficient to reliably distinguish the left hand from the right hand. A modified replication of Experiment 1, focusing on sex differences between the processing of body stimuli and various non-body stimuli and including more detailed error analyses, could lend further support to this interpretation.

Evidence for a motor influence on mental rotation was obtained in Experiment 2 but not in Experiment 1. In hindsight, the absence of a motor effect in Experiment 1 can be attributed to the fact that mental rotation tasks may be solved by applying different strategies, of which only a subset includes the use of motor resources (Kosslyn, Thompson, et al., 2001). Even though Experiment 1 may not have been ideally suited for detecting a motor effect, there is still the result of Experiment 2 that a motor effect was only verifiable for the right hand in kindergartners. Taken together, the present results indicate that motor influences on imagery may not be obligatory, even with the mental rotation of body parts. While our findings are consistent with those obtained by Kosslyn, Thompsons, et al. (2001), they conflict with both Parsons' view (1987, 1994), who considers the mental transformation of body parts as a mental recapitulation of movement, and Wohlschläger's (2001) construal of mental rotation as covert action. Our data are more consistent with the view that imagery and motor planning may share common resources (cf., Kosslyn, Thompson et al., 2001; Amorim et al., 2006; Sack et al., 2007). It should be noted, however, that there seem to be different cues triggering a motor assisted processing of mental rotation and therefore a motor effect may not always be discernable.

Our most recent data (Krüger & Krist, 2009) suggest that the motor effect is most robust in adults and rather variable in children. This is compatible with the present finding that a motor effect only showed up in the right hand in kindergartners. A post-hoc explanation for this particular finding could be that an integration of motor processes and imagery is not required for mental rotation to emerge in early childhood and that it may be even easier for young children to mentally transform simple non-body stimuli than hands or feet. In other words, embodiment may not be the ontogenetic origin of imagery processes but rather the result of an integrative developmental process depending both on increasing general cognitive capabilities (executive functions in particular; see Davidson, Amso, Anderson, & Diamond, 2006, for a recent review) as well as the level of expertise attained in movement planning. While the connection between imagery and motor processes may still be weak in kindergartners, first-graders may have already accomplished the integration of motor processes and imagery for the rotation of pictures of hands. This view fits well with recent theories of core knowledge (Spelke, 1994, 2000; Spelke & Kinzler, 2007; cf. Carey, 2009), in which major changes and reorganizations occurring in children's cognitive development are conceived as involving the integration of domain-specific core knowledge into more flexible and general knowledge systems.

To lend further support to the hypothesis of a progressive integration of motor constraints into visual imagery processes, more research is needed. If true, children younger than five years should not exhibit any sensitivity to motor constraints on imagery. It is regrettable that, as yet, younger children cannot be tested with standard mental rotation paradigms. And, of course, left-handedness has to be considered here. In a German population the incidence of left-handers should only be up to 9% (Reiß & Reiß, 1997). Therefore we assume that participants in Experiment 2 were largely right handed; nonetheless, a comparison of samples of left- and right-handed children in future research may reveal additional information about the emergence of the motor effect, as in left-handed kindergartners the effect should occur in the left hand first.

Revisiting Piaget's theory (Piaget, 1954; Piaget & Inhelder, 1967) and related theories of embodied cognition (e.g., Gibbs, 2006, 2008), the present data do not confirm the assumption that higher-level cognitive processes emerge from the motor system. The qualitative age differences in RT performance found in Experiment 2 suggest a weaker, rather than a stronger, link between the motor system and imagery in kindergartners than in older children and adults. This finding appears to be in marked contrast to the age trends observed by Frick et al. (2009) and Funk et al. (2005). However, the apparent contradiction may be related to differences in how motor influences on imagery are conceptualized and measured. Whereas we were interested in the question whether children would incorporate motor constraints when mentally rotating pictures of hands, the previous developmental studies analyzed interactions between children's hand posture and their ability to mentally rotate hands shown in the same or an inverted posture (Funk et al., 2005) or assessed children's susceptibility to motor interference effects in a mental rotation task (Frick et al., 2009). A plausible alternative explanation for the observation that (negative) motor interference effects become weaker with age is offered by Frick et al. (2009) themselves, namely that inhibitory abilities increase with age (Davidson et al., 2006). Further research is needed, however, to assess the validity of this account and to clarify the age-related motor compatibility effects found in both previous studies as well as in related developmental research (Frick, Daum, Wilson, & Wilkening, in press; Rieser, Garing, & Young, 1994) and to relate them to the emerging sensitivity to motor constraints suggested by the present research.

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.

Bauer, B., & Jolicoeur, P. (1996). Stimulus dimensionality effects in mental rotation. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 82-94.

Carey, S. (2009). *The origin of concepts*. Oxford: Oxford University Press.

Daum, M. M., Sommerville, J. A., & Prinz, W. (in press). Becoming a social agent: Developmental foundations of an embodied social psychology. *European Journal of Social Psychology*.

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, *44*, 2037-2078.

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

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.

Frick, A., Daum, M. M., Wilson, M., & Wilkening, F. (in press). Effects of action on children’s and adults’ mental imagery. *Journal of Experimental Child Psychology*.

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.

Gallese, V., & Lakoff, M. (2005). The brain’s concept: The role of the sensory-motor system in conceptual knowledge. *Cognitive Neuropsychology, 22*, 455-479.

Gibbs, R. W. (2006). *Embodiment and cognitive science*. New York: Cambridge University Press.

Gibbs, R. W. (2008). Images schemas in conceptual development: What happened to the body? *Philosophical Psychology*, *21*, 231-239.

Ingram, D. (1975). Motor asymmetries in young children. *Neuropsychologia, 13*, 95-102.

Kavŝek, M. J. (2003). Infants' perception of directional alignment of texture elements on a spherical surface. *Infant and Child Development, 12*, 279-292.

Kimura, D. (1999). *Sex and cognition*. Cambridge, MA: MIT Press.

Kosslyn, S. M. (1995). Mental Imagery. In S. M. Kosslyn & N. D. Osherson (Eds.), *An invitation to cognitive science: Visual cognition* (Vol. 2, pp. 267-296). Cambridge, MA: MIT Press.

Kosslyn, S. M., Digirolamo, G. J., Thompson, & Alpert, N. M. (1998). Mental rotation of objects versus hands: Neural mechanisms revealed by positron emission tomography. *Psychophysiology, 35*, 151-161.

Kosslyn, S. M., Ganis, G., & Thompson, W. L. (2001). Neural foundations of imagery. *Nature Reviews Neuroscience, 2*, 635-642.

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.

Krüger, M., & Krist, H. (2009). 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*(4), 198-206.

Marmor, G. S. (1975). Development of kinetic images: When does the child first represent movement in mental images? *Cognitive Psychology, 7*, 548-559.

Mash, C., Arterberry, M. E., & Bornstein, M. H. (2008). Mechanisms of visual object recognition in infancy: Five-month-olds generalize beyond the interpolation of familiar views. *Infancy, 12*(1), 31-43.

Moore, D. S., & Johnson, S. P. (2008). Mental rotation in human infants. A sex difference. *Psychological Science, 19*(11), 1063-1066.

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*, *20*, 709-730.

Piaget, J. (1954). *Construction of reality in the child* (M. Cook, Trans.). New York: Basic Books. (Original work published 1937)

Piaget, J., & Inhelder, B. (1967). The child's conception of space (F. J. Langdon & J. L. Lunzer, Trans.). New York: W. W. Norton & Company. (Original work published 1948)

Putz, R., & Pabst, R. (Eds.). (1993). *Atlas der Anatomie des Menschen* (20^{th} ed., Vol. 1, Kopf, Hals, obere Extremität) [Anatomical atlas of man]. München: Urban & Schwarzenberg.

Reiß, M., & Reiß, G. (1997). Lateral preferences in a German population. *Perceptual and Motor Skills, 85*, 569-574.

Rieser, J. J., Garing, E. A., & Young, M. F. (1994). Imagery, action, and young children's spatial orientation: It's not being there that counts, it's what one has in mind. *Child Development*, *65*, 1262-1278.

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

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

Shepard, S., & Metzler, D. (1988). Mental rotation: Effects of dimensionality of objects and type of task. *Journal of Experimental Psychology: Human Perception and Performance, 14*, 3-11.

Spelke, E. S. (1994). Initial knowledge: Six suggestions. *Cognition*, *50*, 431-445.

Spelke, E. S. (2000). Core knowledge. *American Psychologist, 55*, 1233-1243.

Spelke, E. S., & Kinzler, K. D. (2007). Core Knowledge. *Developmental Science, 10*, 89-96.

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin, 117*, 250-270.

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

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin and Review, 9*(4), 625-636.

Wohlschläger, A., & Wohlschläger, A. (1998). Mental and manual rotation. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 397-412.

Wohlschläger, A. (2001). Mental object rotation and the planning of hand movements. *Perception and Psychophysics, 63*(4), 709-718.

Table 1
Mean Reaction Times (and Standard Deviations) by Angle of Rotation, Orientation, and Age Group (Experiment 2).

		Left hand		Right hand	
		M (ms)	*SD*	*M* (ms)	*SD*
Kindergartners	0°	2982	1306	2750	898
	90°	3714	2498	3744	1748
	180°	4768	2841	4214	1819
	270°	4165	2071	3181	1308
First-graders	0°	2640	688	2557	743
	90°	3334	1487	4079	1945
	180°	4225	1721	4852	4384
	270°	5072	2625	3100	1828
Adults	0°	1080	275	1119	367
	90°	1191	384	1331	404
	180°	1895	627	1939	669
	270°	1440	615	1209	331

Figure Captions

Figure 1. Example of the stimulus configuration in Experiment 1: the right-oriented body stimulus at 90°.

Figure 2. Mean reaction times (and standard errors) as a function of the shortest angle of rotation (Experiment 1).

Figure 3. Mean reaction times (and standard errors) as a function of angle of rotation (Experiment 2).

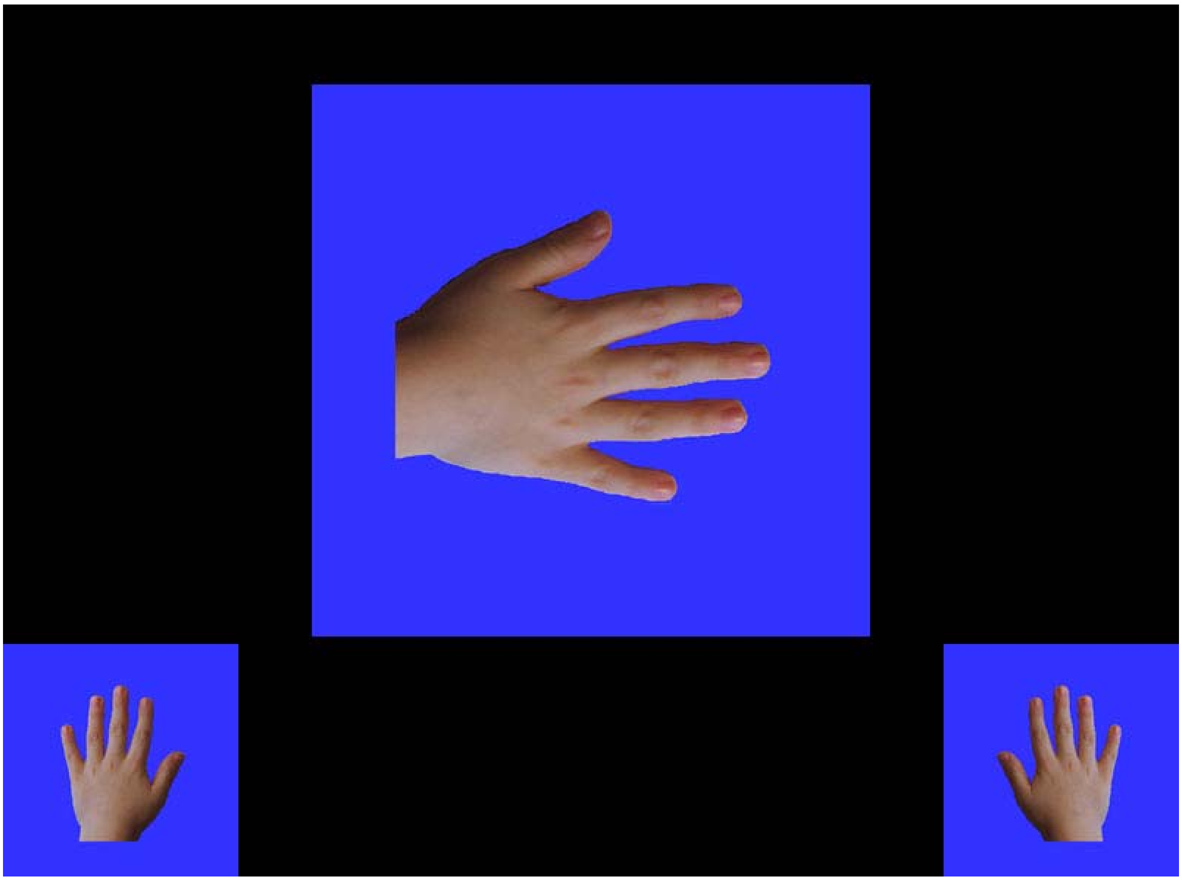
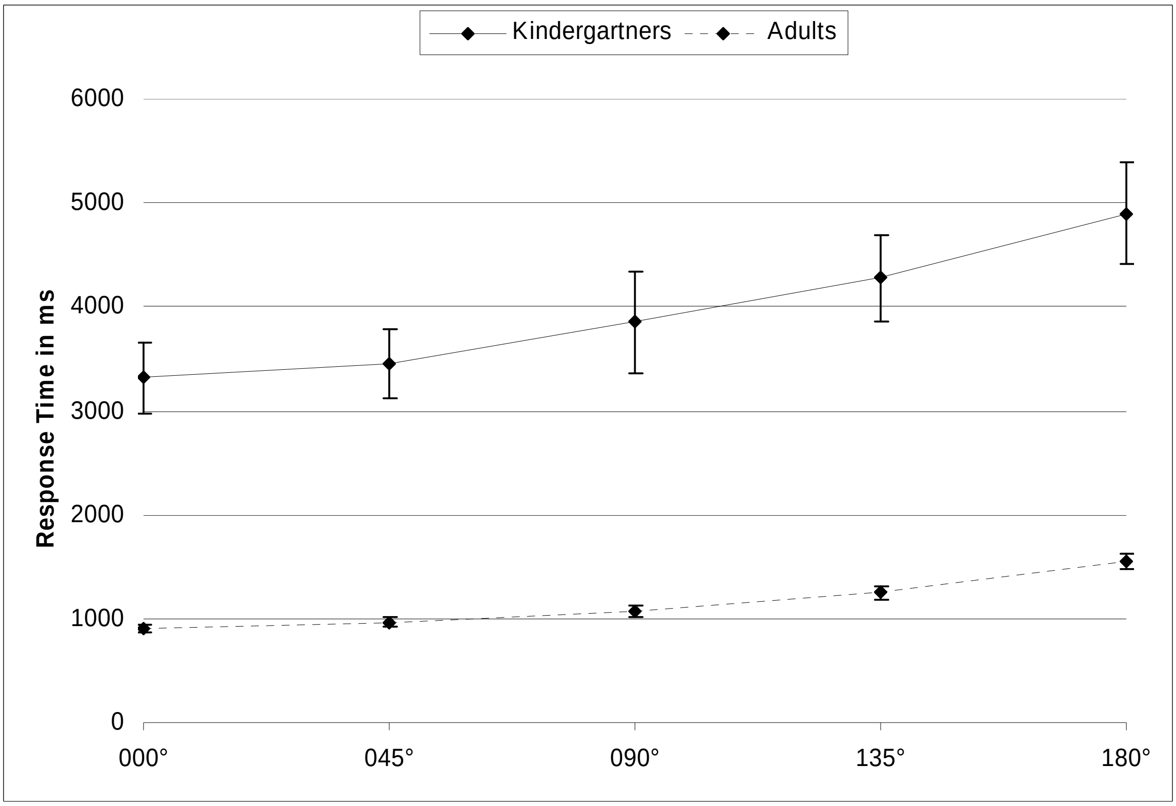


Figure 1



Kindergartners
Adults
6000
5000
4000
3000
2000
1000
0
Response Time in ms
000°
045°
090°
135°
180°

Figure 2

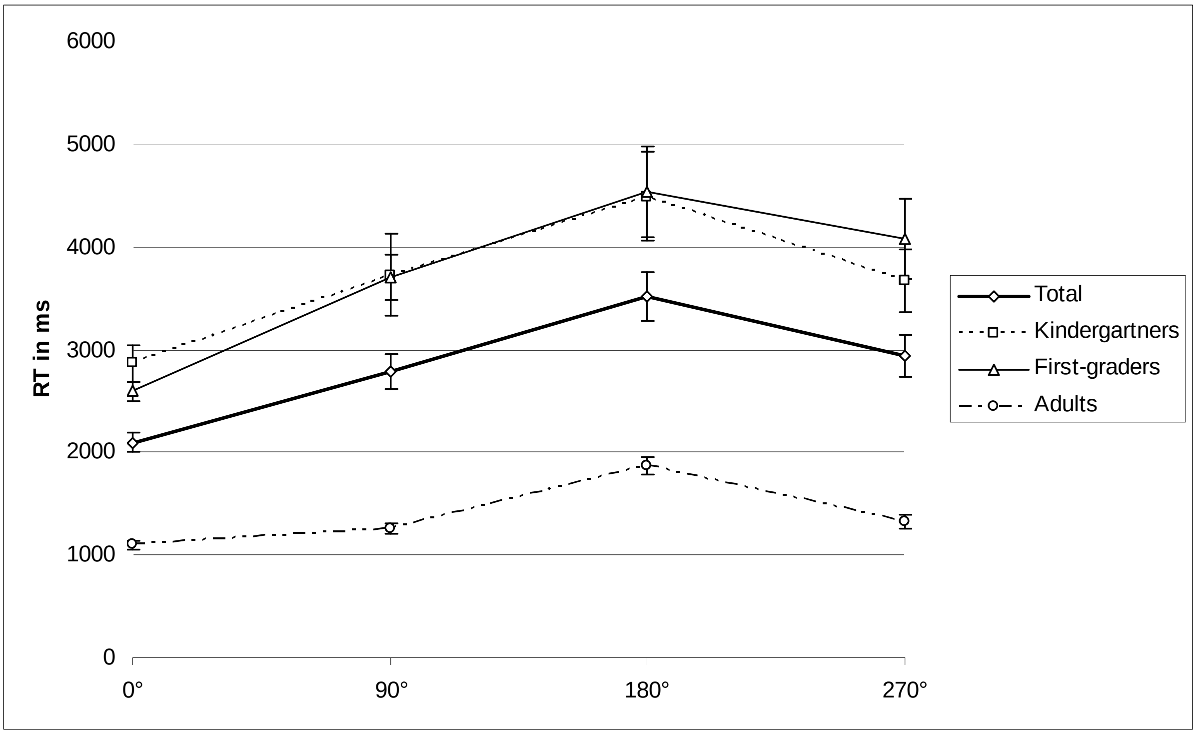

6000
5000
4000
3000
2000
1000
0
RT in ms
0°
90°
180°
270°
Total
Kindergartners
First-graders
Adults

Figure 3