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Motor Processes in Children's Mental Rotation

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Previous studies with adult human participants revealed that motor activities can influence mental rotation of body parts and abstract shapes. In this study, we investigated the influence of a rotational hand movement on mental rotation performance from a developmental perspective. Children at the age of 5, 8, and 11 years and adults performed a mental rotation task while simultaneously rotating their hand (guided by a handle). The direction of the manual rotation was either compatible or incompatible with the direction of the mental rotation. Response times increased with increasing stimulus orientation angles, indicating that participants of all age groups used mental rotation to perform the task. A differential effect of the compatibility of manual rotation and mental rotation was found for 5-year-olds and 8-year-olds, but not for 11-year-olds and adults. The results of this study suggest that the ability to dissociate motor from visual cognitive processes increases with age.

In early research on cognitive development, mental imagery abilities were recognized as a highly important competence (Piaget & Inhelder, 1971b), and several theories emphasized the role of sensory-motor or action-based knowledge (e.g., Bruner, Olver, & Greenfield, 1966; Kosslyn, 1978, 1980; Piaget & Inhelder, 1971a). More recently, research with adult participants and theories on embodied cognition (for an overview see Wilson, 2002) suggests that motor processes are often involved in cognitive processes such as imagery (e.g., Schwartz & Holton, 2000; Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998) or event perception (e.g., Prinz,

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1990, 1997). However, relatively few studies have been carried out to investigate how mental imagery abilities develop and how children's imagery abilities are affected by motor activities. Thus, the present experiment was carried out to investigate the influence of motor activity on mental rotation in children and adults.

Kinetic Imagery in Children

Piaget and Inhelder (1971b) proposed a distinction between static and kinetic mental images. They suggested that imagery in the preoperational child remains essentially static, and therefore, children at this age are neither able to represent movements nor anticipate the results of movements or spatial transformations. According to Piaget and Inhelder, it is not until the concrete operational stage, at about 7 to 8 years of age, that the child is able to use kinetic imagery, which is the ability to represent movements of objects in space, manipulate mental images, or anticipate the outcome of perceptual events.

However, Piaget's methods, which largely relied on drawings, search tasks, and verbal reports, have been criticized repeatedly (e.g., Kosslyn, Margolis, Barrett, Goldknopf, & Daly, 1990; Marmor, 1975), mainly because of the potential confound of performance and competence. Seeking more reliable and quantitative measures, other developmental studies on mental imagery adopted a mental rotation task developed by Shepard and his colleagues (Cooper & Shepard, 1973; Shepard & Metzler, 1971). In this nonverbal paradigm, participants are required to discriminate as fast and accurately as possible whether a rotated figure is exactly the same or a mirror image of an original upright figure. The response times typically showed a V-shaped pattern, with the minimum at 0° (i.e., when both figures had the same orientation). Thus, the time adults required for this discrimination increased linearly with the angular difference in rotation. These results indicated that the participants had mentally rotated one form into the same orientation as the other. It has been concluded that mental transformations are subject to the same spatiotemporal constraints as perceived movements in the external world.

Studies on mental rotation in children (Kosslyn et al., 1990; Marmor, 1975) demonstrated that 5-year-olds can use mental rotation (i.e., their response times showed a linear increase with angular disparity of the two stimuli), but they do so at a slower speed (i.e., the younger the children, the longer it took them to mentally rotate the stimuli). In most of the studies mentioned above, children were instructed or trained to apply a mental rotation strategy to solve the task. Further studies (e.g., Marmor, 1977) suggest that 4- and 5-year-olds are in fact able to use and evoke kinetic imagery spontaneously, without specific instruction to do so. Assessing response time patterns and verbal reports, Estes (1998) showed that 6-year-olds were comparable to adults, both in their spontaneous use and subjective awareness of mental rotation.

In short, developmental research on mental rotation has shown that the capability, spontaneous usage, and awareness of a mental rotation strategy can be found in children as young as 4 or 5 years of age, and that the speed of mental rotation increases with age. Still, it remains unclear whether this increase in rotation speed is merely due to an increase in general processing capacities or whether imagery abilities in children differs rather fundamentally from imagery in adults. It is, for example, conceivable that children's imagery involves other processes.

One type of process that is associated with mental rotation in adults involves the motor system—this will be described in further detail in the next section.

Motor Processes and Kinetic Imagery

Some studies on mental rotation found evidence for increased difficulty to mentally rotate pictures of hands showing physically impossible or awkward positions (Cooper & Shepard, 1975; Parsons, 1987, 1994; Sekiyama, 1982). Furthermore, neuroimaging studies showed activation in motor areas during mental rotation of body parts (e.g., Parsons et al., 1995). These findings led to the assumption that mental rotation can engage motor processes (Jolicoeur & Cavanagh, 1992; Kosslyn, 1994). The activation in motor areas is not restricted to the mental rotation of body parts and can also be found when the stimuli are objects such as the cube shaped Shepard-Metzler figures (Cohen et al., 1996; Kosslyn, Thompson, Wraga, & Alpert, 2001).

In addition to neuroimaging data, behavioral experiments directly tested the effects of motor activities on mental imagery performance. Wohlschläger and Wohlschläger (1998) examined the effect of different kinds of hand movements on mental object rotation in a three dimensional virtual space. The authors found that mental rotation of an object performed in the same direction as a simultaneous manual rotation (about the same axis) is performed faster, compared to when the manual and mental rotation are opposite. More particularly, in a follow-up study, Wohlschläger (2001) found that it is the planning of the action and holding a spatial operation in working memory that most likely interferes with mental rotation. Similar to these studies, Wexler and colleagues (1998) reported shorter response times and fewer errors for the rotation of two-dimensional stimuli when a compatible manual rotation was performed, as opposed to an incompatible manual rotation. This resulted in a lateral shift of the V-shaped curve representing response times as they are normally found in mental rotation tasks. In some cases, manual rotation also had the effect that response times for 0°-trials, in which no mental rotation was necessary, were even longer than for 45° rotations. Thus, when the stimulus had to be rotated slightly in the direction of the motor rotation, it seemed to be easier than when the stimulus did not have to be rotated at all.

A more recent study (Sack, Lindner, & Linden, 2007) investigated interference effects of manual and mental rotations using various types of stimuli. Manual rotations generally impaired the mental rotation of cubes, compared to a baseline condition without manual rotation. However, significant effects of compatibility were found for hand stimuli only (i.e., incompatible hand movements disrupted mental rotation of hands), but not for cubes. These results were replicated in several experiments and proved to be independent of task difficulty.

In a similar line of research, Schwartz and Holton (2000) showed that pulling a string from a spool facilitated participants' mental rotation of an object sitting on the spool. However, the exact same pulling movement facilitated or interfered with the exact same imagery transformation, depending on participants' mental model of the spool, that is, whether the pulling of the spool was thought to result in a compatible or incompatible rotation of the spool. The interference thus largely depended on whether and how participants had mentally modeled a functional connection between the action and the imagined movement. Overall, these studies suggest that visual mental activities and motor activities share some of the same underlying processes.

Motor Processes and Kinetic Imagery in Children

Despite compelling evidence showing that motor activity can interfere with mental transformations in a direction specific manner, relatively little is known about this type of motor interference or facilitation in children. An example is the study by Rieser, Garing, and Young (1994), who showed that walking without vision facilitates 3.5-year-olds' ability to imagine a spatial layout from another perspective. Similarly, Black and Schwartz (1996) showed that physically turning a cup facilitated 3- to 12-year-olds' ability to predict the point at which imaginary water inside the cup would start to spill. More recently, Funk, Brugger, and Wilkening (2005) demonstrated that the actual posture of participants' hands—palms up versus palms down—can influence how fast 5- to 6-year-olds and adults distinguish rotated right and left hands in palm or back view. Moreover, the authors found that the effect of posture on mental rotation time was more pronounced in 5- to 6-year-olds than in adults. These results strongly suggest that proprioceptive information interferes with young children's kinetic imagery, even more so than with adults.

Whereas Funk et al.'s (2005) experiment showed the influence of static posture on mental rotation, the aim of the present study was to explore whether or to what extent actively executed hand movements influence children's imagery performance. The present experiment thus pursued the research questions of whether a manual rotation movement interferes with mental object rotation in children, and how these effects develop with age. In order to investigate these questions, a dual task paradigm was employed similar to Wohlschläger and Wohlschläger (1998) and Wexler et al. (1998). The rationale was the following: if mental rotation and motor rotation share some of the same underlying neural processes, then a secondary task in one of them should affect performance in the other. Following this logic, we especially focused on the question of whether or not a secondary *motor* activity interferes with performance in a main *mental* rotation task.

Compared to these former experiments, we made some major modifications: in the present task the manual rotation and pressing the response button were both executed with the same dominant hand in order to make the task easier for the younger children. As a further advancement, and in order to avoid ambiguity about which stimulus would be rotated mentally,

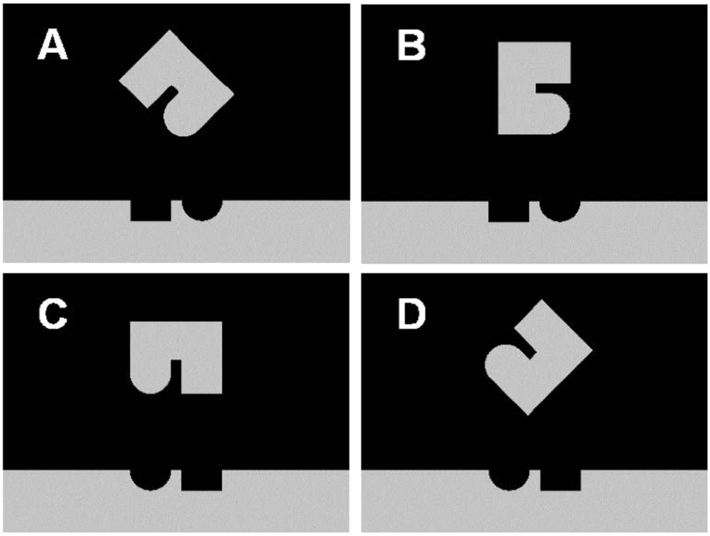

FIGURE 1 Four examples of figure-ground pairs as they appeared on the computer screen. In examples A (+45°) and C (0°), the figure would fit into the ground after an appropriate rotation; in B (−90°) and D (+135°) the figure would not match the holes.

two simple puzzle-like figure-ground stimuli were presented simultaneously (see Figure 1).

The present experiment was carried out with children between the ages of 5 and 11 years. This age range was chosen based on previous findings that 5-year-olds are capable of mental rotation (Estes, 1998; Funk et al., 2005; Kosslyn et al., 1990; Marmor, 1977), but that 10-year-olds' imagery performance still differs from that of adults (Frick, Huber, Reips, & Krist, 2005). Additionally, in respect of Piaget and Inhelder's (1971b) theoretical framework, we could expect a large developmental shift in imagery performance around age 8.

METHOD

Participants

In total, 84 participants were tested. Data of four 5-year-olds were excluded from the analysis due to a lack of attention and compliance with the task. The remaining 80 participants included four age groups, each with 20 participants: 5-year-olds (mean age 5 years; 7 months, range 5;2 to 5;11, male: 11, female: 9), 8-year-olds (mean age 8;6, range 8;0 to 8;11, male: 11, female: 9), 11-year-olds (mean age 11;5, range 11;0 to 11;11, male: 7, female: 13) and adults (mean age 37;4, range 23;10 to 68;4, male: 10, female: 10). Female adults had a mean age of 36;8 (*SD* 13;7) and male adults had a mean age of 38;1 (*SD* 15;7). Children were recruited from different primary schools in the region of Zürich, Switzerland. Informed parental consent was obtained for all children. Participants had normal or corrected-to-normal vision. All participants tested were right handed. To assess the handedness of the 5-year-olds, their parents were consulted; older participants were asked personally.

Apparatus

The experimental apparatus consisted of a laptop computer (Dell Latitude D600, resolution: 1400×1050 pixels, True Colour, with an ATI graphics card and 14-inch TFT display), a rotatable wheel with a handle, and a Cedrus Response Pad (RB 520). Participants were seated at a table on which the laptop was positioned in front of them. The wheel and the response pad were mounted on a T-shaped wooden construction, ensuring a constant distance from the wheel to the response pad (see Figure 2 for a schematic drawing of the apparatus). This T-shaped construction was fixed to the table on the participants' right hand side, so that the arm of the T lay on the table and partly protruded the table top by 19 cm. The wheel was attached to the

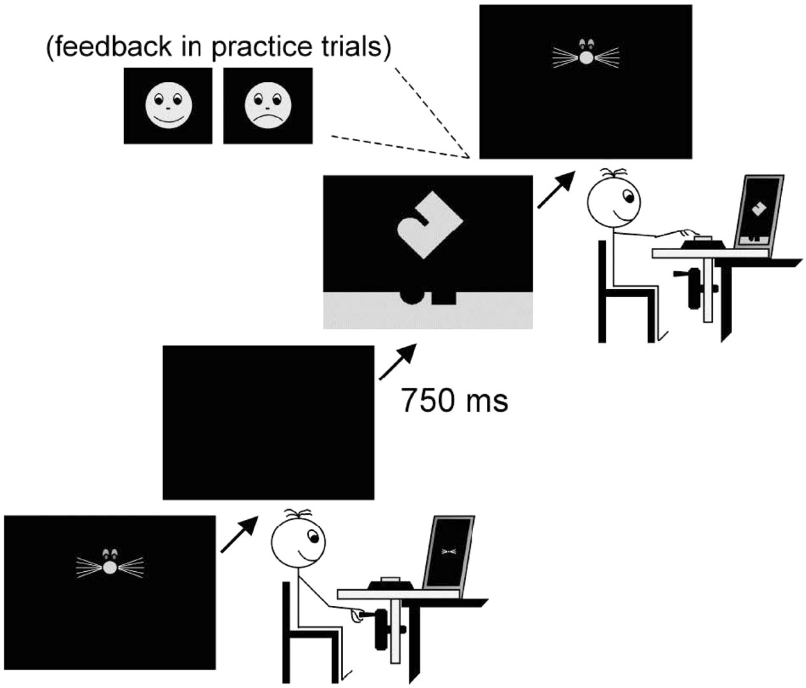

FIGURE 2 Schematic drawing of the sequence of presented stimuli and the concurrent behavioral task within one trial.

stem of the T-shaped construction, 12 cm below the protrusion. The protrusion prevented participants from seeing the wheel and their right hand rotating it. The wheel could be rotated in the participants' frontal plane in either direction. The wheel had a handle, parallel to and 5 cm off the rotation axis, which allowed participants to rotate it without loosening the grip. The response pad was positioned above the wheel, mounted visibly on top of the protrusion. The height of the participant's chair was adjustable, so that each child could comfortably reach the handle of the wheel and from there switch to the response pad on top of the construction, without having to move the upper part of their body.

The response pad was used for measuring reaction times and responses. Two response buttons were enlarged by black or white 4×8 cm cardboard pieces, so that they could be pressed easily and quickly. The distance between the two response buttons was 4.5 cm. The experimenter operated one small button to proceed to the next trial and remained seated to the right of the participant throughout the entire session. From this viewpoint she could see the participant's face, the participant's hand at the wheel, and the computer screen.

Stimuli

The stimuli were presented on the screen of the laptop using the program Superlab Pro (Cedrus Corporation). Two different two-dimensional stimuli were presented simultaneously. In the present experiment it was crucially important to control for the direction in which the stimulus was rotated mentally. Therefore, figure-ground pairs (like a puzzle-game, see Figure 1) were used rather than two similar objects. This paradigm allowed for better control over the direction of mental rotation because it ensured that participants rotated the small figure (in one direction), but not the ground (in the opposite direction).

The larger stimulus, the "ground," was 5 cm high and spanned the whole screen width at the lower margin of the display. In the very middle at the upper rim of this ground there were two holes. One hole had a square shape and one a round shape. The ground was present throughout all trials. The small stimulus, the "figure," was presented centered above these holes in the upper part of the screen. The figure had a size of 6.5 cm $\times$ 7 cm, and on its lower end (in the upright position) one side was square and the other side was round. When moved down on the display, the round and square parts of the small figure would perfectly fit into the round and square holes in the ground. Normal and mirror versions of both figure and ground were presented, which resulted in four figure-ground combinations, two of which matched and two which did not.

The figures were always presented in the same position on the screen but varied in eight different orientations: $0°$, $+45°$, $+90°$, $+135°$, $180°$, $-135°$, $-90°$, $-45°$. In the upright orientation ($0°$) no mental rotation was required to solve the task. A positive angle corresponded to stimuli rotated in a clockwise direction; a negative angle corresponded to stimuli rotated in counterclockwise direction. There were a total of 32 different stimulus pairs: 2 (figure version) $\times$ 2 (match) $\times$ 8 (orientation angle).

Procedure

Children were tested at their school or kindergarten in a separate room. Adults were tested in their or the experimenter's home. The wooden apparatus that could be attached to any kind of table ensured consistency of the experimental setup. The experiment consisted of two training phases and an experimental phase and lasted about 30 minutes.

In the first training phase, the mental rotation task was explained with two cardboard pieces that were magnified replications of the stimuli displayed on the computer screen. The pieces were laid out flat on the table in front of the participant, in the same spatial arrangement in which they later appeared on the computer screen. The experimenter explained that the figure could be turned flat on the table, but not lifted or flipped over. The first trials could be solved by physically turning the figure with the hands. Then participants were asked to imagine what the figure would look like if it were rotated, and thus trying to find out whether it actually fits into the holes. At least five trials were presented to each participant using the four possible combinations of figure and ground and their mirror versions. As soon as a participant had solved three subsequent trials correctly, it was assumed that they understood the mental rotation task and the second training phase began.

In the second training phase, stimuli were presented on the computer screen. Participants were asked to hold the handle of the wheel with their right hand without turning it and not to let go until they found out the answer. At this point, they were supposed to press the correct button on the response pad as accurately and quickly as possible. Participants had to hit the left (white) button for matches, the right (black) button for mismatches. Feedback was given after each practice trial (but not for the experimental trials later): for correct trials a smiley face appeared on the screen, for incorrect trials a frowney face (see Figure 2). Before the next trial began, a cartoon figure appeared centered on the computer screen to attract the participants' attention. The experimenter would then initiate the following trial as soon as the participant's eyes were centered on the computer screen. The stimulus would appear after 750 ms. A predetermined order of 12 practice trials was presented. These trials featured—except for 0° and 180°—different stimulus orientations than those used later in the experimental phase (0°, +22°, −67°, 180°, +112°, −157°, −22°, 180°, +67°, −112°, +157°, 0°). The number of these practice trials was held constant to provide the same amount of practice and feedback for all participants.

The experimental phase consisted of four blocks of 32 trials. The first block (A) was presented in order to obtain an initial baseline performance on a mental rotation task without rotating the handle. The participant's hand rested on the handle without actually moving it; this was done to keep the distance to the response pad comparable with the second (B) and third (B) blocks, in which the handle was rotated manually. The fourth block (A) was again without manual rotation. This ABBA-design provided the same amount of trials with and without rotation, while equally distributing possible training effects. Within each block, all of the 32 different pairs of stimuli were presented in random order. The color of the stimuli was alternated between blocks in order to visually separate them and to make the task less monotonous. In the first and third block, the stimuli were colored orange; in the second and fourth block, they were colored light blue; in practice trials, they were colored red. Figure and ground always had an identical color. The background remained black throughout the experiment.

After the first block (A), participants were trained to turn the wheel continuously at a speed of about 2.5 seconds per cycle. In the experimental trials, participants turned the wheel for about one cycle before the experimenter would initiate the next trial. The experimenter observed the participants' turning movement and asked the participants to adjust the speed whenever the rotation speed changed considerably. We decided not to regulate the manual rotation speed by means of a device such as a pacing motor. As Wexler and colleagues (1998) and Wohlschläger (2001) argued, it is likely that motor planning and the maintenance of a movement plan or spatial operation in working memory are the mechanisms that interfere with mental rotation. Therefore, a passive hand movement would probably have failed to serve our purpose of studying the effect of motor processes on mental imagery.

Half of the participants were instructed to rotate the wheel clockwise; the other half rotated the wheel counterclockwise. These two conditions were presented between subjects in order to avoid confusion about the direction of manual rotation, especially in the younger age groups. For participants in the clockwise group, the positive stimulus orientations $+45°$, $+90°$, and $+135°$ resulted in incompatible manual and mental rotations, the negative orientations $-135°$, $-90°$, and $-45°$ resulted in compatible rotations (e.g., Figure 1B: $-90°$ would be compatible to a clockwise rotation). Conversely, for participants in the counterclockwise group, positive stimulus orientations led to compatible rotations and negative ones to incompatible rotations. Thus, for each participant, 24 trials were compatible, 24 trials were incompatible, and 16 trials were neutral (0° and 180°).

RESULTS

Response times and error rates were measured. In the following, response times will be reported first and analyzed for general age effects, for effects of angle of rotation, and for effects of compatible or incompatible manual rotations. Response time curves were also analyzed regarding the response times for 0°-Trials and regarding their slope. These two measures can provide information about how much time participants needed to encode and compare the stimuli and to mentally rotate the stimuli, respectively.

In a second step, error rates will be reported in order to address the possible role of a speed-accuracy trade off (see also Kail, 1985).

Response Times

For the analysis of response times, only correct trials were used. On average, 4% of all trials were answered incorrectly (adults: 2.8%, 11-year-olds: 1.6%, 8-year-olds: 4.1%, 5-year-olds: 7.3%). Furthermore, reaction times deviating more than three standard deviations from the individual mean were excluded from the analysis. By applying this criterion, 1.7% of the overall data were determined outliers (adults: 1.3%, 11-year-olds: 1.8%, 8-year-olds: 1.9%, 5-year-olds: 1.8%). Response times are illustrated in Figure 3 (in combination with error rates).

Response times were submitted to an analysis of variance (ANOVA) with the within-subject factors stimulus orientation (0°, +45°, +90°, +135°, 180°, −135°, −90°, −45°) and manual rotation (with or without), as well as with the between-subjects factors age, gender, and direction of manual rotation (clockwise vs. counterclockwise). A significant age effect was found, $F(3, 64) = 62.83$, $p < .001$, $\eta^2 = .75$; response times increased with decreasing age. Response times also increased with increasing angle of stimulus

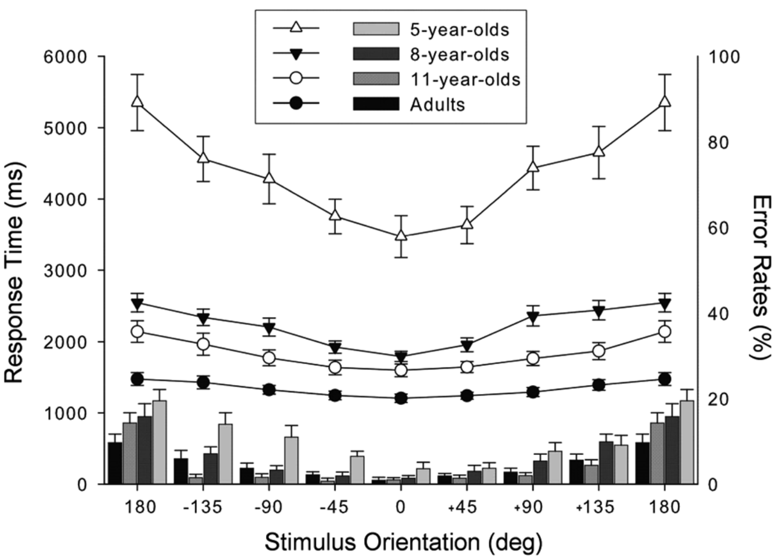

FIGURE 3 Means and standard errors of response times (lines and left y-axis) and error rates (bars and right y-axis) for each stimulus orientation and age group. (Note that means for the 180° stimulus orientation is repeated for aesthetic reasons.)

orientation, $F(7, 448) = 44.51$, $p < .001$, $\eta^2 = .41$. (Separate analyses showed that this was true for all age groups: adults: $F(7, 112) = 24.78$, $p < .001$, $\eta^2 = .61$, 11-year-olds: $F(7, 112) = 24.16$, $p < .001$, $\eta^2 = .60$, 8-year-olds: $F(7, 112) = 23.51$, $p < .001$, $\eta^2 = .60$, and 5-year-olds: $F(7, 112) = 15.63$, $p < .001$, $\eta^2 = .49$). Additionally, age and stimulus orientation interacted, $F(21, 448) = 7.58$, $p < .001$, $\eta^2 = .26$. The increase of response time over orientation angle was larger the younger the participants were.

Response times were shorter when the task was performed without manual rotation compared to with manual rotation, $F(1, 64) = 17.56$, $p < .001$, $\eta^2 = .22$. Manual rotation interacted with the factor age, $F(3, 64) = 4.15$, $p < .01$, $\eta^2 = .16$, which means that the difference in response times between the conditions with and without manual rotation decreased with age. The analysis yielded no effects of gender, $F(1, 64) = 2.95$, $p = .09$, $\eta^2 = .04$, nor direction of manual rotation, $F < 1$.

Compatible Versus Incompatible Rotations

Figure 4 shows that (with one exception only at $+45°$) participants produced longer response times for incompatible trials (filled circles) than compatible trials (empty circles). In order to analyze the influence of compatible and incompatible manual rotation on mental rotation, negative and positive stimulus orientation angles were pooled into compatible and incompatible angles. Response times of the angles 0° and 180° were excluded from data analysis because participants did not need to rotate (0°) or the direction of rotation was arbitrary (180°).

An ANOVA was performed on the response times with the within-subject factors stimulus orientation (45°, 90°, 135°) and compatibility (compatible vs. incompatible manual rotation), as well as the between-subjects factors age, gender, and direction of manual rotation (clockwise vs. counterclockwise). A main effect of compatibility was found, $F(1, 64) = 14.26$, $p < .001$, $\eta^2 = .18$. Response times were shorter with compatible manual rotations than with incompatible manual rotations. However, a significant age by compatibility interaction, $F(3, 64) = 3.86$, $p < .05$, $\eta^2 = .15$, showed that this difference of response times between the compatible and the incompatible condition decreased with age (see Figure 5). A separate analysis of each age group showed that the effect of compatibility could only be found in the two younger age groups (5-year-olds: $F(1, 16) = 6.15$, $p < .05$, $\eta^2 = .28$, 8-year-olds: $F(1, 16) = 9.38$, $p < .01$, $\eta^2 = .37$). The response times of the 11-year-olds and the adults were also faster with compatible manual rotation, but these differences did not reach significance (11-year-olds: $F < 1$, adults: $F(1, 16) = 1.37$, $p = .26$, $\eta^2 = .08$). No effects of direction of manual

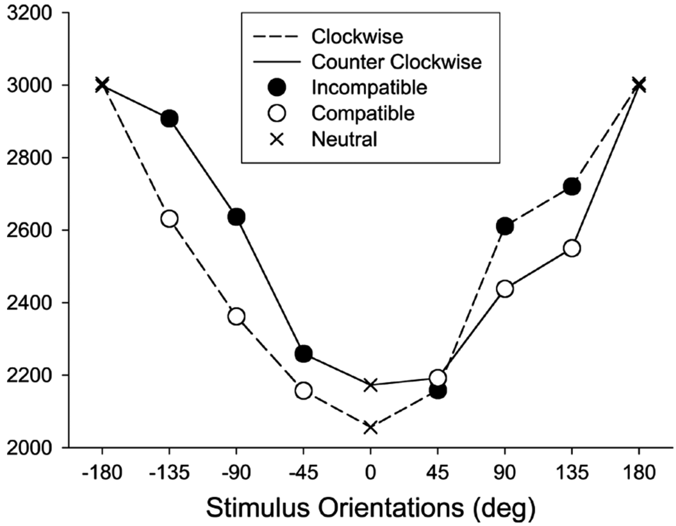

FIGURE 4 Means of response times averaged over age groups. Filled symbols indicate incompatible mental and manual rotations; empty symbols indicate compatible mental and manual rotations. Dashed lines indicate clockwise manual rotation; solid lines indicate counter-clockwise manual rotations. (Note that means for the 180° stimulus orientation is repeated for aesthetic reasons.)

rotation, $F < 1$ or gender, $F(1, 64) = 3.90$, $p = .053$, $\eta^2 = .06$, nor interactions of these two factors with compatibility were found, all Fs < 1.

The overall differences in response times between compatible and incompatible mental and manual rotations are listed in Table 1, showing large effects of compatibility for the two younger age groups, but not for the

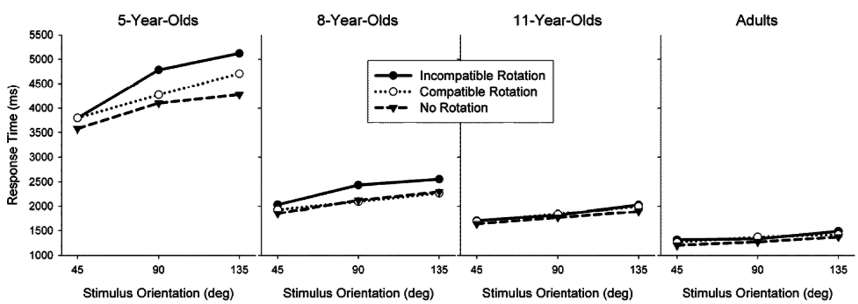

FIGURE 5 Mean of the response times per age group for compatible, incompatible, and no rotation trials.

TABLE 1
Mean Response Times (ms) and Standard Errors for Compatible and Incompatible Manual and Mental Rotations by Age Groups

	Compatible		*Incompatible*		*Difference*		
Age groups	*M*	*SE*	*M*	*SE*	*M*	(%)	
5-year-olds	4261	277	4615	332	354	(8.3)	$p < .05$
8-year-olds	2133	96	2386	152	253	(11.9)	$p < .01$
11-year-olds	1806	118	1818	130	12	(0.7)	n.s.
Adults	1348	67	1376	85	28	(2.1)	n.s.

two older age groups. We also computed the difference in response times of incompatible compared to compatible manual rotations as percentages, because younger children had overall longer response times. These percentage differences also showed a clear gap for the effect of compatibility between 8- and 11-year-olds.

Linearity

In order to analyze whether reaction times increased linearly with increasing angle of stimulus orientation (from 0° to 180°), linear regressions were calculated for each participant. Mean R^2 for the 5-, 8-, 11-year-olds, and adults were 0.58, 0.72, 0.73, and 0.70, respectively. Thus, the observed curves were described fairly well by the linear model. Moreover, the linear fit was in line with previously reported data (e.g., Kail, 1985; Kail, Pellegrino, & Carter, 1980), even though children in the present study were younger.

0°-Trials

For 0°-Trials, no mental rotation was necessary to perform the task. Therefore, the reaction times for these trials indicate the time it took to encode the stimuli, to make a decision, and to press the response button. An ANOVA was performed on the 0°-Trials with the within-subject factors manual rotation (with or without) and measurement repetition, as well as the between-subjects factors age, gender, and direction of manual rotation. The analysis yielded a significant age effect, $F(3, 64) = 38.92$, $p < .001$, $\eta^2 = .65$, with longer response times for younger participants. Response times were faster without manual rotation, $F(1, 64) = 6.14$, $p < .05$, $\eta^2 = .09$. The interaction of the factor manual rotation with age was not significant, $F(3, 64) = 2.07$, $p = .11$, $\eta^2 = .09$, indicating that all age groups responded slower in the dual task with manual rotation. No effects of measurement repetition, $F(1, 64) = 1.40$, $p = .24$, $\eta^2 = .02$, gender, $F(1, 64) = 1.74$, $p = .19$, $\eta^2 = .03$, or direction of manual rotation, $F < 1$, were found.

Mental Rotation Speed (Slope)

The slope of the response time curves, that is, the increase in response time in ms per 1° change in stimulus orientation, was taken as an indicator of the mental rotation speed. Younger participants showed steeper slopes, indicating slower mental rotation speed (see Table 2). The largest difference in mental rotation speeds was found between the 5- and 8-year-olds; the mental rotation speed of 8-year-olds was 152% faster than that of the 5-year-olds.

Although overall response times and response times for 0°-trials were faster without manual rotation, as reported above, an ANOVA comparing slopes for trials with and without manual rotation (2) by age group (4) showed no effect of manual rotation on mental rotation speed, $F < 1$, nor an interaction of manual rotation and age, $F < 1$. Mean mental rotation speeds for trials with and without manual rotation were 200°/s (degrees per second) and 216°/s, respectively. The increase in rotation speed with increasing age (see Table 2) proved to be significant, $F(3, 76) = 22.95$, $p < .001$, $\eta^2 = .48$.

Error Rates

Error rates are displayed in the lower part of Figure 3. Overall, errors occurred in a total of 5.7% of the trials (including trials answered incorrectly and outliers). The error rates were submitted to an ANOVA with the within-subject factors stimulus orientation (0°, +45°, +90°, +135°, 180°, −135°, −90°, −45°), manual rotation and measurement repetition, as

TABLE 2
Slopes (Increase in Response Times [RT]) and Mean Mental Rotation Speeds by Age Groups

	Slope (RT increase in ms per 1°)		*Mean mental rotation speed (in °/s)*	
Age groups	*M*	*SD*	*M*	*Difference from younger age group*
5-year-olds	10.49	6.65	95	
8-year-olds	4.18	2.41	239	+152%
11-year-olds	2.98	1.72	336	+41%
Adults	1.57	1.03	637	+90%

well as the between-subjects factors age, gender, and direction of manual rotation. Error rates increased with increasing angle of mental rotation, $F(7, 448) = 30.84$, $p < .001$, $\eta^2 = .33$. No effect of manual rotation was found, $F(1, 64) = 3.72$, $p = .06$, $\eta^2 = .06$. Participants produced an equal amount of errors in the condition with manual rotation, as in the condition without manual rotation.

Participants who turned their hands clockwise produced fewer errors than participants who turned their hands counterclockwise, $F(1, 64) = 4.43$, $p < .05$, $\eta^2 = .07$. The between-subjects factor age was significant, $F(3, 64) = 12.57$, $p < .001$, $\eta^2 = .37$, showing that, in general, older participants produced fewer errors. However, Figure 3 shows that adults, on some stimulus orientations, made more errors than 11-year-olds. Table 3 specifies that this effect was restricted to compatible trials. There were no significant effects of gender, $F < 1$, nor measurement repetition, $F < 1$.

Compatible Versus Incompatible Rotations

Similar to the response times, error rates were analyzed with respect to compatible and incompatible manual rotations. An ANOVA was performed on the error rates with the within-subject factors stimulus orientation (45°, 90°, 135°), compatibility, and measurement repetition, as well as the between-subjects factors age, gender, and direction of manual rotation. There was a main effect of compatibility, $F(1, 64) = 6.28$, $p < .05$, $\eta^2 = .09$, and the interaction between compatibility and age reached significance, $F(3, 64) = 3.25$, $p < .05$, $\eta^2 = .13$. In the condition with compatible manual rotation, participants produced fewer errors than in the incompatible condition, and this difference decreased with increasing age. In addition, there was a small interaction effect between compatibility and gender, $F(1, 64) = 5.17$, $p < .05$, $\eta^2 = .08$, showing that female participants produced fewer errors

TABLE 3
Error Rates (%) for Compatible and Incompatible Manual and Mental Rotations by Age Groups

	Compatible		*Incompatible*		*Difference*	
Age groups	*M*	*SE*	*M*	*SE*	*M*	
5-year-olds	7.0	2.1	12.1	1.8	5.1	$p < .05$
8-year-olds	4.2	0.7	7.3	1.5	3.1	n.s.
11-year-olds	1.9	0.8	3.1	1.0	1.2	n.s.
Adults	4.6	1.2	3.1	0.8	−1.5	n.s.

in compatible and more errors in incompatible trials than male participants. There was no effect of direction of manual rotation, $F(1, 64) = 3.88$, $p = .053$, $\eta^2 = .06$.

DISCUSSION

The present experiment investigated the effects of manual rotation on mental rotation in different age groups. The results yielded significant effects of compatibility for the younger children (5-year-olds and 8-year-olds) but not for 11-year-olds and adults. Similar effects were found concerning the error rates. Thus, manually turning a wheel in one direction interfered with mental object rotation in the opposite direction for younger children, but not for older children and adults. These results are in line with recent findings (Funk et al., 2005) showing that incompatible hand positions during mental rotation of hands had a larger effect on children than on adults. Our results extend these findings and demonstrate that this developmental trend can also be found with active hand movements and is not restricted to visual stimuli of hands. Taken together, these results provide converging evidence that the ability to dissociate visual mental activities and motor processes develops with age.

Additional effects of age and stimulus orientation on response times, as well as the interaction of these two factors, are consistent with results from previous studies (Kosslyn et al., 1990; Marmor, 1975) and indicate that all age groups mentally rotated the stimuli, and that rotation speed increased with age. This corroborates previous findings that children are capable of using kinetic imagery at a much earlier age than proposed by Piaget and Inhelder (1971b). In line with Kosslyn and colleagues, no gender differences were observed for response times and mean error rates. The only gender difference found was that female participants showed a slightly more pronounced effect of compatibility on error rates. However, the size of this effect was very small, so this result should be interpreted with caution. In the following, we will discuss our main findings concerning the more pronounced compatibility effects in younger children.

The fact that adding a manual rotation task to the mental rotation task led to an increase in response times may suggest an influence due to workload increase. The analysis of 0°-trials and slopes showed, however, that the dual task had merely an additive effect and, therefore, could not explain the selective interference of incompatible rotation. In line with Wexler et al. (1998), compatibility of manual and mental rotation resulted in a shift of the typical V-shaped response time function, favoring the direction of manual rotation. This selective effect cannot be explained simply by age differences in general processing capacities or by an increase in response times evoked by a second task. Further evidence against a simple dual task explanation can be seen in the reaction time patterns of the 8-year-olds (Figure 5). Reaction times were longer for incompatible trials, but comparable for compatible and no rotation trials. Thus, the motor activity selectively slowed down incompatible mental rotations, but not compatible ones.

Similar effects of compatibility on response times and error rates rule out a speed-accuracy trade off in children. It has to be noted, however, that adults committed slightly more errors than 11-year-olds. This result might point to a speed-accuracy trade off, such that adults responded faster compared to 11-year-olds, at the cost of more errors. However, if a compatibility effect became manifest in adults' error rates, we would expect more errors in incompatible trials, which was not the case. Therefore, a speed-accuracy trade off cannot account for the observed age differences in the compatibility effect.

The absence of a compatibility effect for the adults is inconsistent with previous results (Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998). However, the present developmental experiment differed in many respects from these previous studies, and so it is possible that differences in attention demands, task difficulty, speed of manual rotation, or timing between the onset of the motor activity and the stimulus presentation could account for the different results. Wexler and colleagues found that with practice, the compatibility effect decreased and assumed that mental and motor rotations were partially decoupled. Our mental rotation task had to be tailored to the abilities of the youngest age group, and therefore it may have been easy for adults—even without practice. In fact, response times and slopes suggest that adults mentally rotated the figures, but they rotated them at a very fast rate. However, if age differences in mental rotation speed accounted for differences in the magnitude of the interference, we would expect a large decrease in compatibility effect between 5-year-olds and 8-year-olds, because this was the comparison that revealed the largest increase in mental rotation speed. However, the largest difference in the magnitude of the compatibility effect was found between 8- and 11-year-olds, where the increase in mental rotation speed was smallest. Thus, it appears unlikely that the difference in the compatibility effect can be attributed to the differences in mental rotation speed.

Moreover, an analysis of mental rotation speeds showed that, not only for adults, but rather in general, the rotation speeds were quite fast compared to previous studies (Kail, 1985; Kail, Pellegrino, & Carter, 1980; Marmor, 1975). In these studies, rotation speeds slower than $143°/s$ ($>7 ms/°$) were found for 8- to 11-year-olds, as opposed to over $230°/s$ in our study. Thus, our clear-cut and simple figure-ground stimuli may have led to faster responses in general, taking response times to another level for all age groups. Hence, we do not claim that adults are perfect at decoupling mental and motor activities. However, given the remarkable gap between 8-year-olds and 11-year-olds, together with the age differences reported by Funk et al. (2005), we conclude that the age difference in the effect of motor interference is rather robust and due to developmental progress at this age.

In fact, Sack and colleagues (2007) systematically varied the difficulty of their mental rotation task by presenting simpler combinations of fewer cubes or more symmetrical forms of hands. They found the same pattern of results, which showed compatibility effects for hand stimuli, but not for abstract cube stimuli, even though response times were nearly reduced by half for the simpler cube stimuli. Furthermore, these results—in line with our findings—contradicted previous studies with adults (Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998) and showed that compatibility effects in adults are stimulus- and task-specific.

In sum, neither general processing capacities, nor differences in mental rotation speeds can account for the present findings of selective difference between incompatible and compatible manual and mental rotation in younger children. Furthermore, similar response-time patterns rule out the possibility that younger children might have used fundamentally different strategies to solve the task. Instead, the data indicate that there is in fact a developmental shift allowing for better decoupling of visual mental activities and motor processes with increasing age. In order to perform smooth mental transformations, young children might engage motor strategies, such as covertly turning the objects with their hands. Therefore, having to turn a wheel simultaneously might make it hard to internally simulate a rotation in the opposite direction. Whereas motor strategies appear to be essential in children's imagery, adults may have more flexibility and can choose whether to recruit motor strategies or not.

An alternative explanation for the observed age trend in compatibility effects might also be found in the development of cognitive control. Fundamental components of cognitive control are the ability to suppress irrelevant information or interferences and the ability to inhibit predominant response tendencies. Cognitive control has been shown to develop throughout childhood (for a recent overview see Davidson, Amso, Anderson, & Diamond, 2006) and is often associated with the maturation of prefrontal cortex, which develops more slowly than other brain areas, reaching maturation only late in adolescence (e.g., Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002). When considering these findings along with Grush's (2004) emulation theory of representation, it is conceivable that improving inhibitory abilities could account for the developmental trend we observed in compatibility effects. According to this theory, motor areas are driving an emulator (i.e., an internal model of the body) that can be run off-line and thus simulate movements and related proprioceptive and kinesthetic feedback. In order to imagine the event of rotating a shape, a covert motor command is sent to the emulator, which simulates the movement and the corresponding changes in the visual input. Thus, to emulate an object rotation in the incompatible trials of our task, the motor command and the proprioceptive feedback of the executed incompatible hand movement have to be ignored. Children might get better at this as their abilities of cognitive control develop.

In the same vein, we might speculate that children might profit more from gesturing during mental imagery than adults, or young children might have a hard time inhibiting overt gestures. Indeed, recent studies have shown that 5- and 7-year-olds profit more than 9-year-olds and adults from executing a corresponding active hand movement during mental imagery (Frick, Daum, Wilson, & Wilkening, 2008). There is also evidence that 5-year-olds' performance in a mental rotation task is uniquely related to gesturing about moving the stimuli, but not to talking about moving the stimuli, when children were asked to explain how they solved the task (Ehrlich, Levine, & Goldin-Meadow, 2006). However, more systematic research is needed to investigate effects of gesturing on imagery performance.

Interestingly, the motor influence we found for young children occurred when the objects they had to rotate mentally were rather abstract and did not imply any motor component (as would be the case for pictures of body parts). Moreover, the manual turning of the wheel did not affect the visual stimuli at any point in the experiment, so a functional connection between the hand movement and the visual stimuli was not provided by the task. Thus, the present results provide further support for the suggestion that motor processes are strongly involved in visual mental imagery in children (Black & Schwartz, 1996; Rieser et al., 1994), even when the imagined movement does not directly call for a motor strategy and no functional connection between the imagined and the executed movement has been established.

Our results, showing increased motor involvement in young children's cognitive processes, are in line with early developmental theories, which emphasized the emergence of cognitive abilities out of sensory-motor (Piaget & Inhelder, 1971a) or *enactive* (Bruner et al., 1966) abilities. Furthermore, the results support theories of embodied cognition, which propose an integral involvement of sensory and motor functions in cognition (e.g., Prinz, 1990, 1997; for a review see Wilson, 2002). Our results suggest that this involvement might be of particular importance in younger children. Further behavioral experimentation, supported by neuroimaging studies, will help to provide a deeper insight in the developmental specifics and the conditions under which motor activities can interfere with, or even facilitate, children's mental activities. To find out more about the effects of motor activity—or the lack of it—on cognitive development is not only relevant for cognitive sciences, but has important practical value in light of the diminishing amount of motor activities in everyday life.

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