Journal of Experimental Child Psychology 104 (2009) 34–51

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Effects of action on children's and adults' mental imagery

Andrea Frick [a,*,1], Moritz M. Daum [a,2], Margaret Wilson [b], Friedrich Wilkening [a]

[a] Department of Psychology, University of Zurich, CH-8050 Zurich, Switzerland
[b] Department of Psychology, University of California, Santa Cruz, CA 95064, USA

ARTICLE INFO

Article history:
Received 21 July 2008
Revised 13 January 2009
Available online 10 March 2009

Keywords:
Cognitive development
Mental imagery
Mental representation
Motor processes
Embodied cognition
Children

ABSTRACT

The aim of this study was to investigate whether and which aspects of a concurrent motor activity can facilitate children's and adults' performance in a dynamic imagery task. Children (5-, 7-, and 9-year-olds) and adults were asked to tilt empty glasses, filled with varied amounts of imaginary water, so that the imagined water would reach the rim. Results showed that in a manual tilting task where glasses could be tilted actively with visual feedback, even 5-year-olds performed well. However, in a blind tilting task and in a static judgment task, all age groups showed markedly lower performance. This implies that visual movement information facilitates imagery. In a task where the tilting movement was visible but regulated by means of an on-and-off remote control, a clear age trend was found, indicating that active motor control and motor feedback are particularly important in imagery performance of younger children.

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Introduction

Even though tilting a glass and drinking from it is an everyday action, many children appear to be unaware that the surface of water stays horizontal regardless of the orientation of its container. Piaget and Inhelder (1948/1956) showed this with their classic water level task, a paper-and-pencil task that required children to draw the water level in containers that were presented at different orientations. They concluded that the concept of horizontality is not mastered until 9 or 10 years of age. However,

* Corresponding author.
E-mail address: depsy@gmx.net (A. Frick).

1 Present address: Department of Psychology, Temple University, Philadelphia, PA 19122, USA.

2 Present address: Department of Psychology, Max Planck Institute for Human Cognitive and Brain Sciences, D-04103 Leipzig, Germany.

0022-0965/$ - see front matter Published by Elsevier Inc.
doi:10.1016/j.jecp.2009.01.003

replications of this task showed that even adults are far from perfect. College students performed at an error rate of 35% (McAfee & Proffitt, 1991). Waitresses and bartenders, who have a lot of professional experience with filled glasses, showed even worse results (Hecht & Proffitt, 1995). In many studies, males outperformed females (e.g., Liben & Golbeck, 1980; for a meta-analysis, see Kalichman, 1988). After numerous replications, the reasons for these errors are still not clear (for overviews, see Kalichman, 1988; Liben, 1991; Pascual-Leone & Morra, 1991; Vasta, Belongia, & Ribble, 1994). Whereas Piaget and Inhelder's (1948/1956) original interpretation referred to conceptual development, recent explanations include bottom–up mechanisms and propose that errors result from the use of wrong reference systems (e.g., McAfee & Proffitt, 1991), field dependence (Lohaus, Kessler, Thomas, & Gediga, 1994), graphic abilities or graphic tendencies (Gestalt principles) to draw the line perpendicular to the glass (e.g., Liben, 1991; Sommerville & Cox, 1988), and individual differences in perceptual processes and inhibitory skills (Sholl & Liben, 1995).

In another line of research, Schwartz and Black (1999) used a different approach to assess adults' abilities to represent water in tilted containers. Their task required the same basic ability to represent the surface of water as horizontal as in the Piagetian water level task, but it also required the ability to transform mental representations and knowledge about the role of specific stimulus properties such as glass diameter and water level. In this task, adults needed to imagine that two presented glasses of different diameters were filled to the same level with water. When asked which glass would spill first if tilted, participants were usually wrong. However, the study by Schwartz and Black included an additional condition that revealed an important divergence in performance when action plans were involved. When participants were allowed to manually tilt each glass until the imaginary water would reach the rim, they correctly tilted a narrow glass farther than a wide one. This research showed that adults are able to imagine the transformation of the water inside a container and to simulate the tilting movement with their hands without having explicit knowledge about the correct answer and how it is affected by glass diameter and water level.

This finding raises a series of important questions about the sources of information people are using to achieve correct performance and the age at which the ability to use these sources emerges. In the current study, we used a tilting task based on the Schwartz and Black (1999) task to investigate children's abilities to transform mental representations of water inside a container and, more specifically, how manual movement facilitates these mental transformations.

Motor feedback in perception and imagery

It is undisputed that action plans, mental models, cognitive maps, and other internal representations guide our actions. However, the extent to which our actions may influence our internal representations is less evident. Several studies with adult participants suggest that motor activities may feed back on cognitive processes such as perspective taking (Simons & Wang, 1998; Wang & Simons, 1999) and mental rotation (Schwartz & Holton, 2000; Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998). The notion that action plays a central role in cognition has recently attained high visibility under the label of *embodied cognition* (for an overview, see Overton, 2008; Wilson, 2002). Theories of embodied cognition emphasize the importance of sensory and motor functions for cognition and for a successful interaction with the environment. For example, it is argued that embodiment processes underlying infants' early understanding of and interaction with their physical and social environments might still account for a significant proportion of the same skills in adults (Daum, Sommerville, & Prinz, in press). Based on behavioral, neurophysiological, and brain imaging data, it has been proposed that planned actions and perceived events share a common representational domain (Prinz, 1997) or that observed and executed actions activate the same neuronal regions in the brain, the so-called mirror neuron system (for a review see Rizzolatti & Craighero, 2004). Such a close link between action and perception is thought to be especially important in action understanding and imitational learning. The assumption of direct feedback from motor activities to higher cognitive processes might explain how people can predict the consequences of their actions or coordinate their mental representations with their actions (Creem, Wraga, & Proffitt, 2001).

Developmental evidence

This view that our actions may influence the way we think is not completely new. Already in early developmental psychology, Piaget and Inhelder (1948/1956; see also Piaget, 1936/1952) emphasized the importance of actions in cognitive development. They argued that cognitive abilities emerge out of sensorimotor abilities and that movement is the source of the most elementary knowledge. According to their theory, a representation is the inner and symbolic imitation of previously executed actions (Piaget & Inhelder, 1966/1971). However, Piaget's mostly abstract tasks often did not do justice to his view that action plays an important role in cognitive development.

In accordance with Piaget's theory, Kosslyn (1978, 1980) postulated that representational-development progresses from initially sensorimotor knowledge structures (schemata), to spatial pictorial images, to verbal–linguistic representations. Similarly, Bruner, Olver, and Greenfield (1966) postulated a developmental progression from *enactive* (action based), to *iconic* (pictorial), to *symbolic* (abstract) representations. Taking the role of sensorimotor knowledge even further, Thelen (2008) questioned Piaget's fundamental assumption that the goal of development is to rise above the mere sensorimotor and to be increasingly abstract and distanced from perception and action. Thelen rather suggested that the goal for cognition is to be at home within the body and that development consists of the progressive ability to flexibly, dynamically, and adaptively change the coupling strength among mind, body, and environment.

Experimental evidence is beginning to support this view that action and sensorimotor experience play a key role in cognitive development. Some infant studies have shown that active movement, such as crawling and walking, facilitates 12-month-olds' performance in a spatial search task (Acredolo, Adams, & Goodwyn, 1984) and that 8-month-olds' locomotor experience predicts their search performance following a change of perspective (Bai & Bertenthal, 1992). In line with this result, an intervention study, in which 3-month-olds either were given the opportunity to engage in an object-directed contact with an object or were not, showed that motor experience can affect infants' perception and interpretation of others' goal-directed actions (Sommerville, Woodward, & Needham, 2005).

But also beyond infancy, active movement has been shown to have an effect on imagery abilities. Rieser, Garing, and Young (1994) showed that walking a corresponding path facilitates children's ability to imagine a spatial layout from another perspective at 3.5 years of age and older. Recent studies that directly tested the effect of hand movement or hand positions on mental imagery abilities in kindergartners and schoolchildren (Frick, Daum, Walser, & Mast, in press; Funk, Brugger, & Wilkening, 2005) suggest that the younger the children, the greater the effect of motor feedback on imagery performance.

Despite compelling evidence showing that concurrent action interferes with mental imagery, to date it is largely unclear why and how action affects imagery or which aspects of action account for this interference. Furthermore, still relatively little is known about the development of this connection between action and cognition. Thus, the aims of the present study were to compare children's and adults' imagery performance and to investigate which aspects of a concurrent motor activity would affect imagery performance in different age groups.

The water tilting task

A dynamic imagery task that was designed by Schwartz and Black (1999), henceforth called the water tilting task, was used for our study. The basic water tilting task involves two drinking glasses of equal heights but different diameters. Participants are asked to imagine that both glasses would be filled with water to the same level and to tilt the glasses so that the imagined water would reach the rim of the glass. Tilting a glass of water is an everyday movement with which even very young children have a lot of motor experience. On the other hand, we usually do not consciously deliberate about tilting glasses, and the water tilting task poses a physical/geometrical problem that is not addressed in general school curricula. Previous results obtained with numerous variations of this basic task (Schwartz, 1999; Schwartz & Black, 1999) suggest that adults are in fact able to solve the task by manually tilting the glasses. They correctly tilted thin glasses farther than wide ones, although they did not seem to have accurate descriptive knowledge about this. Schwartz and Black (1999) concluded from the dissociation between participants' descriptive knowledge and their performance in the water tilting task that adults solve the water tilting task by mentally simulating the event. Such a simulation requires participants to mentally represent the water inside the glass, to maintain this mental representation and transform it, while the surrounding reference frame (the orientation of the glass/their hand) changes.

Further experiments that varied dynamic aspects of the water tilting task (Schwartz, 1999) indicate that adults solve this task by using dynamic imagery of the whole tilting movement rather than merely picturing the final orientation of the glass based on geometric considerations. These experiments also showed that when participants completed the water tilting task after a verbal judgment, their tilts not only were incorrect but also did not correspond to their judgments. Their initial judgment caused inaccurate tilting, so that most participants tilted the wide glass farther or both glasses to the same angle. However, the activation of people's beliefs interfered with, rather than guided, their actions. Even participants who spontaneously mentioned that they had tried to tilt in accordance with their judgments showed no superior fit between judgments and tilts. Conversely, initial tilts did not have any effect on subsequent judgments.

Movements, however, do not always need to be acted out overtly to support mental simulations. Even an imagined hand movement improved adults' performance (Schwartz & Black, 1999). This result is in line with recent theories on embodied cognition (Wilson, 2002), which claim that mental structures that originally evolved to control action can also be used "off-line" to mentally simulate external events decoupled from the physical inputs and outputs. Thus, motor functions may be used to recruit motor knowledge in a covert way and without overt movement. However, the lack of an active hand movement seemed to make the water tilting task more difficult. Schwartz and Black (1999) argued that there might be situations where the extra information and the constraints provided by a motor activity are necessary to sustain imagery. The questions of when, why, and for whom motor activity has a beneficial effect are still an unresolved theoretical issue.

To our knowledge, there has been only one study that tested children's imagery abilities using the water tilting task (Black & Schwartz, 1996). In this experiment, the diameter of the glasses and the level of the imaginary water inside the glasses were varied on two levels each in a complete factorial design. Unfortunately, the results of this study were described only briefly in a short proceedings paper. They showed that most 3- to 12-year-olds correctly tilted the thin glasses farther than the wide ones, with the exception of 5-year-olds, when tilting glasses with low water levels. The water levels were discriminated only by older children (at least 8 years of age). The 3- and 4-year-olds correctly discriminated the diameters but not the water levels. This result is rather counterintuitive in that the water level would seem to be the "easier" factor for which we have more accurate descriptive knowledge. The authors did not discuss this issue. Based on the results that at least older children (starting at around 8 years of age) discriminated both relevant factors even though they did not show any descriptive knowledge about the effects of diameter on the tilting angle, the authors concluded that the children solved the task by using dynamic imagery.

The current study was motivated by the facts that there is (a) theoretical uncertainty about which factors and conditions determine whether motor activities influence adults' mental imagery performance, (b) rather sparse evidence (Black & Schwartz, 1996) on children's performance on the water tilting task, and (c) previous evidence (Frick et al., in press; Funk et al., 2005) that motor activity might be even more important for younger children's imagery performance. In four different versions of the water tilting task, we addressed the questions of whether (a) visibly executed movement leads to better imagery performance compared with (b) seeing but not executing, (c) executing but not seeing, or (d) not perceiving any movement at all.

In contrast to previous experiments with the water tilting task (Schwartz, 1999; Schwartz & Black, 1999), in the current experiments the glasses were mounted on an apparatus that allowed tilting movements in the frontoparallel plane (picture plane) only. Thus, the movements were more constrained than in previous experiments, where participants tilted the glasses in the air. With this method, measurement of the titling angles was much easier, and presumably more precise, than in the previous experiments. Even more important, this method allowed us to move the glass seemingly by itself, and this was crucial for Experiment 2, in which the glass movement was observed without a concurrent manual tilting movement.

Experiment 1

Method

Participants

In Experiment 1, four age groups were tested: 16 kindergartners (mean age = 5 years 10 months, range = 5 years 2 months to 6 years 6 months, 8 males and 8 females), 16 first-graders (mean age = 7 years 3 months, range = 6 years 10 months to 7 years 9 months, 6 males and 10 females), 16 third-graders (mean age = 9 years 0 months, range = 8 years 7 months to 9 years 5 months, 8 males and 8 females), and 16 adults (mean age = 24 years 11 months, range = 18 years 0 months to 31 years 3 months, 7 males and 9 females). In the following, the age groups are referred to as 5-, 7-, and 9-year-olds and adults. Children were recruited from different public kindergartens and primary schools in the region of Zurich, Switzerland, which serves families of diverse socioeconomic and cultural backgrounds. All children spoke German or Swiss German and were tested accordingly. Informed parental consent was obtained for all children. Most adult participants were students at the University of Zurich.

Apparatus

The experimental apparatus consisted of a wooden background panel with a diameter of 35 cm (see Fig. 1). The panel was round on top and covered with black felt to provide a homogeneous background without landmarks. A shaft went through the center of the panel. At the front end of the shaft, a bracket with magnets allowed fast and effortless mounting of the stimulus glasses, which then could be turned in the frontoparallel plane. At the back end of the shaft, a pointer indicated the angular position of the shaft on a scale. The experimenter, who was seated to the side of the apparatus, could see the scale, but the panel hid the scale from the participants' view.

Stimuli

Six opaque drinking glasses of equal height were used to mount on the shaft. Six transparent glasses of the same shape served as reference glasses. For the experimental trials, the inner diameter

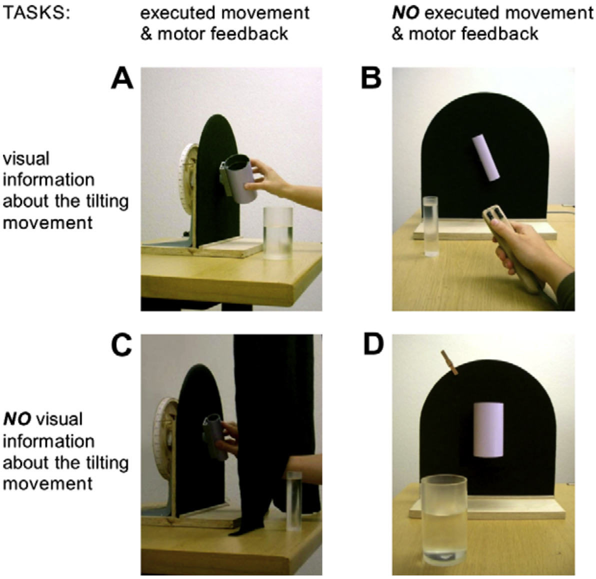

Fig. 1. Experimental setups for the different tasks: (A) manual tilting task—Experiment 1; (B) remote control task—Experiment 2; (C) blind tilting task—Experiment 3; (D) judgment task—Experiment 1.

and the water level were varied systematically on two levels. The glasses had an inner diameter of 25 or 65 mm and were filled with water up to 15 or 45 mm below the rim. Two glasses were used for the practice trials; they were filled up to 30 mm below the rim. Fig. 2 shows schematically the drinking glasses used in the practice and experimental trials. It also shows the angles at which the water would reach the rim if the glasses were actually tilted. The normative tilting angles decrease with increasing water level, and the tilting angles are larger for the thin glasses.

Design

A factorial design was applied with the within-participant factors diameter (2) and water level (2). Each combination of diameter and water level was presented three times. Thus, a total of 12 experimental trials were presented per task. Measurement repetitions were presented in blocks. The order of the stimuli within the blocks varied between participants and was determined by a randomizing program with the restriction that the same levels of one factor did not appear in immediate succession.

Two tasks were presented in a row. In the first task, the manual tilting task, the participants actually tilted the glasses to an angle where the imaginary water inside the glass would reach the rim. The second task was a judgment task in which no movement took place. In this task, the angle at which the water would reach the rim needed to be indicated by attaching a pointer to the panel at the appropriate angle. The order of the two tasks was not counterbalanced so as to avoid provoking erroneous thoughts before the manual tilting task (see Schwartz, 1999). In both tasks, the dependent variable was the angle of tilt in degrees. Thus, in both tasks, the dependent measure was metric and interval scaled, allowing for quantitative inferences about the underlying mental representations. In addition, the response was nonverbal and, therefore, suitable for young children at preschool age because it did not require special verbal skills. Before each task, two practice trials were presented in counterbalanced order with intermediate water levels that did not occur later in the experimental trials.

Procedure

Children were tested one by one in a separate room at their school or kindergarten. Adults were tested in a laboratory room at the University of Zurich. The experiment lasted approximately 20–30 min.

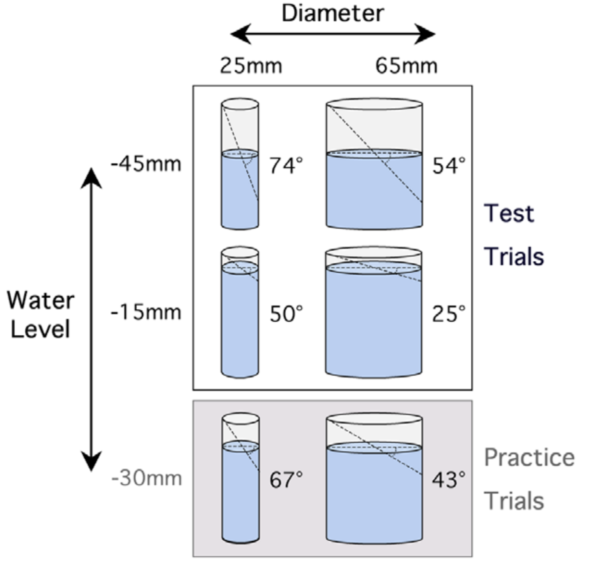

Fig. 2. Stimulus material for experimental trials: variation of glass diameter and water level (distance to rim) on two levels each. Intermediate water level was used for practice trials. Dashed lines and degree values indicate the normative tilting angles.

At the beginning of the experiment, to explain the task, children and adults were asked to drink a tiny little drop out of a conical plastic cup. By doing so, the participants were provided with an example of a tilting angle with a cup of a different shape, and the goal of the task—to bring the water to the rim—could be clarified. Then a glass was attached vertically to the shaft, and it was pointed out to the participants that this glass was empty and could be turned around the shaft. A reference glass that was actually filled with real water was positioned in front of the apparatus on the left-hand side. Children and adults were asked to pretend that the glass on the shaft was filled with exactly the same amount of water and to turn it so that this imaginary water would reach the rim of the glass but would not spill. To help the children understand the task, a puppet was held next to the glass in the first practice trial. Children were told to help the puppet drink a tiny little drop of water—just like they did before with the plastic cup. After another practice trial without the puppet, the test trials were presented. Neither in the practice trials nor in the test trials was a full glass ever tilted.

The participants were allowed to adjust their tilts as often and as long as they liked. The last position was registered. The direction in which the glasses were turned (clockwise or counterclockwise) was not specified; however, most of the participants were right-handed and spontaneously turned the glasses with their right hand counterclockwise. Left-handed participants preferred the clockwise

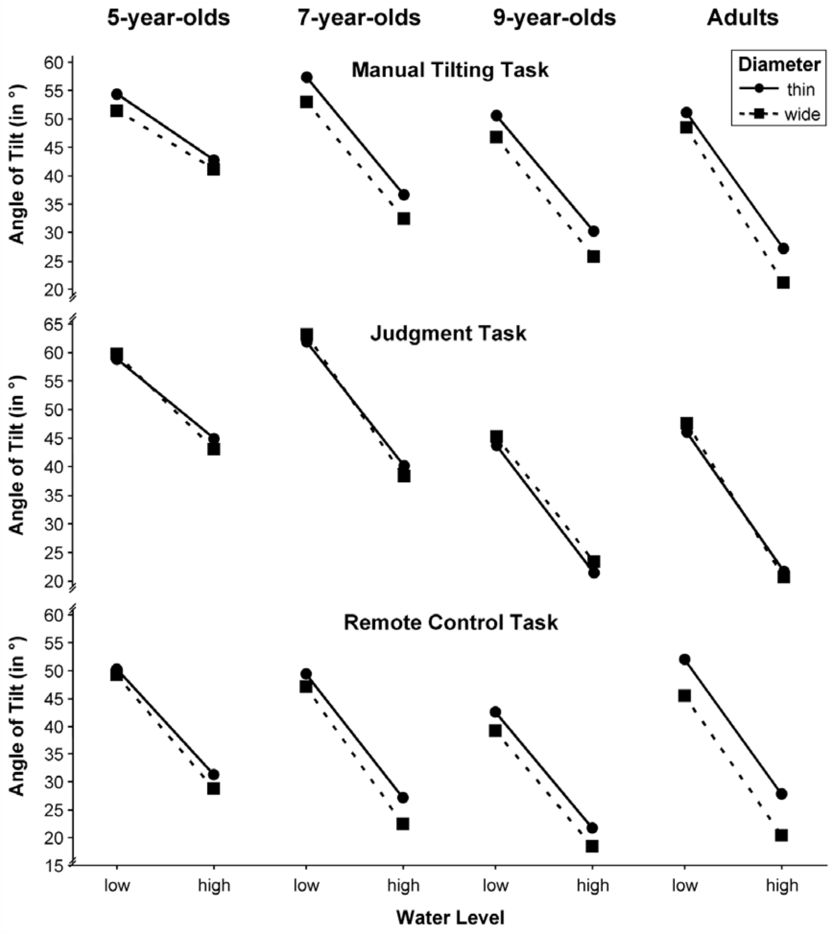

Fig. 3. Means of produced tilting angles (in degrees) per age group in the manual tilting task and judgment task of Experiment 1 and in the remote control task of Experiment 2.

direction. Once they had chosen a direction, participants were asked to stick to it during the whole experiment. No feedback was provided about the correctness of the tilts.

In the judgment task, participants were asked to position a pointer to indicate the angle of the glass at which the water would reach the rim. They were instructed to attach the pointer so that it would be in line with the vertical axis of the glasses. In a first practice trial, the glass on the shaft was then actually turned in line with the pointer to show the participants what their judgment would signify. In the second practice trial and in the experimental trials, the glasses were never tilted.

Results

Manual tilting task

Tilting angles of those participants who turned the glasses clockwise were converted by subtracting the tilting angles from 360° so that the data were comparable. Means of produced tilting angles (in degrees) for each age group in the manual tilting task are presented in the upper panel of Fig. 3. An overall analysis of variance (ANOVA) was calculated with the within-participant factors diameter (2) and water level (2), the between-participants factors age (4) and sex (2), and the tilted angles as the dependent variable. The analysis yielded significant main effects of the factors diameter, $F(1,56) = 50.00$, $p < .001$, $\eta^2 = .47$, water level, $F(1,56) = 277.59$, $p < .001$, $\eta^2 = .83$, and age, $F(3,56) = 3.71$, $p < .05$, $\eta^2 = .17$. A significant interaction between the factors water level and age, $F(3,56) = 6.79$, $p < .01$, $\eta^2 = .27$, showed that the older the participants, the more they discriminated the two water levels, as reflected by the increasingly steep graphs in the upper panel of Fig. 3. There was no interaction between the factors diameter and age, $F < 1$, showing that all age groups equally discriminated the two diameters. Females discriminated the varied water level slightly more than did males, $F(1,56) = 4.81$, $p < .05$, $\eta^2 = .08$. However, a strong effect of water level was also observed for males. There was no sex difference regarding the differentiation of the diameters, $F < 1$.

Separate statistical analyses of the tilting angles per age group (ANOVA: Diameter (2) × Water Level (2)) yielded significant main effects of water level for 5-, 7-, and 9-year-olds and adults, $Fs(1, 15) = 13.20$, 85.62, 76.97, and 281.49, respectively, all $ps < .01$, all η^2s > .46. The analysis also yielded significant effects of diameter for 5-, 7-, and 9-year-olds and adults, $Fs(1, 15) = 12.13$, 19.51, 21.23, and 9.26, respectively, all $ps < .01$, all η^2s > .37. There were no significant interactions of these two factors, all $ps > .19$. Fig. 3 shows that all age groups on average tilted glasses with low water levels farther than those with high water levels and tilted thin glasses farther than wide ones. A comparison with the normative angles (see Fig. 2) shows that the tilting angles for the thin glasses were generally underestimated.

Judgment task

Means of judged angles (in degrees) for each age group in the judgment task are presented in the middle panel of Fig. 3. An overall ANOVA was calculated with the within-participant factors diameter (2) and water level (2), the between-participants factors age (4) and sex (2), and the mean judged angles as the dependent variable. The analysis yielded significant main effects of the factors water level, $F(1,56) = 168.47$, $p < .001$, $\eta^2 = .75$, and age, $F(3,56) = 7.79$, $p < .001$, $\eta^2 = .29$. There was no main effect of diameter, $F < 1$, and was there no interaction between diameter and age, $F < 1$, or between water level and age, $F(3,56) = 1.70$, $p = .18$, $\eta^2 = .08$. Thus, all age groups equally discriminated the different water levels, but the diameters were not discriminated throughout. There also was a significant but small interaction effect between diameter and water level, $F(1,56) = 4.76$, $p < .05$, $\eta^2 = .08$, which shows in a slight intersection of the lines in the middle panel of Fig. 3. There was no interaction among diameter, water level, and age, $F < 1$. No main effect of sex was found, $F < 1$, and no interaction between sex and diameter, $F < 1$, or between sex and water level, $F(1,56) = 3.17$, $p = .08$, $\eta^2 = .05$, was found. Because sex did not seem to be a relevant factor in either the judgment or manual tilting task reported above, it was omitted from subsequent analyses for the sake of interpretability of the factors of main interest.

Separate analyses per age group showed no statistically significant effects of glass diameter for 5- and 7-year-olds and adults, all $Fs < 1$, or for 9-year-olds, $F(1,15) = 2.21$, $p = .16$, $\eta^2 = .13$. However, effects of the factor water level were comparable to those in the manual tilting task and statistically significant for 5-, 7-, and 9-year-olds and adults, $Fs(1, 15) = 11.46$, 46.23, 84.02, and 150.17, respectively, all $ps < .01$, all $\eta^2s > .42$. Fig. 3 shows that all age groups on average indicated that glasses with low water levels can be tilted farther than those with high water levels. However, the lines are overlapping for most age groups, showing that the glass diameters were not discriminated. The lines for the 9-year-olds are not overlapping but even reversed, showing that participants in this age group indicated that the wide glass can be tilted farther than the thin glass.

Manual tilting versus judgment

To compare the manual tilting task with the judgment task, an ANOVA was calculated with the within-participant factors task (2), diameter (2), and water level (2) and the between-participants factor age (4). The analysis yielded a significant interaction of task and diameter, $F(1,60) = 41.26$, $p < .001$, $\eta^2 = .41$. Thus, the diameters were significantly better discriminated in the manual tilting task than in the judgment task regardless of age, $F(3,60) = 1.79$, $p = .16$, $\eta^2 = .08$. There was no main effect of task, $F < 1$, meaning that participants did not tilt the glasses farther in one of the two tasks. There was no interaction of task with any other factor, all $ps > .14$, all $\eta^2s < .09$.

Consistencies

To get an idea about how consistent the children's and adults' tilting movements and judgments were, the measurement repetitions were correlated. Pearson correlations among the three blocks were calculated and then were Fisher's Z-transformed and averaged. The consistencies for 5-, 7-, and 9-year-olds and adults in the manual tilting task were $rs = .55$, .87, .94, and .96, respectively. In the judgment task, the consistencies were $rs = .37$, .86, .92, and .98, respectively. Thus, the correlations were very similar in the two tasks for all age groups but the youngest one. An ANOVA with the average consistencies as the dependent variable (Z values) and the factors task (2) and age (4) showed no significant difference in consistencies between the two tasks, $F < 1$, and no interaction with age, $F(3,60) = 1.13$, $p = .35$, $\eta^2 = .05$.

Discussion

Results from the manual tilting task indicate that children and adults considered both diameter and water level when they actively tilted the glasses. Age trends regarding an increase of the effect of water level with increasing age were in line with results from previous studies (Black & Schwartz, 1996). However, all age groups equally considered the factor diameter and correctly tilted the thin glasses farther than the wide ones.

In the judgment task, on the other hand, children and adults focused on water level only and did not discriminate the two diameters. Hence, the judgment task differed significantly from the manual tilting task in terms of the knowledge children and adults showed about the effect of glass diameter on the tilting angle. The fact that participants did not show any knowledge about the effect of diameter in the judgment task but correctly tilted the thin glasses farther in the manual tilting task suggests that the manual tilting allowed them to access some action-based knowledge they could not retrieve in an abstract judgment task. This dissociation also implies that the manual tilting task was in fact solved by using an imagery strategy and was not based on abstract formal knowledge (cf. Schwartz, 1999; Schwartz & Black, 1999). Furthermore, the large effect size of water level in the judgment task and the highly similar consistencies rule out the possibility that the absence of an effect of diameter was due to noisier data or a mere lack of power. They rather show that participants were able to handle the judgment task quite well.

Unlike forced-choice judgments that have been used previously (Schwartz, 1999; Schwartz & Black, 1999), this judgment task used a nonverbal and interval scaled dependent variable. Thus, theoretically, it would have been possible for participants to imagine the tilting movements and simply indicate the final position of the imagined movement. However, the absence of any effects of diameter suggests that an imagery strategy either was not used in the judgment task or was hardly successful.

On the contrary, the manual tilting task facilitated the successful use of an imagery strategy. However, this task differed in several aspects from the judgment task. At this point, it is unclear which aspects of the manual tilting task facilitated imagery performance. As indicated in Fig. 1, the judgment task differs from the manual tilting task in that it does not provide any visual information about the glass movement that could serve as a reference frame for the imagination of the water level. In addition, the judgment task does not provide any motor information about the tilting movement because there is no active "hands-on" movement taking place. This implies that the judgment task also lacks haptic information about the glass diameter, and this could make the dimension less salient. The following experiments were designed to further probe the question of which one of these task differences accounts for the observed performance dissociation. They tested whether not executing the movement (Experiment 2) and not seeing the tilting movement (Experiment 3) would reduce performance in the manual tilting task.

Experiment 2

The aim of Experiment 2 was to test whether motor activation per se facilitates imagery or merely facilitates visual imagery by providing cues about the spatiotemporal changes that might be crucial for a smooth mental transformation. The task again involved turning a glass with imaginary water so that the water would reach the rim. However, the glass was not turned manually but rather was turned by means of a remote-controlled motor. Thus, children and adults were provided with visual information about the changes in time and space without letting them actively execute a corresponding hand movement. It was of special interest whether children and adults would still turn the thin glasses farther than the wide ones under these conditions because this would suggest the successful use of an imagery strategy.

Method

Participants

Experiment 2 was carried out with 16 kindergartners (mean age = 5 years 11 months, range = 5 years 2 months to 6 years 9 months), 16 first-graders (mean age = 7 years 5 months, range = 6 years 11 months to 8 years 2 months), 16 third-graders (mean age = 9 years 2 months, range = 8 years 7 months to 9 years 10 months), and 16 adults (mean age = 29 years 0 months, range = 19 years 10 months to 38 years 9 months). Each age group consisted of 8 females and 8 males. In the following, the age groups are referred to as 5-, 7-, and 9-year-olds and adults. Children were recruited from different kindergartens and primary schools in the region of Zurich. Informed parental consent was obtained for all children. Most adult participants were students at the University of Zurich.

Apparatus

The apparatus was identical to that in Experiment 1 except that a motor was attached to the backside of the shaft behind the panel. Participants did not tilt the glasses manually but rather adjusted the tilting angle by operating a remote control. Pressing the left button on this remote control caused a turning movement at a speed of 12 angular degrees per second in a counterclockwise direction, and pressing the right button caused a turning movement in clockwise direction. On releasing either button, the movement would stop instantaneously.

Stimuli and design

The stimuli were identical to those in Experiment 1. The experimental design was analogous to the manual tilting task in Experiment 1.

Procedure

In the first practice trial, the glass was initially tilted manually—just as in Experiment 1. Then the remote control was introduced, and the first practice trial was repeated by using the remote control to start and stop the movement. The second practice trial and the subsequent experimental trials were carried out only with the remote control. Participants were allowed to correct the angle as long and as often as they liked; only the last position was registered.

Results

Remote control task

Means of produced tilting angles (in degrees) for each age group in the remote control task are presented in the lower panel of Fig. 3. An overall ANOVA was calculated with the within-participant factors diameter (2) and water level (2), the between-participants factor age (4), and the tilting angles as the dependent variable. The analysis yielded significant main effects of the factors diameter, $F(1,60) = 51.99$, $p < .001$, $\eta^2 = .46$, and water level, $F(1,60) = 366.57$, $p < .001$, $\eta^2 = .86$. There was no interaction between the factors water level and age, $F(3,60) = 1.00$, $p = .40$, $\eta^2 = .05$, showing that all age groups equally discriminated the two water levels. However, a significant interaction between the factors diameter and age, $F(3,60) = 4.05$, $p < .05$, $\eta^2 = .17$, showed that the older the participants, the more they discriminated the two diameters. This is also evident in the increasingly separated graphs in the lower panel of Fig. 3 and in increasing effect sizes of the factor diameter (partial eta-square) in Fig. 4.

Separate statistical analyses of the tilting angles per age group (ANOVA: Diameter (2) × Water Level (2)) yielded a significant main effect of water level for 5-, 7-, and 9-year-olds and adults, $Fs(1, 15) = 29.18$, 117.21, 190.20, and 509.25, respectively, all $ps < .001$, all η^2s > .65. The factor diameter had a statistically significant effect on tilting angles for 7- and 9-year-olds and adults, $Fs(1, 15) = 6.82$, 33.72, and 36.04, respectively, all $ps < .05$, all η^2s > .30, but not for 5-year-olds, $F(1,15) = 2.80$, $p = .12$, $\eta^2 = .16$.

Consistencies

As in Experiment 1, the correlations between measurement repetitions were calculated in the remote control task. These consistencies were very high overall; for 5-, 7-, and 9-year-olds and adults, Pearson's correlations were $rs = .71, .92, .95$, and .97, respectively. The 5-year-olds showed even higher consistencies than in the manual tilting task in Experiment 1. An ANOVA with the average consistencies (Z values) as the dependent variable and the factors experiment (2) and age (4) showed a slight but significant difference between the two experiments (i.e., whether the glasses were tilted manually or with the remote control), $F(1,120) = 3.98$, $p < .05$, $\eta^2 = .03$, but no interaction with age, $F < 1$.

Comparison of Experiments 1 and 2

Whereas effect sizes (partial eta-square) of the factor water level were very high throughout both experiments, all η^2s > .42, there were task- and age-specific differences regarding the effect sizes of

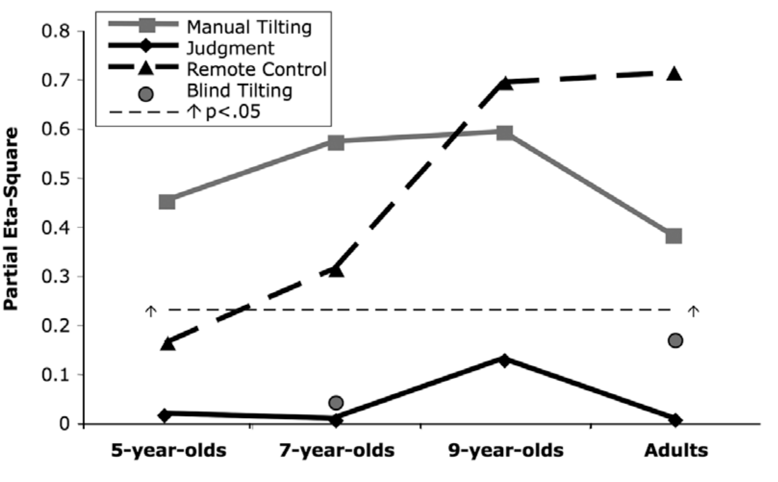

Fig. 4. Effect sizes (partial eta-square) of the factor diameter for the four age groups and the different tasks in Experiments 1 through 3. Effects above the thin dashed line did reach statistical significance ($p < .05$).

diameter. These can be taken as indicators of differing imagery performance in the various tasks. Fig. 4 shows an overview of the effect sizes of the factor diameter for the different age groups and the different tasks in Experiments 1 through 3 (the "blind tilting" task is reported below). The more or less horizontal lines for the manual tilting task and the judgment task show that there were no significant age trends in these two tasks. Whereas no age group considered the factor diameter in the judgment task, the effects for diameter in the manual tilting task were far beyond the significance level of .05. The ascending graph for the remote control task shows a clear age trend for effects sizes of diameter. Thus, younger children discriminated the diameters less when they turned the glasses by means of a motor instead of their own hands. For 5-year-olds, the effect of diameter did not reach the significance level of .05, but also 7-year-olds showed smaller effects compared with the two older age groups and compared with the task where they turned the glasses manually. For 9-year-olds and adults, the glass diameter had large effects even without motor feedback.

Discussion

At 7 years of age and older, observing the tilting movement provided enough information to tilt the thin glasses significantly farther than the wide ones, indicating that children at this age were able to successfully use an imagery strategy even without motor feedback. The 5-year-olds, however, did not show an effect of glass diameter even though their tilting angles were highly consistent.

The consistencies, as measured by the correlation between measurement repetitions, were in fact higher than in the manual tilting task for all age groups. Apparently, the slow and steady movement of the motor allowed a very precise adjustment of the angle. It might be that the younger children's not yet fully developed fine motor skills did not work to their disadvantage in this task. However, the consistencies were also higher than in the judgment task of Experiment 1, where no special fine motor skills were needed. Therefore, it might also be possible that the steady turning movement was beneficial for maintaining the mental representation of the water inside the glass. In the task where children and adults turned the glasses manually, they might have turned the glass faster or in a more jerky movement, and this might have caused the mental image to decay.

Thus, the younger children did not generally turn the glasses less precisely. The effect of diameter, therefore, did not fail to reach statistical significance because of higher error variance. It is more likely that the younger children in fact considered the glass diameter to a lesser extent. In combination with the results of Experiment 1, where the glass diameter was considered when the glasses were tilted manually, it can be concluded that actively executed actions are of central importance and have a beneficial effect on younger children's mental transformations. Even at 7 years of age, performance was not quite as good in the remote control task as with hands-on manual tilting. However, with increasing age, transforming mental representations becomes increasingly independent from motor activity.

Experiment 3

Experiment 3 tested whether inhibiting visual feedback about the tilting movement by positioning a curtain in front of the to be tilted glass would deteriorate performance in the manual tilting task. This experiment was carried out with 7-year-olds and adults because the 7-year-olds already showed fairly high consistencies and a strong effect of diameter in Experiment 1. So, if obstructing the visual information results in diminishing the effects of diameter in these two age groups, the same can be expected for other ages.

Method

Participants

Experiment 3 was carried out with 16 first-graders (mean age = 7 years 3 months, range = 6 years 10 months to 7 years 11 months, 8 males and 8 females) and 16 adults (mean age = 26 years 8 months, range = 20 years 2 months to 42 years 11 months, 7 males and 9 females). In the following, the age groups are referred to as 7-year-olds and adults. Children were recruited from a primary school in the region of Zurich. Informed parental consent was obtained for all children. Most adult participants were students at the University of Zurich.

Apparatus

The apparatus was identical to that in Experiment 1 except that a curtain obstructed participants' view. Participants reached through an opening in the curtain and turned the glasses without visual feedback.

Stimuli and design

The stimuli were identical to those in Experiment 1. The experimental design was analogous to the manual tilting task in Experiment 1.

Procedure

The first practice trial was initially explained and carried out without the curtain. Then the curtain was lowered, and the first practice trial was repeated without visual feedback. The second practice trial was presented only behind the curtain. All experimental trails were also presented without visual feedback about the tilting movement, and the experimenter exchanged the glasses behind the curtain so that participants did not see the opaque glasses. Participants saw only the transparent reference glass that was positioned in front of the curtain and showed which water level needed to be imagined.

Results

Blind tilting task

Separate ANOVAs (Diameter (2) × Water Level (2)) per age group with tilting angles as the dependent variable yielded significant effects of water level for 7-year-olds, $F(1,15) = 179.36$, $p < .001$, $\eta^2 = .92$, and adults, $F(1,15) = 156.01$, $p < .001$, $\eta^2 = .91$. The 7-year-olds tilted the glasses with low and high water levels on average 41.2° and 23.2°, respectively. Adults tilted the glasses with low and high water levels on average 35.8° and 19.5°, respectively. However, no significant effects of diameter were found either for 7-year-olds, $F < 1$ (thin 32.7°, wide 31.7°), or for adults, $F(1,15) = 3.17$, $p = .10$, $\eta^2 = .17$ (thin 28.3°, wide 26.0°). These effect sizes are plotted as two circles in Fig. 4 for comparison with the other tasks. This shows that the effect sizes when tilting without visual feedback were nearly as small as in the judgment task.

Consistencies

As in Experiment 1, the correlations between measurement repetitions were calculated for the blind tilting task. Pearson's correlations for 7-year-olds and adults were *r*s = .84 and .94, respectively.

Effects of visibility

To compare participants' performance when tilting with or without visual feedback, the data of the blind tilting task were combined with the data of the 7-year-olds and adults from Experiment 1, where glasses were tilted with visual feedback. An ANOVA was calculated with the within-participant factors diameter (2) and water level (2), the between-participants factors age (2) and visibility (2), and tilting angles as the dependent variable. The analysis yielded significant main effects of diameter, $F(1,60) = 23.44$, $p < .001$, $\eta^2 = .28$, and water level, $F(1,60) = 596.67$, $p < .001$, $\eta^2 = .91$. However, of main interest for the current analysis was the significant interaction between diameter and visibility, $F(1,60) = 4.74$, $p < .05$, $\eta^2 = .07$, showing that the diameters were discriminated less without visual feedback (thin 30.5°, wide 28.9°) than with visual feedback (thin 43.1°, wide 38.8°). Also, the water levels were discriminated less in the blind tilting task (low 38.0°, high 21.3°) compared with with visual feedback (low 52.5°, high 29.4°), $F(1,60) = 15.85$, $p < .001$, $\eta^2 = .21$, and the angles produced were smaller in the blind tilting task, $F(1,60) = 25.17$, $p < .001$, $\eta^2 = .30$. The factor age did not interact with diameter or with water level, both *F*s < 1. A significant main effect of age, $F(1,60) = 8.26$, $p < .01$, $\eta^2 = .12$, showed that overall children tilted the glasses farther than adults (7-year-olds 38.5°, adults 32.1°).

Discussion

Experiment 3 showed that without visual feedback about the tilting movement, only the water level was considered, but the different diameters had no significant effects on tilting angles. Tilting without visual feedback differed significantly from tilting with visual feedback in Experiment 1, where thin glasses were tilted farther than wide ones. This was the case for both tested age groups. The large effect sizes of the factor water level and the high consistencies rule out the possibility that the absence of an effect of diameter without visual feedback was merely due to noisier data or a lack of power. This allows the conclusion that visual information about the tilting movement had a facilitating effect on children's and adults' performance in this task.

It is possible that the visual information about the glass movement served as a reference frame for the imagined water inside the glass, thereby helping to smoothly transform the mental representation of the water. Furthermore, it seems possible that the visible movement of the glass allowed smooth pursuit movements of the eyes that might have mediated a smooth mental transformation. In the blind tilting task, on the other hand, without a moving visual cue to hang onto, the eyes might have jumped in saccades or even stayed fixated.

Differences in eye movements might also explain the discrepancy of our results with those of Schwartz and colleagues (Schwartz, 1999; Schwartz & Black, 1999). In their experiments, adults tilted the thin glasses farther than wide ones even without visual feedback. However, in their experiments participants had their eyes closed, whereas in our experiment participants had their eyes open and a curtain was lowered between the participants and the apparatus. With the eyes closed, it is possible to simulate smooth pursuit eye movements, whereas with the eyes open and no possibility of visual tracking, participants probably executed saccades (Lenox, Lange, & Graham, 1970). Alternatively, the restrictions in our task (tilting in one plane only vs. tilting freely in the air) might account for the different results. It is possible that our more technical apparatus facilitated a more cognitive approach.

A significant main effect of visibility showed that the angles of tilt were generally smaller without visual feedback. Hence, the physically correct angles were underestimated more without visual feedback. This can be explained by the fact that the glass diameter was not discriminated, so the thin glasses were tilted to the same angle as the wide glasses even though in fact the thin glasses should have been tilted much farther. The 7-year-olds tilted all glasses on average farther than the adult participants and, therefore, underestimated the tilting angles less than adults. This is further discussed in the following section.

General discussion

In this study, we investigated whether and at what age children are able to imagine dynamic events that require the representation and transformation of water inside a moving glass and which factors are necessary or beneficial for this imagery performance. A primary focus was on the question of whether visual or motor information about the movement would facilitate performance in this dynamic imagery task.

The results showed that children as young as 5 years of age successfully applied an imagery strategy in an action task where the glasses could be tilted with visual control. In a judgment task, however, all age groups showed markedly lower performance. Furthermore, results showed that visual information had a beneficial effect on imagery performance. However, even with available visual information, younger children depended on executed movements and motor feedback to imagine the events. These results indicate that motor activities are particularly important in imagery performance of younger children. As children develop, transforming mental representations becomes increasingly flexible and depends less on motor activity. In the following, we discuss these results in more detail and compare them with existing claims regarding the development of mental representations. Finally, we provide some practical implications of our results.

In a task where participants actively turned the glasses, already 5-year-olds showed remarkable knowledge about the physical relations by considering the two relevant dimensions of the glasses:

diameter and water level. However, children and adults did not seem to have access to that knowledge in a more abstract judgment task. In the judgment task, children and adults only considered the factor of water level or showed false beliefs about the effect of glass diameter on the tilting angle. This indicates that in the manual tilting task 5-year-olds successfully used an imagery strategy, whereas in the judgment task they were not able to mentally imagine the transformation. Therefore, the results contradict Piaget and Inhelder's (1966/1971) claim that children are not capable of kinematic imagery before the concrete operational stage at around 7 years of age. But our data are in line with previous studies showing that younger children are able to imagine movement and transformations (Black & Schwartz, 1996; Estes, 1998; Frick et al., in press; Funk et al., 2005; Kosslyn, Margolis, Barrett, Goldknopf, & Daly, 1990; Marmor, 1975; Marmor, 1977; Rieser et al., 1994).

When participants tilted the glasses by means of a remote control, we found a significant age trend of increasing use of glass diameter as a relevant factor with increasing age. This result provides converging evidence that the younger the children, the more they rely on motor information and active execution of movements to maintain and control mental images. These results are in line with recent studies showing that young children's mental rotation performance was influenced more by concurrent motor activities than was older children's performance (Frick et al., in press; Funk et al., 2005).

Results from the blind tilting task further indicate that it was not haptic information about the glass diameter that was responsible for superior performance in the manual tilting task. In the blind tilting task, participants grasped the glasses through an opening in the curtain and, thus, had access to haptic information about the diameter, but they still did not use this information. Therefore, we conclude that dynamic sensorimotor information conveyed by the tilting movement, rather than static information about the diameter, facilitated a mental simulation.

An active execution of the tilting movement, although necessary for younger children, was not sufficient to enable successful mental transformations. Even with an active tilting movement, visual information was crucial for a continuous mental transformation. Visual information about the glass movement might provide a reference frame for the to-be imagined water inside the glass or might allow smooth pursuit eye movements and, thereby, help to smoothly transform the mental representation of the water. One might conclude that this visual information is actually the key to successful imagery performance and that tilting the glasses facilitates performance only by providing visual information about the tilting movement.

However, the results for the 5-year-olds show that the tilting movement does not just facilitate imagery performance by yielding visual information about the transformation because there was just as much visual information available in the remote control task. Furthermore, this result challenges the suggestion of Schwartz and colleagues (Schwartz, 1999; Schwartz & Black, 1999) that motor activity facilitates imagery by generating timing information, or information about the changes in time and space, because such spatiotemporal information was also abundantly available in the remote control task. Apparently, the active execution of the tilting movement conveys more information than the visually observed movement in the remote control task could provide—at least for younger children. Therefore, it is more likely that motor activity facilitates imagery by activating motor knowledge or motor schemata. This seems especially plausible if we take into account that the water tilting task requires a simulation of how gravity and tilting the container cause the water to deform in a nonrigid manner. Thus, the motor system might tap into such implicit causal schemata that might not yet be accessible through visual simulation or reflection.

One might further speculate about the question of how motor activity could facilitate imagery performance considering another special feature of our task. Unlike most other imagery tasks, which require a rigid transformation of either an object or a frame of reference, the current task requires coordinating two pieces of information: the movement of the water and the movement of the container. Therefore, motor activity might help children to coordinate these two movements, for example, by taking advantage of already prewired mechanisms of eye–hand coordination (von Hofsten & Rönnqvist, 1988). Furthermore, motor activity might divide the workload between the visual and motor systems by outsourcing one part of the simulation to the hand. However, these ideas are speculative so far, and further research is needed to explain the mechanisms behind the effects of motor activity on mental imagery.

For the observed age differences in the remote control task, there are two possible explanations. First, younger children and older children might have used different imagery strategies. Whereas older children and adults might have solved the manual tilting task using a purely visual imagery strategy, it is possible that younger children solved the task by applying a motor imagery strategy, thereby trying to imagine the necessary action. To do this, they might need to draw on learned motor schemata or motor experience, for which motor activity might be necessary. Second, it is possible that all age groups used motor imagery to solve the task but that older children and adults were able to *covertly* simulate hand movement, whereas younger children were not able to imagine their hands to move without actually moving them. Further experiments are needed to decide which of these two possible explanations is closer to the truth. For now, we can say that the two explanations have in common that mental (visual or motor) simulations become increasingly independent from overt motor activities as the age of the children increases.

The assumption that children's imagery abilities become more and more independent from overt motor activities is in line with Piaget and Inhelder's (1948/1956; see also Piaget, 1936/1952) theory insofar as these authors emphasized the emergence of cognitive abilities out of sensorimotor abilities. However, according to their theory, differences in the importance of sensorimotor feedback would be expected much earlier, at the transition from the sensorimotor stage to the preoperational stage. The current results, and more specifically the visualization of the effect sizes of the factor diameter in Fig. 4, show that the developmental pattern is not as stepwise as the use of statistical significance levels might purport. The pattern rather suggests a continuously increasing independence from sensorimotor feedback with age. This interpretation is in line with Thelen (2008), who proposed that there is a tight coupling among action, perception, and cognition early in life—a coupling that remains well into adulthood but becomes more flexible and adaptive during the course of development.

Although the absolute accuracy of the tilting angles was not of primary interest in the current study, we found as an interesting side result that all age groups systematically underestimated the tilting angles for the thin glasses, especially adults and when tilting without vision. A possible explanation for this could be that adults took a more cognitive approach, whereas younger children relied more on their (accurate) motor simulations. Schwartz and Black found similar effects and (referring to Schwartz & Hegarty, 1996) argued that adults often choose their "head over their hands" and preferably rely on their beliefs rather than on the results of their simulations. This interpretation would also be in line with Kosslyn's (1978, 1980) hypothesis of representational development and with his results (Kosslyn, 1976) that 6-year-olds spontaneously fell back on imagery strategies more frequently than older children and adults.

In line with previous research (e.g., Acredolo et al., 1984; Benson & Uzgiris, 1985; Black & Schwartz, 1996; Frick et al., in press; Rieser et al., 1994), our results emphasize that motor activities might be especially important for supporting mental transformations in children. Furthermore, our results revealed a clear developmental trend, demonstrating that motor activities are more beneficial the younger the children are. These results have important practical implications. If motor processes and embodied knowledge play such an important role in the development of cognitive abilities, it is even more important that children have the opportunity to practice motor skills, in other words, have time and room to play. Knowing more about the effects of motor activity—or the lack of it—on cognitive competencies, therefore, not only is relevant in light of cognitive sciences but also has important practical value for the planning and improvement of school curricula, sports, and recreational activities.

Acknowledgments

We are grateful to Walter Schmid and Henry Gossweiler for technical assistance. We also thank David F. Bjorklund, Daniel L. Schwartz, and an anonymous reviewer for helpful comments on previous versions of the manuscript.

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