Using a Touch Screen Paradigm to Assess the Development of Mental Rotation Between 3½ and 5½ Years of Age

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Abstract

Mental rotation is an important spatial skill. However, there is controversy concerning its early development and susceptibility to intervention. In the present study, we assessed individual differences in the mental rotation abilities of children between 3½ and 5½ years of age, using a touch screen paradigm to simplify task demands. A figure or its mirror image was presented in 8 different orientations, and children indicated in which of two holes the figure would fit by touching one of the holes on the screen. Task instructions were varied in three conditions, giving the children the opportunity to gather manual or observational experience with rotations of different stimuli, or giving no additional experience. Children's error rates and response times increased linearly with increasing angular disparity between the figure and the hole by the age of 5 years, but 4-year-olds were found to respond at chance for all angular disparities, despite the use of a touch screen paradigm. Both manual and observational experience increased the response accuracy of 5-year-olds, especially for children already performing well. However, there was no effect on 4-year-olds. Results point to an emerging readiness to use mental rotation and profit from observational and manual experience at age 5.

Keywords: mental rotation, cognitive development, spatial cognition, preschool children, motor experience

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The ability to represent and reason about objects in space is a fundamental aspect of everyday cognition. In order to interact with our environment, we must be able to represent the positions of objects in our surroundings and recognize objects from different perspectives. Furthermore, in an environment full of motion and transformation, we also must be able to adjust our mental representations in order to maintain an accurate model of the ever-changing world around us. Dynamic and flexible representations aid us when making predictions regarding the future consequences of object motion, for instance, when entering a building through revolving doors, or in order to avoid collisions when crossing a street.

Much of the previous research on mental spatial transformation skills has focused on a specific kind of transformation, namely mental rotation. Mental rotation is the imagined movement of an object (or array of objects) in 2- or 3-dimensional space. Mental rotation has been thoroughly investigated in adults beginning in the early 70's (Cooper & Shepard, 1973, Shepard & Metzler, 1971). Studies with children younger than 6 years have been less common, and have yielded diverging indications of when this ability emerges and what factors influence performance. In particular, research using looking time paradigms has demonstrated a sensitivity to correspondences between rotated figures in infants as young as 4 to 6 months (Hespos & Rochat, 1997; Möhring & Frick, in press; Moore & Johnson, 2008; Quinn & Liben, 2008; Rochat & Hespos, 1996), but studies using paradigms more similar to the ones used with adult participants have found that children are only able to perform mental rotations at the age of 4 to 5 years, and then at a slower speed than adults (e.g., Kosslyn, Margolis, Barrett, Goldknopf, & Daly, 1990; Marmor, 1975, 1977). In fact, a follow-up study that employed the same procedure as Marmor with different stimuli found even later success:

4- to 6-year-olds performed near chance level (Dean & Harvey, 1979), and analyses of individual children's response time patterns (Estes, 1998) suggested that only a small proportion of 4-year-olds appeared to apply a mental rotation strategy. These findings indicate that there are important individual differences in mental rotation abilities in preschoolers. Furthermore, it appears that even though some very simple ability to anticipate outcomes of rotational movements may be present in infancy, preschoolers still struggle with mental rotation tasks.

Sex differences are frequently reported in studies on adults' spatial abilities (for meta-analyses, see Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995 – but see Terlecki & Newcombe, 2005, for evidence that some of these gender differences in mental rotation might be mediated by differences in computer experience). However, reports of sex differences in young children are inconsistent. Linn and Petersen's meta-analysis did not include children younger than 10 years old, and three of the four studies listed by Voyer et al. with children below the age of 10 found no significant effects of sex on mental rotation (Caldwell & Hall, 1970; Jahoda, 1979; Kaess, 1971). Among more recent studies with young children aged 4 years and older that were not covered by these meta-analyses, some found no sex differences (Estes, 1998; Frick, Daum, Walser, & Mast, 2009; Kosslyn et al., 1990; Platt & Cohen, 1981), whereas others found higher error rates in boys (Krüger & Krist, 2009), or sex differences in older but not younger children (i.e., younger than 4.5 years of age, Levine, Huttenlocher, Taylor, & Langrock, 1999).

Aside from the question of the early origins and individual differences in mental rotation abilities, research on whether mental rotation skills are susceptible to intervention or instruction has yielded inconsistent results. Marmor (1977) investigated whether training 4- and 5-year-olds to use a mental rotation strategy would affect their mental rotation performance. She administered seven training trials in an instruction phase prior to the mental rotation test, in which children saw two unaligned stimuli (bears or cones) and were asked whether they were the same or different. On the first training trial, children watched the experimenter rotate the stimulus to an upright position; on the next three trials, children were allowed to rotate the stimulus to upright themselves; and on the last three trials children were asked to rotate the stimulus "in their mind" without using their hands. In a control condition, children received seven feedback trials, in which they were told whether their responses were correct, without rotating the stimuli to upright. Results showed no significant effect of training, from which Marmor concluded that 4- and 5-year-olds are able to spontaneously use and evoke mental rotations.

In contrast, a subsequent replication study (Platt & Cohen, 1981) showed significant training effects in 5-year-olds, using essentially the same training procedure as Marmor's (1977), with the exception that red mittens were added to the bear's paws and children in the control group went directly to the test trials without receiving any feedback. Additionally, Platt and Cohen did not exclude any participants, whereas in Marmor's studies a substantial number of children were excluded from analyses due to failure to comply or pass test criteria in a pre-training phase (23 % of 4-year-olds in Marmor, 1977; 23 % of 5-year-olds in Marmor, 1975). These facts may be important, as pre-training procedures and highly selective inclusion criteria at the onset of the experiment could contribute to a skewed picture of individual differences and the trainability of children's mental rotation skills at this age.

Platt and Cohen's (1981) study left the question unanswered of whether the training effects were stimulus-specific, or whether the experience would generalize to stimuli other than the trained cones and bears. Another open question was which aspects of the training procedure affected performance most, i.e., whether observing the rotation of the stimuli and receiving visual feedback, or whether manually rotating the stimuli was crucial to improvement. Early theories of cognitive development underscored the importance of sensorimotor or action-based knowledge (e.g., Bruner, Olver, & Greenfield, 1966; Gibson & Pick, 2000; Kosslyn, 1978, 1980; Piaget, 1952/1936; Piaget & Inhelder, 1956/1948, 1971/1966). Piaget and Inhelder proposed that cognitive abilities emerge from sensorimotor experience, such that self-movement is the source of the most basic knowledge. In their account, mental representations may be characterized as symbolic imitations of previously executed actions. Based on these theories, it would be reasonable to believe that manual rotation was the crucial aspect of Platt and Cohen's training.

Indeed, previous research supports the notion that mental transformations in young children may be affected by motor activity (Black & Schwartz, 1996; Frick, Daum, Walser et al., 2009; Frick, Daum, Wilson, & Wilkening, 2009), motor constraints (Funk, Brugger, & Wilkening, 2005; Krüger & Krist, 2009) and even gesturing (Ehrlich, Levine, & Goldin-Meadow, 2006). Moreover, in a recent study, Möhring and Frick (in press) found that 6-month-old infants who were given the opportunity to gather hands-on experience with a test object were more apt to detect violations to rotational events in a subsequent mental rotation task than infants who only had observational experience. In a follow-up study, Frick and Möhring (2012) found that by the age of 10 months, prior observational experience sufficed for infants to detect the violation, suggesting that they became increasingly able to learn from observational experience with increasing age. Interestingly, this development appeared to be related to by infants' motor development.

The main objective of the present study was to further investigate the role of visual and manual feedback in task instruction at the preschool age. Similar to Marmor (1977) and Platt and Cohen (1981), we provided children with training trials, in which children watched the experimenter rotate the stimulus to an upright position, or were allowed to manually rotate the stimuli to upright themselves. However, in contrast to the original studies, these instructions were administered to different groups of children, in order to investigate the relative effects of visual and manual feedback on children's mental rotation performance. A third group did not receive either of these instructions, to serve as a baseline for children's spontaneous ability to use mental rotation. In the present study, children were not excluded on the basis of pre-test performance; instead, all children proceeded to the mental rotation test, in order to obtain a more complete picture of the effects of visual and manual information on all children's mental rotation ability. In contrast to previous work, a different set of stimuli was used for the instruction trials, and surface features of the task were slightly altered. This procedure allowed us to investigate whether manual or observational experience would generalize to a different task with different stimuli.

In the present study, we tested children between 3½ and 5½ years, at an age range that covered the lower margin of previous studies (i.e., 4-year-olds: Estes, 1998; Kosslyn et al., 1990; Marmor, 1977; Platt & Cohen, 1981), and also included children who were half a year younger. In consideration of the very young age of our participants, simplified two-dimensional Shepard-Metzler-like figures were presented, which consisted of two orthogonal segments of differing lengths, rather than the original four segments (Shepard & Metzler, 1971). These figures were presented in different orientations on a touch screen, and the task was to indicate in which of two holes each figure would fit. Thus, unlike many previous studies of mental rotation, the present procedure did not require the conveyance of the complex notions of "congruency," "mirror image", or what constitutes a "different" figure, which simplified task instructions. A similar figure-hole paradigm has been successfully used in previous research, which demonstrated mental rotation abilities in 5-year-olds (Frick, Daum, Walser et al., 2009). Furthermore, the ability to fit objects into apertures has been shown to be well established by the age of 3 (Shutts, Örnkloo, von Hofsten, Keen, & Spelke, 2009). To further simplify the task, children gave their responses by directly touching one of the holes on a touch screen. In contrast to previous work with older children and adults, this direct response measure did not require remembering any buttons for same or different responses, and thus the cognitive demands associated with executing the behavioral response were low.

Method

Participants

Participants were 48 children between 3½ and 4½ years (*M* = 4;0, *SD* = 3.2 months, range: 3;6 to 4;5), and 48 children between 4½ and 5½ years (*M* = 5;0, *SD* = 3.4 months, range: 4;6 to 5;6). For the sake of readability, these groups will be referred to as 4-year-olds and 5-year-olds, respectively. Within age group and sex, children were randomly assigned to one of three instruction conditions: no experience, manual experience, or observation. Ages were virtually identical (*M* = 4;6) across groups. Six additional children were tested but excluded from analyses due to either failure to comply with task instructions (one 4-year-old), perseverative response behavior (three 4-year-olds made all or all but one responses to one side), or incomplete data due to technical difficulties (two children). The sample was predominantly white, middle class, and was recruited from suburban areas of a large US city. All children spoke English and were tested in English.

Stimulus Material

Stimuli in the *instruction phase* consisted of cut-outs of black presentation board that were covered on one side with a light blue foam sheet. Each cut-out piece fit into a hole in a ground-piece of the same color (14.5 by 5.5 cm) when turned appropriately. Three of the cut-outs were symmetrical (rectangle, half-circle, and equilateral triangle) and two pieces were asymmetrical (see Figure 1 for selected examples). For the asymmetrical pieces, there also were mirror images of both the figure- and the ground components. All of these stimuli differed in shape and color from the stimuli used in the main experiment.

Stimuli in the *main experiment* were presented using the program Cedrus SuperLab 4 and displayed on a 17” touchscreen monitor (Elo TouchSystems 1739l). At the beginning of each trial, a blue “fingerprint” appeared centered on the lower edge of a dark grey (RGB-color: 62/62/62) screen. Upon pressing the fingerprint, an orange (RGB-color: 250/200/0) L-shaped figure (or its mirror image) was presented in the middle of the upper half of the screen (see Figure 2). The figure measured 4.8 cm by 8.0 cm, and the arm and stem of the “L” were 2.4 cm wide. Simultaneously, an orange ground (33.5 cm wide and 5.8 cm high) was presented, which extended along the lower edge of the screen. It was divided into two equal-sized areas by a thin vertical line in the same neutral color as the background. Two presented “holes” were centered on each side of the ground. One hole had the same size and shape as the L-shaped figure; the other hole had the same shape and size as its mirror image. The distance between the lower edge of the figure and the ground was between 8.0 and 10.2 cm (depending on the orientation of the figure).

Two response areas were defined that were 10.5 cm wide and 8 cm high and generously covered the left and right “holes”. These two response areas were equidistant from the figure as well as the fingerprint. Responses inside these areas were coded as either correct or incorrect; responses outside these areas caused the trial to be repeated. If there was no response within 10 seconds, the trial was rerun. Response times were registered as the time in milliseconds between pressing the fingerprint and pressing one of the response areas.

Procedure

Participants were tested in a laboratory room. As a warm-up, children were asked to finish a puzzle depicting a caterpillar that was missing three final pieces. Children were then told that they would now play a different kind of puzzle game.

Children in the *manual experience* condition received 18 training trials with the blue cardboard pieces. The pieces were presented one at a time on a black surface, in combination with a ground in which they would either fit or not fit, according to a predetermined order. The first three trials presented pieces in the same orientations as the holes, thus a simple translational movement was necessary to fit them into the holes. Typically, the children rotated the pieces on the black cardboard surface and hardly ever lifted them, as the task lent itself to slide the pieces on the black board. In very rare cases children lifted a piece and tried to fit in upside-down during the instruction trials, so they were told that they were not allowed to flip the piece in this game because the backside was not of the matching blue color. Next, five trials were presented for each of three angular discrepancies between the pieces and the holes: 45°, 90° (in either direction) and 180°. These pieces had to be translated and rotated in order to fit into the holes. Of these 5 trials per angle, one trial showed a symmetrical shape with the correct hole and one trial showed a piece with the wrong-shaped hole (e.g., triangular piece with b-shaped hole). These trials were rather easy and implemented in order to keep children motivated. Three trials per angle presented asymmetrical shapes with either matching or mirror-reversed holes. At the beginning of every trial, children were asked to first guess whether the piece would fit into the hole, and were then permitted to manually move the piece and push it into the hole. Note that in contrast to subsequent test trials, only one hole was presented and the child's task was to decide whether the piece would fit or not.

In the *observation* condition, the same trials were presented, but the children were not permitted to turn the pieces themselves. After they made their guess as to whether the piece would fit, the experimenter slowly rotated the piece and moved it to the hole. Children were allowed to push the piece in the last two millimeters in order to maintain engagement in the task. Immediately after the training, children proceeded to the main experiment and were told that they would now play the same game on the computer. In the *no experience* condition, children directly proceeded to the main experiment after the warm-up puzzle.

The main experiment was first introduced and explained with cardboard stimuli that had the same shape and color as the stimuli depicted on the touch screen, but were slightly smaller (88%, see Figure 2). Children were asked to help a small toy figure “fix his road”, so that he would not fall into the holes in the road when trying to walk across. In three instruction trials, the experimenter placed a cardboard piece centered above the two holes and asked the child to pick the hole in which the piece would fit and to try to fit it in themselves. The three instruction trials alternated between the L-shaped figure and its mirror image, and the figures were placed at roughly 45° or 135° (in either direction). Children were instructed that they were not allowed to flip the pieces because the other side was not of the matching orange color.

After the instruction trials, children were told that they would next play the same game, but on the computer. Children started each trial by pressing the blue fingerprint on the touch screen. A figure and two holes appeared on the screen, and children were instructed to point to the hole that they thought the piece would fit if turned the right way. Children first received 4 practice trials on the touch screen, after which the smiling or frowning face of the toy figure provided feedback (in accord with selection of the correct or incorrect hole), followed by 16 experimental trials without feedback. Prior to the experimental trials, children were informed that the smiley face would not show up anymore. After half of the experimental trials, children were allowed to take a short break, and a progress bar would show the children how much they had accomplished and how many holes were left to fill. At the conclusion of the experiment, the same progress bar with all the holes filled in was presented along with a smiley face, indicating that the child had successfully fixed the road. (This presentation was not contingent upon level of performance.)

Design

The L-shaped figure and its mirror image were presented in eight different orientations, from 0° to 315° (clockwise) in steps of 45°, which resulted in 16 different trials. On 0°-trials, the pieces were presented in the same orientation as the hole and only a translational movement was necessary to mentally match the pieces with the holes. However, with increasing angular discrepancy between the pieces and the holes (45° up to 180°) a rotational as well as translational movement was necessary to mentally align the pieces with holes. Trials were presented in one of four different predefined quasi-random orders, with the restriction that every angle was presented once in the first and second half, respectively.

Furthermore, there were two versions of the grounds: in Version A, the L-shaped hole was presented on the left side, in Version B the L-shaped hole was presented on the right side. Children were assigned randomly to one of the versions and orders, with the restriction that there was an equal number of 4- and 5-year-old boys and girls for each versions and order in each instruction condition.

Results

Using a touch screen allowed us to record children's choices and response times. We first analyzed how many of the 16 experimental trials each child solved correctly, as an indicator of their overall performance. We next analyzed whether error rates and response times increased with increasing angular distance of the figure to the hole, which was to be expected if children mentally rotated the figure to solve the task (cf. Estes, 1998). Additionally, we performed separate analyses using data from children whose overall performance was relatively strong, to examine whether inclusion of data from children who responded randomly might have obscured some effects.

Overall performance (total correct trials)

Figure 3 shows the distribution of performance scores for the entire sample and for the two age groups separately. All of the histograms exhibit a dip at the point corresponding to nine correct responses, which suggests that the sample may be composed of two separate groups: one group of children who responded at chance level (obtaining about 8 out of 16 correct responses), and a group who responded better. According to the binomial distribution, more than 11 trials correct out of 16 trials with two choice alternatives would be considered as above chance level (with $p < .05$). Given the dip in the histograms at 9 correct choices, and to minimize a beta-error of missing children who were not guessing, a slightly more lenient cut-off point of more than 10 correct choices was used to define good performance (binomial $p = .105$). According to this criterion, out of the total 96 participants, 35 children (36%) were classified as good performers. Among these, 13 children (27%) were 4-year-olds and 22 children (46%) were 5-year-olds, $\chi^2(1, N=96) = 3.64$, $p = .056$.

There was a significant relationship between overall performance and accuracy on the two 0°-trials, which required translation but no mental rotation, $\chi^2(1, N=96) = 27.6$, $p < .001$. Out of 96 children, 74 (= 77%; 75% of 4-year-olds and 79% of 5-year-olds) showed consistent results, in that they either were classified as good performers and solved both 0°-trials correctly (29%), or performed at chance and erred on at least one of the 0°-trials (48%). Only 6 children (6%) performed well overall but solved one of the 0°-trials incorrectly, and one child made two errors. Finally, there were 15 children (16%) who solved both 0°-trials correctly but still showed chance performance.

Error rates

In order to investigate whether error rates (ER) rose with increasing amount of rotation needed to fit the figure into a hole, errors for trials with equal angular disparity (but opposite direction of rotation) were averaged. Specifically, responses for 45° angles were averaged with responses for 315º angles, 90º with 270º, and 135º with 225º. This resulted in a new variable we shall refer to as "disparity", with five levels (0º, 45º, 90º, 135º, and 180º angular distance to the hole). Furthermore, errors for trials that presented L-shaped figures and their mirror images were collapsed.

A repeated measures ANOVA was performed with disparity (5) as a within-subject variable, age group (2), instruction condition (3), and sex (2) as between-subjects variables, and mean ER as the dependent variable. This analysis showed a significant main effect of disparity, $F(4, 336) = 2.41$, $p < .05$, $\eta^2 = .03$, with a significant linear component, $F(1, 84) = 5.71$, $p < .05$, $\eta^2 = .06$. Furthermore, the analysis showed a significant effect of age group, $F(1, 84) = 10.55$, $p < .01$, $\eta^2 = .11$, with 4-year-olds on average solving fewer trials correctly ($M = 8.6$, $SD = 2.4$) than 5-year-olds ($M = 10.6$, $SD = 3.3$), a significant interaction of age group and sex, $F(1, 84) = 5.12$, $p < .05$, $\eta^2 = .06$, and a tendency to an interaction of age group and disparity, $F(4, 336) = 2.24$, $p = .065$, $\eta^2 = .03$. All other effects were non-significant, all *p*s > .15, all $\eta^2 < .05$.

To further investigate the above interactions, separate ANOVAs for each age group were calculated (otherwise analogous to the above). These analyses showed that disparity had a significant, $F(4, 168) = 5.62$, $p < .001$, $\eta^2 = .12$, and linear, $F(1, 42) = 14.38$, $p < .001$, $\eta^2 = .26$, effect in 5-year-olds, but not in 4-year-olds, $F < 1$. Figure 4a illustrates that 4-year-olds responded roughly at chance (50 % correct) for all disparities, whereas 5-year-olds' error rates increased with angular disparity between the figure and the holes. In 5-year-olds, males ($M = 11.7$, $SD = 3.4$) performed better than females ($M = 9.4$, $SD = 2.9$), $F(1, 42) = 7.36$, $p < .05$, $\eta^2 = .15$, but there was no difference between males ($M = 8.6$, $SD = 2.3$) and females ($M = 8.6$, $SD = 2.6$) in 4-year-olds, $F < 1$. The interaction between instruction condition and disparity approached significance in 5-year-olds, $F(8, 168) = 1.94$, $p = .058$, $\eta^2 = .08$, but not in 4-year-olds, $F < 1$.

Response times

Response times were analyzed using only correct responses. Furthermore, 6 outliers of response times faster than 500 ms (2 incorrect and 4 correct) were discarded. Similar to error rates, response times were pooled across trials with angles of equal disparity between figures and holes and across L-shaped figures and their mirror images.

A repeated measures ANOVA was performed with disparity (5) as within-subject variable, age group (2), instruction condition (3), and sex (2) as between-subjects variables, and mean RT as dependent variable. This analysis yielded a significant interaction of age group and disparity, $F(4, 192) = 2.77$, $p < .05$, $\eta^2 = .06$. Figure 4b illustrates that 5-year-olds' but not 4-year-olds' response times showed an overall positive relationship with disparity, similar to the results for error rates above. All other effects and interactions were non-significant, all *p*s > .10, all $\eta^2 < .06$. Again, separate ANOVAs for each age group (otherwise analogous to the above) confirmed that disparity had a significant, $F(4, 104) = 4.47$, $p <. 01$, $\eta^2 = .15$, and linear, $F(1, 26) = 11.15$, $p < .01$, $\eta^2 = .30$, effect in 5-year-olds, but not in 4-year-olds, $F < 1$.

Effects of experience

The above analyses hinted at effects of instruction condition on 5-year-olds' error rates. However, the inclusion of children who respond near chance level may have obscured effects by contributing a large amount of error variance. Furthermore, previous studies often found that only children with some cognitive readiness (e.g., as revealed in gestures, see Church, & Goldin-Meadow, 1986; Perry, Church, & Goldin-Meadow, 1988) profited from training. Therefore, in the following analyses good performers and near chance performers were considered separately.

Separate ANOVAs with disparity (5) as within-subject variable, instruction condition (3), and sex (2) as between-subjects variables, and ER as dependent variable showed that effects of instruction condition were statistically significant for good performers, $F(2, 16) =$

5.09, $p < .05$, $\eta^2 = .39$. Post-hoc comparisons (Hochberg's GT2) indicated that good performers made fewer errors with manual experience than without any experience, (mean difference = 16 %, $p < .05$), and fewer errors with observational experience than without any experience (mean difference = 17 %, $p < .05$). The difference between manual and observational experience was non-significant (mean difference = 0.6 %, $p = .99$, see Figure 5). This group also showed a significant linear increase in ER with increasing disparity, $F(4, 64) = 4.34$, $p < .01$, $\eta^2 =.21$; lin. $F(1, 16) = 7.48$, $p < .05$, $\eta^2 = .32$. All other effects were non-significant, all *p*s > .59, all $\eta^2 < .10$. Near-chance performers, on the other hand, exhibited no significant effect of instruction condition, $F > 1$, or disparity, $F(4, 80) = 1.55$, $p = .20$, $\eta^2 = .07$. A trend for an interaction between instruction condition and disparity, $F(8, 80) = 1.98$, $p = .059$, $\eta^2 = .17$, was largely due to a very high error rate at 180° without experience. All other effects were non-significant, all *p*s > .15, all $\eta^2 < .08$[1].

Similar analyses with RT as dependent variable showed a significant linear effect of disparity in good performers, $F(4, 56) = 5.03$, $p < .01$, $\eta^2 =.26$; lin. $F(1, 14) = 10.38$, $p < .01$, $\eta^2 = .43$[2]. No main effects of instruction condition, or interactions of instruction condition with disparity were found ($F < 1$).

Discussion

In the present study, the mental rotation abilities of 4- to 5-year-olds were assessed using a touch screen paradigm. Results suggest developmental changes in mental rotation abilities between the ages of four and five. Five-year-olds on average solved more trials correctly than 4-year-olds, and analyses of children's responses as a function of angular disparity from the figure to the hole also suggested developmental progression between 4 and 5 years of age. Whereas 5-year-olds's error rates and response times increased linearly with increasing angular disparity between the figure and the hole, 4-year-olds responded roughly at chance and at the same speed for all disparities. Linearly increasing response patterns are generally accepted as being indicative of mental rotation and have been shown to be strongly associated with reports of the subjective experience of using mental rotation strategies in adults (e.g., Shepard & Cooper, 1982) and in 4- to 6-year old children (Estes, 1998). Thus, the linearly increasing response time and error patterns of the group of 5-year-olds suggest that they used a mental rotation strategy, in general making more errors and taking longer amounts of time to rotate the stimuli at greater degrees of rotation. In contrast, the flat graphs of the 4-year-olds suggest that they either did not apply mental rotation or tried but failed to do so.

The finding that the majority of 4-year-olds performed near chance level in this mental rotation task is consistent with previous reports by Estes (1998) that only a quarter of 4-year-olds reached a rotator criterion based on a significant linear trend in response times. Furthermore, Estes found that at a mean age of 56 and 66 months children responded correctly on 60% and 74% of the trials, respectively. Children in the present study were about half a year younger with a mean age of 48 and 60 months, solved 8.6 (54%) and 10.6 (66%) out of 16 trials correctly. Taken together, results of these two studies suggest a progressive increase in accuracy (54%, 60%, 66%, 74% correct trials) with increasing age (48, 56, 60, 66 months). Given that the paradigms used by Estes and the present study are quite different from one another, it is even more remarkable that this increase in accuracy with increasing age was found to be so regular. This congruency of results speaks to the validity of this new measure.

A fairly large proportion of children erred on at least one of the 0°-trials. One potential explanation for this result is that children had difficulties with matching a figure to a hole, or in other words, comparing the shape of positive and negative spaces. However, this interpretation seems unlikely in light of previous findings that by 30 months of age, the ability to fit objects into holes is fairly well established (Shutts et al., 2009). A more likely explanation rests on the fact that on 0°-trials, although the piece did not have to be rotated, it still had to be mentally moved (for example in a diagonal translation) to be matched with the hole. A previous study that compared rotational and translational mental transformations in 4- to 6-year-olds (Levine et al., 1999) showed that even though translational items were solved significantly more often than rotational items, scores on translational items were far from perfect (on average, 4.41 and 4.66 out of 8 items correct for horizontal and diagonal translations, respectively). Consistent with our results, 5-year-olds performed significantly better than 4-year-olds, providing convergent evidence that there is considerable progression in rotational as well as translational mental transformation abilities during this developmental time period.

Another task demand that deserves consideration and could account for young children's problems with mental rotation tasks involves the presentation of mirror images. Presenting mirror images is a preferred means to prevent participants from using feature strategies (as already suggested by Shepard & Metzler, 1971), yet the confusion of mirror images has been discussed as the source of school children's difficulties distinguishing between the letters b, d, p and q (e.g., Davidson, 1935). On the other hand, mental rotation studies showing that already infants can distinguish between mirror images presented in different orientations (e.g., Möhring & Frick, in press; Moore & Johnson, 2008, Quinn & Liben, 2008) suggest that the foundation for this ability is in place early on. Moreover, Wohlwill and Wiener (1964) reported a high level of proficiency in 4-year-olds' differentiation of up-down and left-right mirror reversals. Caldwell and Hall (1969) came to the conclusion that mirror confusions are most likely due to children's (task-)inappropriate concept of "same" and "different" rather than perceptual abilities. The present study tried to avoid this problem by not asking for same-or-different responses, but to ask children which piece would fit into a hole. Nevertheless, on the basis of the present results it cannot be ruled out that cognitive limitations in differentiating mirror images may in part account for individual differences in mental rotation.

In order to shed light on which factors may determine children's mental rotation performance, we compared three different instruction conditions, which gave children the opportunity to *manually turn* or *observe* an experimenter turn different stimuli, or no such experience. Results showed that the group of 4-year-olds was not affected by either form of experience, suggesting that they were not cognitively ready to profit from the additional manual and visual information. In contrast, 5-year-olds showed a tendency to profit from experience, and in an analysis that focused on children who performed well, the instruction condition was found to have a significant effect on error rates. This result is in line with findings from previous training studies indicating that only children with some cognitive readiness (e.g., as revealed in gestures, see Church, & Goldin-Meadow, 1986; Perry et al., 1988) benefit from training.

Post-hoc tests indicated that manual and observational experience had a similar positive effect, as compared to the baseline condition without additional instruction. Since the stimuli used in the instruction phase were different from the ones used in the later experimental trials, increased familiarity with the stimuli cannot account for these effects. Furthermore, because surface features of the task were different, effects cannot simply be explained by increased familiarity with the basic task format. More likely, children benefitted from observing the rotational movement and manipulating the pieces, and were able to transfer this knowledge to the subsequent mental rotation task.

Based upon the above-mentioned reports of positive effects of motor activity in children (e.g., Ehrlich et al., 2006; Frick, Daum, Wilson et al., 2009) and infants (Frick & Wang, 2012; Möhring & Frick, in press), we might have expected active manual experience to have more impact on performance than observational experience alone. However, there is recent evidence that effects of observational experience increase with age and infants' own motor abilities (Frick & Möhring, 2012). Thus, by 5 years of age, our children may have been old enough to learn from observational experience. Furthermore, task differences may explain differences to the above studies that found superior performance after active movement in children. In Ehrlich and colleagues' study children were gesturing or observing gestures, and in Frick and colleague's study the movement was remote controlled. Thus, direct interaction of an observed human model with the stimulus may be a precondition for successful learning through observation. Given the applied value of such interventions for education, future research should further investigate which factors promote observational learning and which are necessary preconditions if young children are to profit from observational experience.

In line with previous reports of sex differences in older participants (for a meta-analyses, see Linn & Petersen, 1985) and infants (e.g., Moore & Johnson, 2008; Quinn & Liben, 2008), error rates of 5-year-old boys were lower than those of girls. However, when children who responded near chance level were excluded from analyses, 5-year-olds showed no sex effects, and therefore these results should be interpreted with caution. Furthermore, there are several studies on mental rotation performance in 4- and 5-year-olds that reported no significant effects involving sex (Estes, 1998; Kosslyn et al., 1990) or only 3- and 5-way interactions that were not explored any further (Marmor, 1975, 1977). Thus, it appears that sex differences are not robust in 4- to 5-year-olds.

Our results indicate that preschool-age children still have difficulties with a very simplified mental rotation task that was designed to put as few demands on working memory, attention span, and verbal comprehension as possible. Even with these considerations, only a small number of 4-year-olds showed good performance. These results seem to contradict recent findings of early mental rotation competence in infants (e.g., Moore & Johnson, 2008;

Quinn & Liben, 2008). However, these discrepancies may be due to differences in research paradigms that are used in studies targeting different age groups. The manner of stimulus presentation often differs considerably, and – more importantly – infant studies generally utilize looking time methods, and thus the dependent measure necessarily differs from those practicable with older children. Looking time measures may be more sensitive and detect more subtle cognitive abilities that may be obscured when children have to make a conscious choice and execute a motor response. Thus, looking time paradigms may detect precursors of mental rotation abilities, such as a basic understanding of rotation processes and anticipation of object movement, but these insights may not yet have behavioral consequences. Previous studies have shown that it takes several more months for this precursory understanding to become behaviorally applicable, so that infants can successfully rotate objects in order to fit them through apertures (e.g., Örnkloo & von Hofsten, 2007). Our results extend these findings by showing that even by age 5, when manual dexterity is no longer a limiting factor, there are still considerable developmental progression and individual differences in the ability to mentally rotate an object.

More sensitive and age-appropriate methods are needed to reconcile these divergent findings in different age groups. The present study took a first step in this direction by employing a touch screen method that provided an immediate and direct input method, requiring little explanation and entailing low memory demands. Future research should aim to find out more about the development of this spatial ability and the ontogenesis of individual differences. Recent research has shown that individual differences in spatial skills are predictive of later careers in STEM disciplines (Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009). Therefore, it is of important practical relevance to learn more about individual differences in mental rotation abilities, their origins, and means to foster this spatial skill at a young age.

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Footnotes

[1] Analyses for 4-year-old good performers showed no effects of disparity, $F(4, 32) = 1.31$, $p = .29$, $\eta^2 = .14$, and no main effect of or interaction with instruction condition ($F < 1$).

[2] There was no such effect in 4-year-old good performers ($F < 1$).

Figure Captions

Figure 1. Examples of stimuli used in the instruction phase: asymmetrical or symmetrical figure- and ground-pieces.

Figure 2. Examples of stimuli used in the main experiment: (a) 0°-trial, L-shaped stimulus, ground version A; (b) 135°-trial, mirror image of L-shaped stimulus, ground version B.

Figure 3. (a) Histogram showing the total number of children for each performance score (correct trials out of 16), and (b) separate histograms for each age group.

Figure 4. (a) Mean error rates, and (b) mean response times for correct trials only by angle of disparity, for the two age groups.

Figure 5. Error rates by instruction condition for good performers and near-chance performers in each age group.

Figure 1

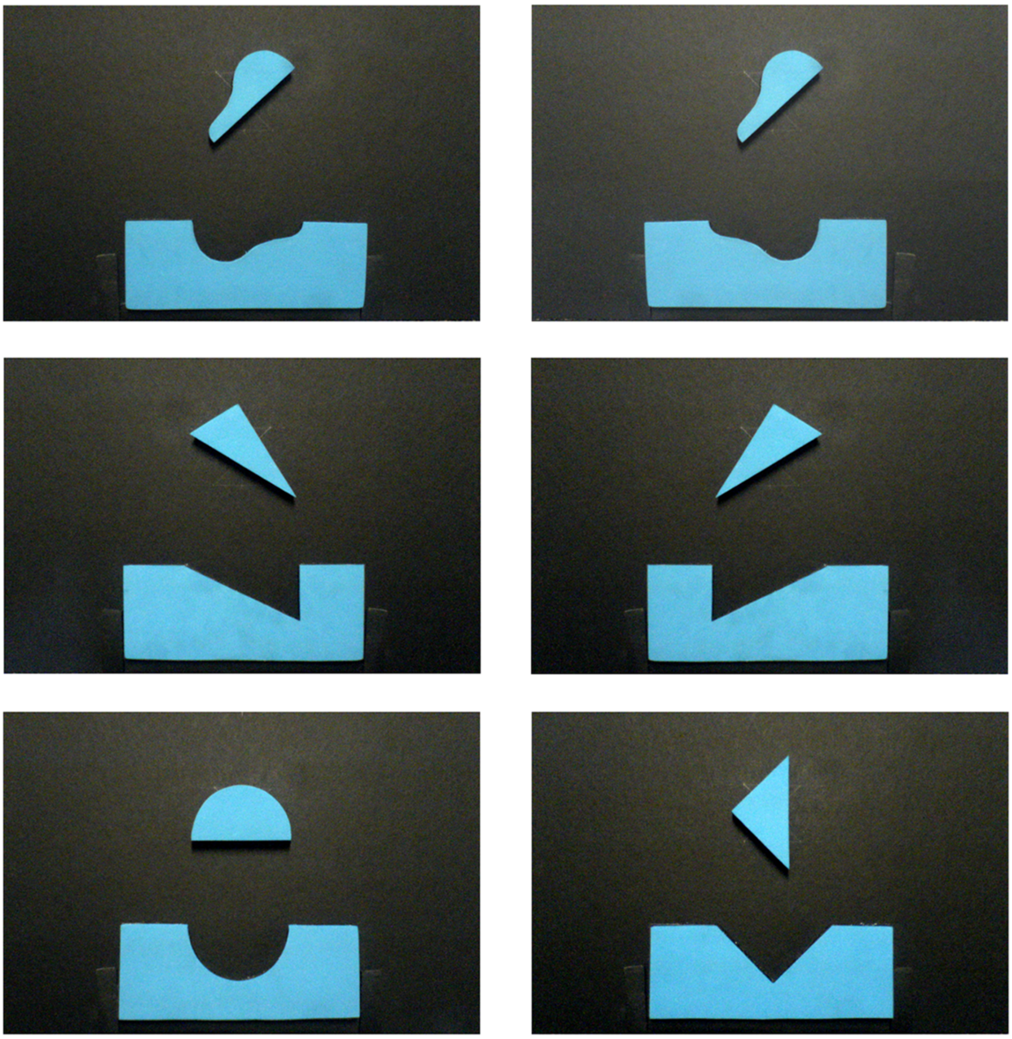
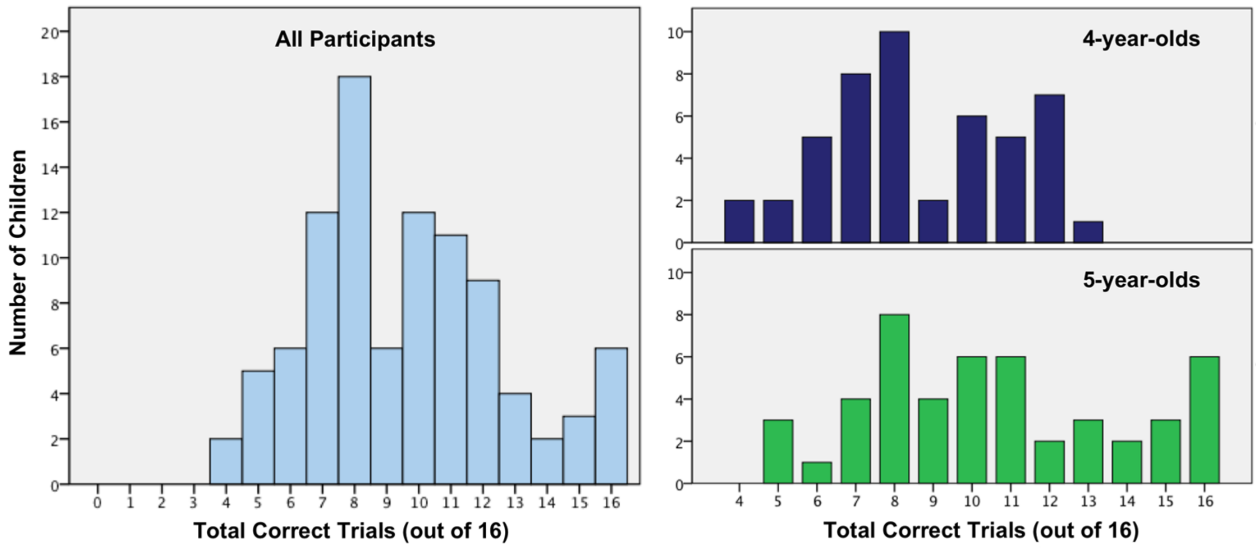


Figure 2

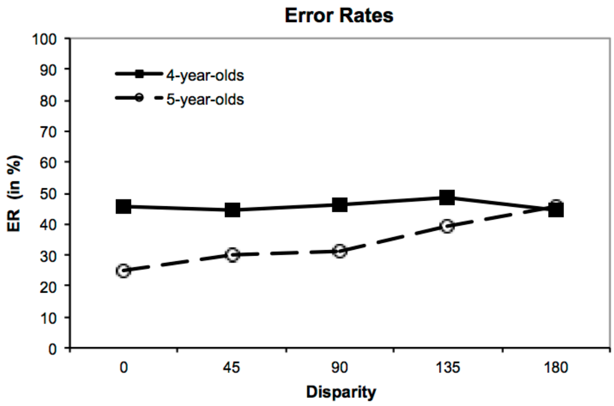
a) b)

Figure 3

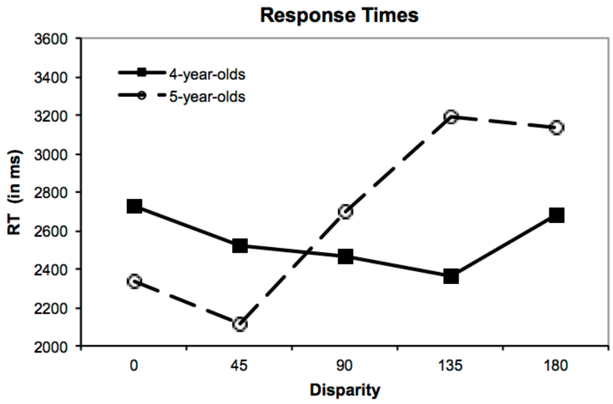

All Participants
Number of Children
Total Correct Trials (out of 16)
4-year-olds
5-year-olds
Total Correct Trials (out of 16)

a) b)

Figure 4

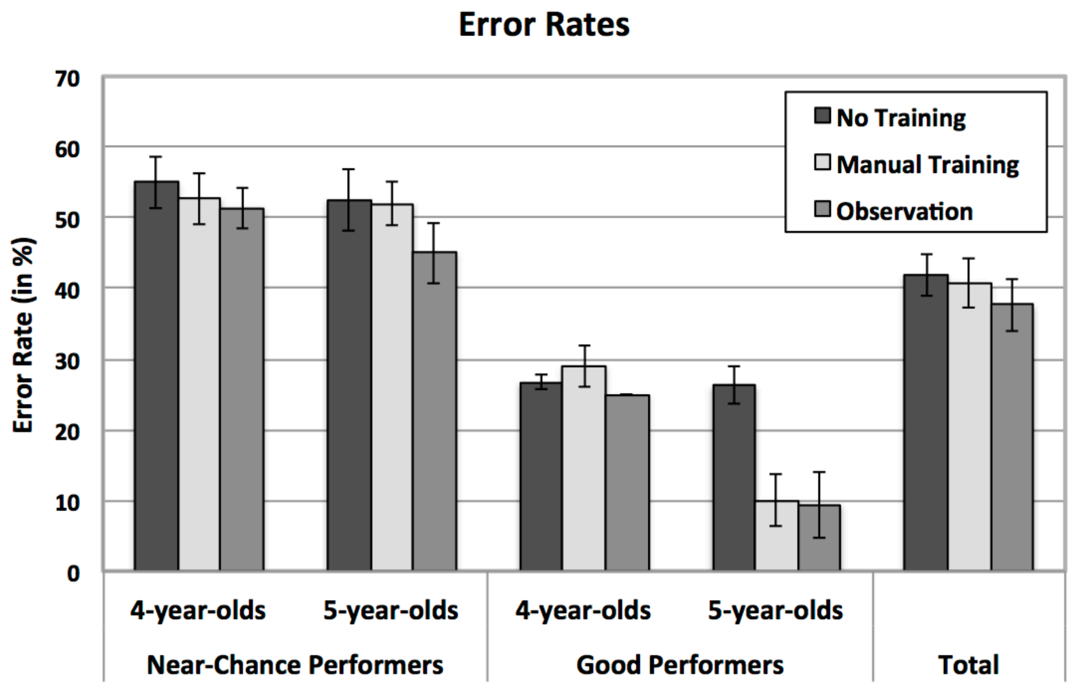

Error Rates
100
90
80
70
60
50
40
30
20
10
0
ER (in %)
4-year-olds
5-year-olds
0
45
90
135
180
Disparity

a)


Response Times
3600
3400
3200
3000
2800
2600
2400
2200
2000
RT (in ms)
4-year-olds
5-year-olds
0
45
90
135
180
Disparity

b)

Figure 5


Error Rates
70
60
50
40
30
20
10
0
Error Rate (in %)
No Training
Manual Training
Observation
4-year-olds
5-year-olds
4-year-olds
5-year-olds
Near-Chance Performers
Good Performers
Total