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Touching Up Mental Rotation: Effects of Manual Experience on 6-Month-Old Infants' Mental Object Rotation

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In this study, 6-month-olds' ability to mentally rotate objects was investigated using the violation-of-expectation paradigm. Forty infants watched an asymmetric object being moved straight down behind an occluder. When the occluder was lowered, it revealed the original object (possible) or its mirror image (impossible) in one of five orientations. Whereas half of the infants were allowed to manually explore the object prior to testing, the other half was only allowed to observe the object. Results showed that infants with prior hands-on experience looked significantly longer at the mirror image, while infants with observational experience did not discriminate between test events. These findings demonstrate that 6-month-olds' mental rotations benefit from manual exploration, highlighting the importance of motor experience for cognitive performance.

Research on mental imagery has long been confined to introspective approaches, until Shepard and his colleagues (Cooper & Shepard, 1973; Shepard & Metzler, 1971) came up with an innovative paradigm that allowed for a more objective approach to mental processes. In their task, participants were instructed to discriminate as fast and accurately as possible whether a rotated figure was exactly the same or a mirror image of an original upright figure. The time that adults typically required for this discrimination increased linearly with the angular difference between the stimuli. This indicated that adults mentally rotated one of the stimuli to align and compare it with the other, and that such mental transformations are subject to the same spatiotemporal constraints as movements in the physical world. That is, the further an object has to be mentally rotated the more time it takes, just like object transformations in the physical world. Thus, research on mental rotation abilities is not only interesting in its own right; it also provides access to and evidence for analog mental representations in general and the ability to dynamically transform such images, which is a fundamental process of our thinking.

To date, only a few studies have been undertaken to investigate infants' mental rotation abilities (e.g., Moore & Johnson, 2008, 2011; Quinn & Liben, 2008). Thus, the question of whether infants use analog representations similar to adults (e.g., Kosslyn, 1980, 1981) is far from answered. To find out more about the early developments of mental rotation abilities is important in light of recent evidence showing: (a) considerable gender and socioeconomic differences in spatial tasks, notably those involving mental rotation (e.g., Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005), and (b) evidence that spatial abilities are related to success in geometry and verbal problems (e.g., Delgado & Prieto, 2004) and are predictive of later careers in STEM (science, technology, engineering, and mathematics) disciplines (Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009). Research on the origins of spatial performance differences and factors that facilitate mental rotation performance is essential for designing early interventions and providing equal opportunities for spatial learning early in life.

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The Development of Mental Rotation

In developmental research, classic mental rotation tasks, or slightly adapted versions thereof, were successfully applied down to the age of 4–5 years (e.g., Estes, 1998; Frick, Daum, Walser, & Mast, 2009; Funk, Brugger, & Wilkening, 2005; Kosslyn, Margolis, Barrett, Goldknopf, & Daly, 1990; Marmor, 1975, 1977; Platt & Cohen, 1981). A general conclusion that can be drawn from these studies is that around this age, children are using mental rotation, although they do so at a slower speed than adults. Furthermore, as reviewed by Newcombe and Frick (2010), there are still important individual differences (see also Estes, 1998; Frick, Ferrara, & Newcombe, in press), and mental rotation abilities have been shown to continuously strengthen through early childhood (Estes, 1998; Levine, Huttenlocher, Taylor, & Langrock, 1999; Okamoto-Barth & Call, 2008).

To date, few studies have investigated mental rotation in infants and toddlers. Naturally, the research method has to be adapted to this very young age range, given that infants: (a) cannot press buttons for "same" and "different" responses, and (b) cannot be verbally instructed to distinguish between identical and mirror reversed objects. To solve the first problem, infant studies have taken advantage of the fact that babies tend to distinguish novel from familiar objects, by looking at them for different amounts of time, or to react with prolonged looking times to events that violate their expectations. To solve the second methodological challenge, researchers came up with various ploys to prompt infants to perform a mental rotation.

One way is to show an object initially moving in a rotational trajectory, and to test whether infants can rotate the object beyond the presented movement. This approach was taken by Rochat and Hespos (1996), who presented events in which an object rotated through a 120° arc and continued its trajectory for 60 more degrees behind an occluder. When revealed at the end of the event, the object was in a probable or improbable orientation. Results showed that infants as young as 4 months looked longer at the improbable than at the probable outcome, suggesting that they formed dynamic mental representations of the events and were able to track and anticipate the final orientation outcome of an invisible transformation. These results were interpreted as first evidence of "some rudiments of mental rotation" in infancy. Interestingly, Hespos and Rochat (1997) showed in a follow-up study that when the invisible part of the transformation was increased from 60° to 150°, 4-month-olds failed to discriminate between probable and improbable orientations of the object. In contrast, extending the invisible part of the trajectory did not affect performance of 6-month-olds. The authors ruled out that increasing memory load due to longer retention intervals accounted for these results given that time of occlusion was held constant. These findings suggest that 4-month-olds' success in anticipating the orientation outcome was limited to relatively small transformation angles.

A more recent study by Moore and Johnson (2008) showed that 5-month-old boys were able to mentally rotate an object. After being habituated to an object that underwent a 240° rotation, male infants looked longer at a mirror image of the object that rotated through the previously unseen 120°. However, this and the above-mentioned infant studies differ from mental rotation studies in adults and older children in that they presented a substantial proportion of the rotational movement of the test object in habituation or familiarization trials. Thus, infants might have simply extrapolated the presented movement, which may be an easier task than initiating a mental rotation (cf. Bremner, Bryant, Mareshal, & Volein, 2007).

In a study by Quinn and Liben (2008), this possibility was attenuated, because the rotation of the object was made plausible by showing seven different static views in steps of 45°, before showing the test orientation. In line with Moore and Johnson (2008), results suggested that 3- to 4-month-old boys, but not girls looked longer at the mirror reversed compared to the original stimulus. Even though in this task only static stimuli were shown, it still differed from the original mental rotation task insofar as several orientations were presented. As a result, the angular difference between the test orientation and the closest presented orientations was relatively small (i.e., 45°), and the test orientation could have been inferred by interpolating two presented stimuli.

A similar method was used in a recent study (Schwarzer, Freitag, Buckel, & Lofruthe, 2012), in which the influence of crawling on 9-month-old infants' mental rotation abilities was tested. The authors used the same three-dimensional (3D) objects as in the study of Moore and Johnson (2008). However, exactly as in the study by Quinn and Liben (2008), they showed a series of static pictures of the rotated object throughout habituation. Results showed that crawling infants looked longer at the mirror object, suggesting that mental rotation abilities are linked to the development of self-locomotion.

Taking a different approach, Frick and Wang (in press) prompted infants to expect a rotational transformation by placing an object on a turntable, before completely hiding the object and turning the turntable by 90°. This procedure avoided showing the object in motion or even different orientations, and results indicated that with this procedure it was not until 15–16 months that infants looked longer at the improbable orientation outcome. Furthermore, this study showed that 13- to 14-month-olds who had hands-on training with the turntable prior to the mental rotation task, looked longer at an improbable compared to a probable outcome. In contrast, observational experience did not have the same beneficial effects. These results suggested that active manual experience increased infants' ability to predict the outcome of a rotation event.

In fact, this finding is in line with recent research showing that motor activity and motor constraints play an influential role especially in young children's mental transformation abilities. For instance, mental object rotation was strongly influenced by simultaneous hand movements in young children up until about 8 years of age, but less so in older children and adults (Frick, Daum, Walser, et al., 2009; Frick, Daum, Wilson, & Wilkening, 2009). Moreover, mental rotation of hand stimuli has been found to depend on the participants' own hand postures (Funk et al., 2005) and this effect was more pronounced in kindergarteners than in adults. Similarly, 6- and 7-year-olds' as well as adults' mental rotation of hand stimuli has been shown to be affected by biomechanical constraints (Krüger & Krist, 2009). Again, response time differences between biomechanically awkward and comfortable hand orientations were more pronounced in 7-year-olds than in adults.

The idea that sensorimotor or action-based experience is important for the development of cognitive abilities is not a new one. Already Piaget and Inhelder (1948/1956, 1966/1971; Piaget, 1936/1952) claimed that cognitive abilities emerge from sensorimotor experience and viewed movement as the source of the most elementary knowledge. Furthermore, they believed that representations are symbolic imitations of previously executed actions. Similar propositions can be found in the work of other researchers (e.g., Bruner, Olver, & Greenfield, 1966; Gibson & Pick, 2000; Kosslyn, 1978, 1980). Indeed, there is evidence that the onset of independent locomotion has a strong influence on spatial abilities, such as distance perception and spatial search (for a review, see Campos et al., 2000) and that manual exploration experience affects infants' perception of goal-directed action (e.g., Sommerville, Woodward, & Needham, 2005). However, there is little research on effects of manual experience on mental rotation in infants thus far.

The Present Study

The aim of this study was to clarify whether and under which conditions 6-month-old infants are able to mentally rotate objects, using a paradigm that was adapted to the young age of our participants, but still as comparable to the classic mental rotation paradigm as possible (cf. Shepard & Metzler, 1971). We investigated 6-month-old infants' mental rotation abilities, using the violation-of-expectation paradigm. Infants saw video sequences with a simple asymmetrical object. The object was presented by a human hand, moved straight down, and then disappeared behind an occluder. When the occluder was lowered, the object (possible event) or its mirror version (impossible event) was revealed in one of five different orientations. Thus, a total of 10 test events were presented to each infant. If 6-month-olds were capable of mental rotation, we expected them to look longer at the impossible than at the possible outcome. That is, after mentally rotating the object and recognizing that a different object is presented at the end of the impossible event, infants' expectation of object consistency should be violated. We would therefore expect prolonged looking times toward the impossible test event, because infants need time to process the unexpected outcome. If, however, infants were not able to mentally grasp the object's change in orientation, we expected no differences in looking times between possible and impossible events, because both objects should be regarded as new.

In contrast to previous studies (Hespos & Rochat, 1997; Moore & Johnson, 2008; Rochat & Hespos, 1996), infants did not see any rotational movement of the test object around the same axis as in the test events. In addition, the test object was never shown in any other orientation but upright, which contrasts with methods used in recent studies (Quinn & Liben, 2008; Schwarzer et al., 2012). Instead, the object was moved behind an occluder on a vertical translational trajectory. A rotation behind the occluder was made plausible to the infants by familiarizing them with the rotational movement using a different object prior to testing. This procedure aimed to investigate whether 6-month-old infants are able to initiate a mental rotation of objects by themselves, and thus the present study is the first infant study that never implied a rotation of the test object in the habituation or familiarization phase.

We investigated effects of multiple angles of rotation by presenting objects that varied in orientation from 0° up to 180°, in steps of 45°, in a within-subject design. This design allowed for investigating whether results can be extended to larger angles than previously tested (e.g., 45° in Quinn & Liben, 2008), and whether performance would break down at larger angles of rotation (cf. Hespos & Rochat, 1997, between subjects). In the latter case, we would expect looking time differences between impossible and possible events for small changes in orientation, but no differences in larger changes. Surprisingly, orientation has never been varied within subjects in infant research before, even though such an approach is typical for mental rotation studies with adult participants and has the potential to yield valuable information about the extent of mental rotation abilities.

And finally, we explored effects of manual experience on infants' mental rotation performance. Frick and Wang (in press) found effects of hands-on experience on 13- to 14-month-olds' mental rotation abilities. However, to date it is unclear whether infants younger than 13 months would profit from manual exploration. In the present study, we tested infants at the age of 6 months, when they had just started to develop their systematic grasping skills, and coordinated manipulation of objects under visual control emerges (cf. Needham, Barrett, & Peterman, 2002; Piaget & Inhelder, 1948/1956; Rochat, 1989). To explore the ways in which manual experience and exploration promote mental rotation abilities in young infants, half of the infants were allowed to touch an asymmetrical object prior to testing and the other half was only allowed to observe the same test object.

Method

Participants

Forty healthy and full-term infants (M_{age} = 5 months 30 days, *SD* = 9 days) participated in this study. Twenty infants were assigned to the manual exploration condition (M_{age} = 6 months 3 days, *SD* = 9 days) and 20 to the observation condition (M_{age} = 5 months 27 days, *SD* = 8 days). Half of the infants were boys (M_{age} = 5 months 30 days, *SD* = 8 days) and half were girls (M_{age} = 5 months 30 days, *SD* = 11 days). Three additional infants were tested but excluded from the sample due to experimenter error (1) and failure to pass the familiarization criterion (2). According to this criterion, infants were excluded if they looked less than the duration of one complete event presentation on two of three familiarization trials, to make sure they had a chance to become familiar with the general pattern of subsequent trials. Infants were recruited from a pool of families who had volunteered to take part in studies of child development. Infants were predominantly Caucasian, from middle-class backgrounds, and lived in urban and suburban areas of a Swiss city. Parents filled out a consent form prior to the study and infants received a small toy and a certificate for their participation.

Stimuli

The object used for the familiarization trials was symmetrical and had the form of the letter T. The T object was made of plywood, painted blue, and was 10 cm high and 7.5 cm wide. The objects used for the test trials were two asymmetrical objects in the shape of a p and a q, made of plywood, and painted blue in front (see Figure 1). Each object was 10 cm high and 5 cm wide. To have two objects that were mirror objects and could not be brought into congruency with each other by rotation along any axis, the backs of the p and q were constructed to look and feel very different: five concentric plywood circles of decreasing diameter, painted alternating in red and yellow, were glued onto the yellow backs of the objects. The red and yellow

Figure 1. Front (top row) and back sides (bottom row) of the symmetrical object (T) used in the familiarization events, and the asymmetrical objects (p and q) used in the test events.

circles made the back visually distinct, and the 3D step-structure made it haptically distinct from the front.

Apparatus

Events were filmed on a stage with a wooden backboard (66 cm high and 100 cm wide) that was painted white, but still showed some of its wooden structure. An opening (20 cm wide and 20 cm high) at the center of the bottom edge of the backboard allowed an experimenter to insert her right arm to present and move the objects. An invisible glass pane that was mounted parallel to the backboard aided the experimenter in holding the object steadily by slightly pressing it against the glass, and allowed for smooth object movements in the picture plane. At the beginning of each trial (except for the second and third familiarization trials) a gray occluder (21 cm wide and 21 cm high), placed parallel in front of the glass pane, completely covered the view of the smaller cutout in the backboard.

Events

Events were short video sequences that were edited using the program Adobe Premiere Pro CS3. Each infant saw three different familiarization events followed by 10 test events. During the first familiarization event, a human hand presented the T-shaped object on top of the screen (1 s). The T was grasped halfway down the stem, with a precision grip from behind, so that the full T shape was visible. Next, the T was moved down vertically by 30 cm (3 s), disappeared behind the occluder, and continued its movement (0.5 s) until it reached the middle of the occluder. After a short time interval (1 s) the occluder dropped (0.3 s), and revealed the object. In the first familiarization trial the object was revealed in the same 0° orientation as it disappeared and presented for 3 s.

During the second familiarization event, no occluder was present, so that the infants were able to see the whole trajectory of the object, as well as the hand that moved the object at all times. Similar to the first familiarization event, the T was held steadily (1 s) and moved straight down (3.5 s). At the point where the object would have reached the midpoint of the occluder, the hand turned the object 30° clockwise in the picture plane (1 s) and then paused (3.3 s).

In the third familiarization event, the human hand held the T at the top of the screen (1 s), moved it straight down (3.5 s), rotated it 150° clockwise in the picture plane (1 s), and held it steadily in this final orientation (3.3 s).

Each familiarization event lasted a total of 8.8 s and was shown repeatedly, with a black screen of 1.2 s between each repetition. The events shown aimed at familiarizing infants with the occlusion event, the straight-down movement, as well as the rotational movement. Note that these rotational movements were only shown using a different object (the T object) and different rotation angles (30° and 150°) than those used in subsequent test events.

The test events were identical to the first familiarization event, except for the objects used and the outcomes infants saw after the occluder was lowered. In the test events, one of the asymmetrical objects in the shape of the letters p or q (depending on condition) was presented at the top of the screen (1 s), moved straight down (3 s), and disappeared behind the occluder. After enough time for the experimenter to move the object to the middle of the occluder (0.5 s) and rotate it behind the occluder (1 s), the occluder was lowered (0.3 s). Either the same object (possible event) or its mirror version (impossible event) was revealed in one of five different orientations (see Figure 2). Each test event was shown once and infants watched the final paused scene with the object remaining in its

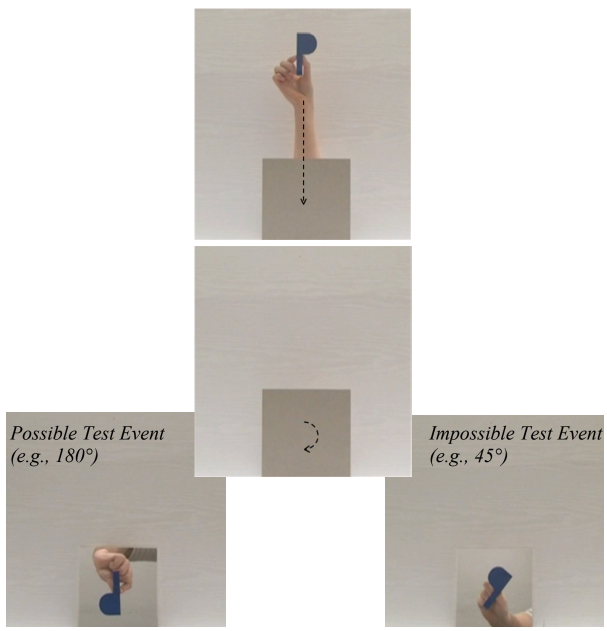

Figure 2. Sequence of a test event (from top to bottom) with examples of a possible (left) and an impossible (right) outcome. Dashed lines indicate the trajectory of the stimulus object.

outcome orientation. The beginning of the event as well as the dropping of the occluder was accompanied by a ding sound (Windows Media ding.wav) to direct infants' attention to the object as well as the outcome of the disclosure.

Procedure

At the beginning of the experiment, infants were given the opportunity to thoroughly encode the test object that they would later see disappearing behind the occluder (i.e., p or q, depending on condition). An experimenter turned the object in front of the infants, rotating it along its vertical axis for a total of 2 min. The main purpose of this encoding phase was to make sure that infants saw that the back and front sides of the object were very different, so that a rotation around the vertical axis could not be assumed as a possible explanation in the case of the "impossible" event. During this presentation, half of the infants were allowed to touch and manually encode the object (*manual exploration condition*) and half of the children were only allowed to observe the object (*observation condition*). In the observation condition, infants were prevented from grasping the object by means of a Plexiglas window (75 cm high and 50 cm wide) that was mounted at the edge of the table. The experimenter moved the object behind this window analogously to the manual exploration condition.

Immediately after the encoding phase, infants proceeded to the mental rotation test. Infants were seated on the caregiver's lap approximately 60 cm in front of a 30-in. TFT computer screen. Dark brown curtains hung from the ceiling to the floor, fully enclosed the viewing area, and also covered the area around the screen, thus minimizing visual distraction. A camera centered 3.5 cm above the computer screen was used to observe and record infants' looking behavior. Each trial began with an attention getter (rapidly alternating geometric shapes) directing infants' attention to the upper part of the computer screen—the position where the object would appear. Once the infant looked at the attention getter, the experimenter started the trial by pressing a computer key. Recording of the infants' looking time began as soon as the trial started. Familiarization and test trials ended when the infant looked away for 2 consecutive seconds or when 60 s had elapsed.

Infants' looking times were measured online by the experimenter. Videos of 20 randomly chosen infants were coded offline by a second naïve experimenter, to calculate interrater reliability (10 infants in each condition). The average Pearson correlation of looking times during test trials between the two observers was $r = .95$ in each condition.

Design

Each participant saw 10 test trials that varied in outcome orientation (0°, 45°, 90°, 135°, 180°, clockwise in picture plane) and type of test event (possible, impossible). Possible and impossible events of each orientation were paired and presented one after the other. However, it was counterbalanced between participants in which order they saw the different events and outcome orientations. Five orders of outcome orientations were determined using a Latin-square to ensure that each order started with a different orientation. The order in which participants saw the possible (p) and impossible (i) events followed one of two patterns (pi ip ip pi ip—or—ip pi pi ip pi). Furthermore, it was varied between participants (and held constant within participants) whether they always saw the q object or the p object disappearing behind the occluder. This resulted in 20 different combinations, each of which was randomly assigned to one participant in each the manual exploration and observation condition.

Results

Test Events

The following analyses are based on infants' looking times at the final paused scenes in the test trials after the occluder had dropped. If an infant had looked away for more than 2 consecutive seconds *before* the occluder was lowered and therefore missed a considerable part of the event, missing values were replaced by the average looking times of infants for that particular orientation, test event, and condition. This was the case in 5% of the possible test trials and 7% of the impossible trials. None of the children ever watched the test events for the whole 60 s.

A preliminary analysis of variance showed that the counterbalanced variables sex, type of disappearing object (p or q), and order of the test events (possible vs. impossible first) had no main effects on infants' looking times during test trials, all Fs < 1, and did not interact with the variables of primary interest: test event (possible vs. impossible), orientation (0°, 45°, 90°, 135°, 180°), or experience

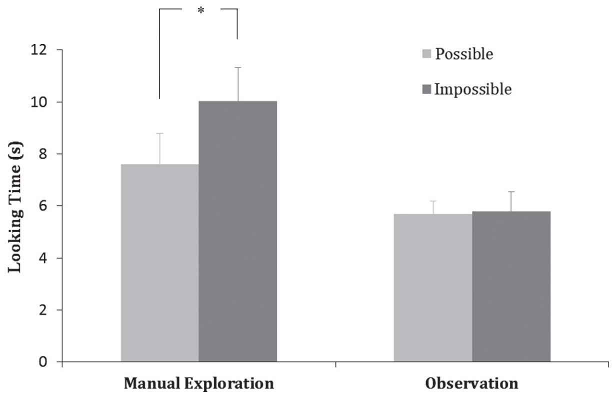

Figure 3. Mean looking times at possible and impossible test events for infants with manual exploration and observational experience. Error bars represent standard errors.

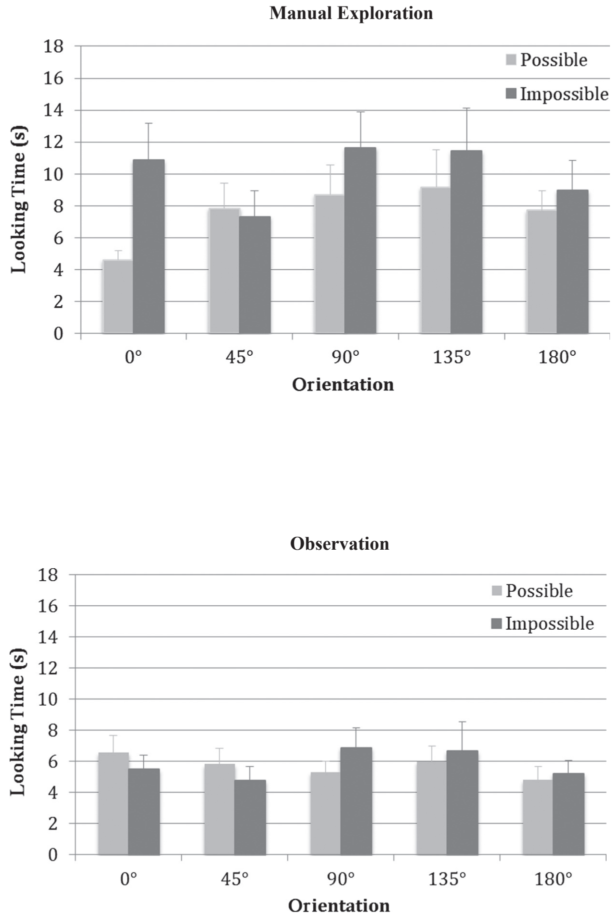

Figure 4. Mean looking times at possible and impossible test events by outcome orientation for infants with manual exploration and observational experience. Error bars represent standard errors.

(manual exploration vs. observation), all Fs < 1.76, all ps > .14. Therefore, these variables were not included in the following analyses.

An analysis of variance (ANOVA) with the within-subject variables test event (possible vs. impossible) and orientation (0°, 45°, 90°, 135°, 180°), and the between-subjects variable experience (manual exploration vs. observation) was calculated. The ANOVA revealed a significant main effect of test event, $F(1, 38) = 6.00$, $p < .05$, $\eta^2 = .14$, with infants looking longer at the impossible ($M = 7.91$, $SE = 0.74$) than at the possible test events ($M = 6.64$, $SE = 0.64$). Furthermore, there was a significant main effect of experience, $F(1, 38) = 5.71$, $p < .05$, $\eta^2 = .13$, showing that infants with manual experience looked longer at the test events ($M = 8.82$ s, $SE = 0.91$) than infants who had observational experience ($M = 5.74$ s, $SE = 0.91$). Moreover, the analysis yielded a significant interaction between test event and experience, $F(1, 38) = 5.12$, $p < .05$, $\eta^2 = .12$, showing that infants with different prior experience differed in their looking behavior during the test events (see Figure 3). There was no statistically significant effect of orientation, $F(4, 152) = 1.50$, $p = .20$, $\eta^2 = .04$, and no interaction of orientation and test event, $F < 1$ (see Figure 4). All other interactions were nonsignificant, all Fs < 1.2, all ps > .35.

To interpret the above interaction between test event and experience, pairwise tests (Bonferroni corrected) were performed, showing that infants in the manual exploration condition looked significantly longer at the impossible ($M = 10.04$ s, $SE = 1.27$) than at the possible test events ($M = 7.60$ s, $SE = 1.18$), $p < .01$. In contrast, infants in the observation condition did not differ in their looking times during possible ($M = 5.69$ s, $SE = 0.51$) and impossible test events ($M = 5.78$ s, $SE = 0.77$), $p = .90$. These results were confirmed by nonparametric tests, showing that in the manual exploration condition, 15 of 20 participants on average looked longer at the impossible than at the possible test events (75%, binomial, $p < .05$). In the observation condition, 9 of 20 infants, looked longer at the impossible than the possible test events, which did not differ from chance (45%, binomial, $p > .05$).

Familiarization

To find out whether infants in the two conditions differed in terms of their looking times during the three familiarization trials, a repeated measures ANOVA with familiarization event (1, 2, and 3) as within-subject variable and experience (manual exploration vs. observation) as between-subject variable was calculated. The dependent variable was infants' looking times at the final paused scene after the occluder was lowered or after the object had stopped moving (in Familiarization Events 2 and 3). The ANOVA revealed a near-significant effect of experience, $F(1, 38) = 3.97$, $p = .054$, $\eta^2 = .10$. Infants in the manual exploration condition tended to look longer throughout the familiarization phase ($M = 23.81$, $SE = 2.63$) than infants in the observation condition ($M = 16.39$, $SE = 2.63$). However, the analysis yielded no main effect or interaction of familiarization event, both Fs < 1.4, both ps > .27. Thus, infants of both experiments did not differ in their looking times toward a particular familiarization event.

Encoding Phase

Finally, it was investigated whether there were differences in how much infants made use of the opportunity to visually and manually encode the object at the outset of the experiment. In the manual exploration condition, infants on average touched the object for 68.84 s ($SD = 20.35$, range = 28.72 to 103.68) and looked at the object for 86.50 s ($SD = 17.27$, range = 55.76 to 115.76). In the observation condition, infants on average touched the window for 53.53 s ($SD = 29.52$, range = 0 to 103.04) and looked at the object for 85.70 s ($SD = 16.39$, range = 44.76 to 111.32). A t test comparing the looking times toward the object showed that infants with manual and observational experience did not differ, $t(38) = 0.15$, $p = .88$, $d = .05$. Furthermore, t tests yielded no significant sex differences in the visual attention toward the object, $t(38) = 1.19$, $p = .24$, $d = .38$, or in the duration infants touched the object in the manual exploration group, $t(18) = 0.83$, $p = .42$, $d = .39$.

Discussion

Results of this study suggest that 6-month-old infants are capable of mentally rotating objects from a static upright position regardless of outcome orientation, but only if they are given the opportunity to manually explore the test object beforehand. The present findings are in line with previous studies reviewed in the Introduction, insofar as they are showing that even young infants can succeed in mental rotation tasks. However, they qualify and extend previous results in a number of ways.

First, our result showed that a looking time pattern indicative of mental rotation was only found for infants who had previously gathered hands-on experience with the test object, but not for those who only had observational experience. These results are in line with the results from Frick and Wang (in press) showing that hands-on experience appears to be instrumental in 13- to 14-month-olds' mental rotation performance. However, our results extend these findings by showing that manual experience facilitates mental rotation performance in infants as young as 6 months old.

Second, to our knowledge the present study is the first to test multiple rotation angles in a within-subject design with infants, although this is the standard in mental rotation studies with adults. In presenting objects that varied in orientation from 0° up to 180°, we were able to show that infants' mental rotation abilities can even be observed with large angles. Interestingly, there was no effect of object orientation or interaction of event and orientation, which suggests that infants' mental rotation performance was not significantly affected by the angle of rotation. In this regard, it should be noted that the looking times used as the dependent variable in the present paradigm must not be confused with response times in classic mental rotation paradigms. There, a linear increase in response times is generally taken as evidence for the use of a mental rotation strategy (e.g., Estes, 1998; Shepard & Metzler, 1971), as it takes more time to simulate a longer than a shorter movement. The looking times used here, on the other hand, are assumed to be indicative of the time infants need to cognitively process the presented event outcomes. Thus, there *could* be an increase in looking times for larger degrees of rotation, but looking times are not *necessarily* a direct measure of the time needed to mentally simulate the rotational movement. Therefore, our finding of no significant increase in looking times with increasing object orientation does not imply that infants did not mentally rotate the stimuli. Rather, the absence of a significant main effect of orientation or interaction with event (in combination with the significant main effect of event) suggests that infants were capable of differentiating impossible and possible events regardless of outcome orientation, and that performance did not break down after a certain degree of rotation.

However, even though infants' discriminations of impossible and possible test events did not differ as a function of orientation, group means suggest less pronounced effects for the 45° and 180° orientations. A possible explanation why some infants might not have differentiated the possible and impossible events in the 45° orientation may be that if infants mentally continued the vertical movement of the disappearing p object (in 0° orientation), the round part of the p object would have ended up in a similar position as the round part of the q object after a 45° rotation. In other words, because the round part of the p object protruded to the right and the one of the q object protruded to the left, the switch from a 0° p-object to a 45° q object might have gone unnoticed. Similarly, the 180° trials presented a special case, because in the impossible event the round part remained on the same side of the vertical line, whereas in the possible event it switched sides. This switch might have been visually salient and caused some infants to look longer at the possible outcome. Similar results have been obtained with older participants. For example, a study with 6- to 9-year-olds (Perrucci, Agnoli, & Albiero, 2008) revealed lower accuracies for different than for same images at 180°, and in general lower accuracies and longer response times on 180° trials. The authors assumed that some participants might have applied a less successful "flipping" strategy (cf. Loring-Meier & Halpern, 1999, for similar results in adults). However, such strategies could not have been very frequent in this study, or we would have found a significant opposite pattern of looking longer at the possible events.

Third, the present results add to previous findings by showing that young infants can perform mental rotation even under harder conditions. Many of the previous studies with young infants differed from studies with older children and adults, in that a substantial proportion of the rotational movement was presented (Hespos & Rochat, 1997; Moore & Johnson, 2008; Rochat & Hespos, 1996). The presentation of rotational movement might have had the effect that the appearance of the object in the test orientation could have been inferred by extrapolating the presented movement. The present study showed that such a presentation of the test object was not necessary and that 6-month-olds were able to perform a mental rotation, even though infants only saw the test object in upright orientation and had to initiate a mental rotation by themselves. The only occasion for infants to see a rotational movement in the picture plane was in the second and third familiarization trials; however, for those a different symmetrical object was used.

Finally, previous studies with young infants (Moore & Johnson, 2008; Quinn & Liben, 2008) found looking time patterns that were indicative of mental rotation only in boys, but not in girls. Our results contradict these findings, by showing that male and female infants did not differ in their looking times toward possible and impossible events. However, our results are in line with findings from a number of studies in infants (Frick & Wang, in press; Hespos & Rochat, 1997; Rochat & Hespos, 1996; Schwarzer et al., 2012) and children (Estes, 1998; Frick, Daum, Walser, et al., 2009; Kosslyn et al., 1990; Platt & Cohen, 1981) that also reported no significant sex differences, or only three- and five-way interactions that were not discussed any further (Marmor, 1975, 1977).

One possible explanation for conflicting results regarding sex differences in infants' mental rotation abilities may lie in differences of stimulus presentation. The infant studies that found sex differences used computer-generated 2D videos of 3D stimuli on a black background (Moore & Johnson, 2008) and 2D letters on white posterboard (Quinn & Liben, 2008). The studies that did not find sex differences in infants so far used 3D live presentations on puppet stages (Frick & Wang, in press; Hespos & Rochat, 1997; Rochat & Hespos, 1996) and thus provided much more 3D information about the object and its spatial environment. The present study used video presentations; however, the videos were taken from real 3D objects that were filmed against a stage-like background that provided substantial depth information. Furthermore, infants had the opportunity to see or even touch the real object prior to the task. Thus, information about the 3D quality of the objects during or before the mental rotation test may serve to reduce sex differences.

Overall, our study showed that 6-month-old infants are capable of performing mental rotations, even in a task that tested multiple rotation angles and prompted infants to initiate mental rotations by themselves. Thus, this study demonstrates precursors of mental rotation abilities using a task that is more comparable to mental rotation tasks in adult studies than the ones used in previous infant studies. However, an essential precondition for infants' ability to perform mental rotations in our task was prior manual exploration of the stimulus object. Thus, our findings support theoretical accounts that posit a central role of motor experience for cognitive abilities (e.g., Bruner et al., 1966; Gibson & Pick, 2000; Kosslyn, 1978, 1980; Piaget, 1936/1952; Piaget & Inhelder, 1948/1956, 1966/1971).

This research presents an initial step toward clarifying the role of action experience in infants' cognitive processes. However, the underlying mechanisms of the observed facilitation effects are yet unclear. It can be ruled out that infants' active engagement in the exploration phase might have simply led to more visual experience with the object, based on the finding that infants' looking times toward the object during both encoding phases did not differ significantly. If anything, it is very probable that infants in the manual exploration group received less visual information, because sometimes their own hands were obstructing the view. In addition, it may be conceivable that active engagement in the exploration phase might have led to an increase in visual attention during the test phase. In fact, results indicate that infants were generally more attentive to subsequently presented events after manual exploration. However, this explanation cannot fully account for the result that infants selectively looked longer at the impossible events. It is more likely that a deeper encoding of the object during manual exploration led to a more stable mental representation of the object, which in turn enabled infants to maintain their mental representation and thus made it more resistant to decay. In fact, this interpretation is supported by research (Wilcox, Woods, Chapa, & McCurry, 2007) showing that infants were more likely to attend to object properties (e.g., color) after combined visual and tactile exploration. The authors hypothesized that bimodal exploration of objects facilitated the formation of more detailed and robust representations than visual exploration alone.

This brings into question whether facilitation effects are specific to manual experience or whether *any* bimodal encoding would be beneficial. There is in fact evidence that bimodal information does not always help. For example, Bahrick, Lickliter, and Flom (2006) showed that 3- and 5-month-old infants did not detect an orientation change in an object after receiving bimodal (audio-visual) information, but after unimodal (visual) information. However, in this case, the auditory modality did not provide relevant information about how the object was oriented. The motor system, on the other hand, may be especially suitable as a secondary source for encoding spatial and spatiotemporal (i.e., movement) information. In the present study, manual exploration may have drawn infant's attention toward spatiotemporal stimulus properties and thus may have helped them to form a dynamic representation of the object and to mentally simulate the rotational movement.

Interestingly, manual exploration was beneficial, even though infants were tested at an age when they had just begun to systematically reach for and grasp objects (starting around 5 months; cf. Needham et al., 2002) and bimodal manual and visual exploration emerges (Rochat, 1989). Nevertheless, 6-month-olds were able to integrate the information from two sources to form more robust representations and successfully rotate them. Multimodal integration of visual and haptic input may be especially important at this age, and the focus of infants' attention may lie especially on motor information. This interpretation is in line with Piaget and Inhelder's (1948/1956) work, positing that starting around the age of 4–5 months (at the stage of "secondary circular reactions") infants begin to systematically manipulate objects and to coordinate vision with grasping. This enables infants to distinguish their own movements from those of the object, and to coordinate different views of the object.

Based on these considerations, it would be informative to investigate whether motor development and individual differences in the development of grasping and bimodal manipulation skills are systematically linked to mental rotation performance. There is indeed evidence for effects of motor development (Schwarzer et al., 2012), showing that crawling infants outperformed noncrawling infants in a mental rotation task. This raises the question of what the underlying mechanisms of this facilitation could be. One possibility is that experiencing a self-initiated change in perspective may enable infants to think about space in more allocentric terms. That is, they may start to think about spatial relations between objects (or objects and agents) independent from their own location and perspective. Another possibility is that the locomotor status may be an indicator of motor development in general, and that children who are early walkers are also able to sit independently early, opening up more opportunities to manually explore objects. Our results that 6-month-olds succeeded in our task *only* if they had the opportunity to touch the object prior to the test even just for a few minutes, shows that the ability of young infants to engage in mental rotation is strongly affected by manual experience. This has two major implications. First, it suggests that individual differences found later in development (e.g., Levine et al., 2005) may to a large extent be caused by differential early experience, as opposed to being genetically predetermined. Second, our results highlight the importance of embodied experience in cognitive development and suggest that providing opportunities for manual exploration may be instrumental in promoting mental rotation abilities and in designing training programs and early interventions.

References

Bahrick, L. E., Lickliter, R., & Flom, R. (2006). Up versus down: The role of intersensory redundancy in the development of infants' sensitivity to the orientation of moving objects. *Infancy*, *9*, 73–96.

Bremner, A. J., Bryant, P., Mareshal, D., & Volein, A. (2007). Recognition of complex object-centred spatial configurations in early infancy. *Visual Cognition*, *15*, 896–926.

Bruner, J. S., Olver, R. R., & Greenfield, P. M. (1966). *Studies in cognitive growth*. New York: Wiley.

Campos, J. J., Anderson, D. I., Barbu-Roth, M. A., Hubbard, E. M., Hertenstein, M. J., & Witherington, D. (2000). Travel broadens the mind. *Infancy*, *1*, 149–219.

Cooper, L. A., & Shepard, R. N. (1973). The time required to prepare for a rotated stimulus. *Memory and Cognition*, *1*, 246–250.

Delgado, A. R., & Prieto, G. (2004). Cognitive mediators and sex-related differences in mathematics. *Intelligence*, *32*, 25–32.

Estes, D. (1998). Young children's awareness of their mental activity: The case of mental rotation. *Child Development*, *69*, 1345–1360.

Frick, A., Daum, M. M., Walser, S., & Mast, F. W. (2009). Motor processes in children's mental rotation. *Journal of Cognition and Development*, *10*, 18–40.

Frick, A., Daum, M. M., Wilson, M., & Wilkening, F. (2009). Effects of action on children's and adults' mental imagery. *Journal of Experimental Child Psychology*, *104*, 34–51.

Frick, A., Ferrara, K., & Newcombe, N. S. (in press). Using a touch screen paradigm to assess the development of mental rotation between 3½ and 5½ years of age. *Cognitive Processing*.

Frick, A., & Wang, S. (2012). (in press). Mental spatial transformations in 14- and 16-month-old infants: Effects of action and observational experience. *Child Development*.

Funk, M., Brugger, P., & Wilkening, F. (2005). Motor processes in children's imagery: The case of mental rotation of hands. *Developmental Science*, *8*, 402–408.

Gibson, E. J., & Pick, A. D. (2000). *An ecological approach to perceptual learning and development*. New York: Oxford University Press.

Hespos, S. J., & Rochat, P. (1997). Dynamic mental representation in infancy. *Cognition*, *64*, 153–188.

Kosslyn, S. M. (1978). The representational-development hypothesis. In P. A. Ornstein (Ed.), *Memory development in children* (pp. 157–189). Hillsdale, NJ: Erlbaum.

Kosslyn, S. M. (1980). *Image and mind*. Cambridge, MA: Harvard University Press.

Kosslyn, S. M. (1981). The medium and the message in mental imagery: A theory. *Psychological Review*, *88*, 46–66.

Kosslyn, S. M., Margolis, J. A., Barrett, A. M., Goldknopf, E. J., & Daly, P. F. (1990). Age differences in imagery ability. *Child Development*, *61*, 995–1010.

Krüger, M., & Krist, H. (2009). Imagery and motor processes–When are they connected? The mental transformation of body parts in development. *Journal of Cognition and Development*, *10*, 239–261.

Levine, S. C., Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial skill. *Developmental Psychology*, *35*, 940–949.

Levine, S. C., Vasilyeva, M., Lourenco, S. F., Newcombe, N. S., & Huttenlocher, J. (2005). Socioeconomic status modifies the sex difference in spatial skill. *Psychological Science*, *16*, 841–845.

Loring-Meier, S., & Halpern, D. F. (1999). Sex differences in visuospatial working memory: Components of cognitive processing. *Psychonomic Bulletin and Review*, *6*, 464–471.

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

Marmor, G. S. (1977). Mental rotation and number conservation: Are they related? *Developmental Psychology*, *13*, 320–325.

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

Moore, D. S., & Johnson, S. P. (2011). Mental rotation of dynamic three-dimensional stimuli by 3-month-old infants. *Infancy*, *16*, 435–445.

Needham, A., Barrett, T., & Peterman, K. (2002). A pick me up for infants' exploratory skills: Early simulated experiences reaching for objects using "sticky" mittens enhances young infants' object exploration skills. *Infant Behavior & Development*, *25*, 279–295.

Newcombe, N. S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education*, *4*, 102–111.

Okamoto-Barth, S., & Call, J. (2008). Tracking and inferring spatial rotation by children and great apes. *Developmental Psychology*, *44*, 1396–1408.

Perrucci, V., Agnoli, F., & Albiero, P. (2008). Children's performance in mental rotation tasks: Orientation-free features flatten the slope. *Developmental Science*, *11*, 732–742.

Piaget, J. (1952). *The origins of intelligence in children* (M. Cook, Trans.). New York: International Universities Press (Original work published 1936)

Piaget, J., & Inhelder, B. (1956). *The child's conception of space* (F. J. Langdon & J. L. Lunzer, Trans.). London: Routledge and Kegan Paul (Original work published 1948)

Piaget, J., & Inhelder, B. (1971). *Mental imagery in the child: A study of the development of imaginal representation* (P. A. Chilton, Trans.). New York: Basic (Original work published 1966)

Platt, J. E., & Cohen, S. (1981). Mental rotation task performance as a function of age and training. *Journal of Psychology: Interdisciplinary and Applied*, *108*, 173–178.

Quinn, P. C., & Liben, L. S. (2008). A sex difference in mental rotation in young infants. *Psychological Science*, *19*, 1067–1070.

Rochat, P. (1989). Object manipulation and exploration in 2- to 5-month-old infants. *Developmental Psychology*, *25*, 871–884.

Rochat, P., & Hespos, S. J. (1996). Tracking and anticipation of invisible spatial transformation by 4- to 8-month-old infants. *Cognitive Development*, *11*, 3–17.

Schwarzer, G., Freitag, C., Buckel, R., & Lofruthe, A. (2012, March). Crawling is associated with mental rotation ability by 9-month-old infants. *Infancy*. Early online publication. doi:10.1111/j.1532-7078.2012.00132.x

Shea, D. L., Lubinski, D., & Benbow, C. P. (2001). Importance of assessing spatial ability in intellectually talented young adolescents: A 20-year longitudinal study. *Journal of Educational Psychology*, *93*, 604–614.

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

Sommerville, J. A., Woodward, A. L., & Needham, A. (2005). Action experience alters 3-month-old infants' perception of others' actions. *Cognition*, *96*, B1–B11.

Wai, J., Lubinski, D., & Benbow, C. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, *101*, 817–835.

Wilcox, T., Woods, R., Chapa, C., & McCurry, S. (2007). Multisensory exploration and object individuation in infancy. *Developmental Psychology*, *43*, 479–495.