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Mental Spatial Transformations in 14- and 16-Month-Old Infants: Effects of Action and Observational Experience

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Infants' ability to mentally track the orientation of an object during a hidden rotation was investigated (N = 28 in each experiment). A toy on a turntable was fully covered and then rotated 90°. When revealed, the toy had turned with the turntable (probable event), remained at its starting orientation (improbable event in Experiment 1), or turned to the opposite side (improbable event in Experiment 2). Results demonstrated a developmental progression between 14 and 16 months of age in infants' sensitivity to spatial object relations and their ability to track the orientation of an object during hidden rotation. Experiment 3 showed that 14-month-olds' performance improved with hands-on training, highlighting the role of action experience in cognitive development.

As children observe or act upon the physical world, they frequently encounter events involving multiple moving objects. For example, children may push a box with a doll inside, causing it to roll over, spin a plate with a spoon sitting on it, or pull a blanket that brings the toy atop within their reach. In these events, a spatial property (e.g., orientation or location) of an object changes as a result of the action performed on another object. The ability to keep track of spatial properties of objects is crucial for maintaining an accurate representation of the world, allowing us to move about and effectively interact with the physical environment. Moreover, understanding the consequences of an action on spatial properties of objects may be a prerequisite for action planning and tool use (Wolpert & Flanagan, 2001). Research on children's ability to track spatial changes of objects can further our understanding about the developments of spatial cognition and mental representations. The present research investigated the development of infants' reasoning about rotational object movement in events involving multiple objects, and the effect of action experience on this ability.

Past research on spatial thinking and tool use has highlighted the role of manual experience and the linkage between perception and action (e.g., Gibson, 1988; Gibson & Pick, 2000; Sommerville, Hildebrand, & Crane, 2008; Sommerville, Woodward, & Needham, 2005). In fact, the emphasis on sensorimotor or action-based experiences was made back in early theories on cognitive development (e.g., Bruner, Olver, & Greenfield, 1966; Piaget, 1936/1952; Piaget & Inhelder, 1948/1956, 1966/1971). For example, Piaget and Inhelder (1948/1956, 1966/1971) believed that cognitive abilities emerge from sensorimotor experience, such that movement is the source of the most elementary knowledge and a representation is an internal imitation of a previously executed action.

However, the notion of a close link between perception and action was challenged by the findings that whereas infants succeeded in looking tasks, toddlers failed in action tasks that required them to apply the same concept (e.g., Berthier, DeBlois, Poirier, Novak, & Clifton, 2000; Hood, Carey, & Prasada, 2000; Keen, 2003; Spelke, Breinlinger, Macomber, & Jacobson, 1992). The discrepancies between looking and action tasks led to the debate about whether perception and action operate as separate systems or whether they draw upon a

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shared representational system (e.g., Bertenthal, 1996; Campos et al., 2000; Kellman & Arterberry, 1998; Willatts, 1997).

Research findings have converged to support the shared-system perspective. First, with careful controls of task demands, infants can succeed in both looking and action tasks (e.g., Hespos & Baillargeon, 2006; Keen & Berthier, 2004; Wang, Baillargeon, & Paterson, 2005; Wang & Kohne, 2007). Therefore, it is likely that the differential responses in looking and action tasks may be due to different task demands. Second, learning in one modality can be transferred to infants' responses in the other modality (e.g., Needham, 2000; Needham, Barrett, & Peterman, 2002; Wang & Kohne, 2007). For example, manual exploration experience has been shown to affect infants' perception of other people's goal-directed actions (e.g., Sommerville et al., 2005), and infants' own grasping abilities influence their understanding of others' grasping action (Loucks & Sommerville, 2012). In addition, infants' independent sitting skills, which free up their hands for visual-manual exploration, are correlated with infants' object completion abilities (Soska, Adolph, & Johnson, 2010).

Furthermore, advancements in motor development, such as the onset of independent locomotion, are associated with improvements in *spatial* abilities (for a review, see Campos et al., 2000), supporting the interplay between perception and action. For example, the locomotor status of 8-month-olds predicted whether they were able to track the location of a hidden object and to search for it after they were moved around the table (Bai & Bertenthal, 1992). Studies that manipulated infants' action experience experimentally have also shown that active movement, such as crawling or walking, facilitated 10- to 12-month-olds' performance in spatial search tasks (Acredolo, Adams, & Goodwyn, 1984; Benson & Uzgiris, 1985). However, positive results have been obtained primarily when the observer's perspective changes. In fact, Bai and Bertenthal (1992) found no correlation between infants' locomotor status and their ability to track object location when it was changed by rotating the table. In addition, studies with children (Huttenlocher & Presson, 1973; Nardini, Burgess, Breckenridge, & Atkinson, 2006) and adults (Simons & Wang, 1998) have shown that the ability to keep track of the appearance of objects or arrays during a *perspective change* differs from the ability to imagine a rotation of the object or array. Thus, it remains an open question whether action experience affects infants' ability to update the mental representations of their spatial surroundings when spatial changes are brought about by object movement rather than by perspective change.

Recent research has yielded initial evidence that 6-month-old infants' understanding of object rotations can be improved if they are allowed to touch the to-be-rotated object before the test (Möhring & Frick, 2013). Besides this report though, evidence in infants is scarce. On the other hand, diverse lines of research with children and adults have provided converging evidence that action experience positively affects mental transformations of objects. For example, hand movements, or even just hand gestures, have been shown to affect the ability to imagine an object rotation in children (e.g., Ehrlich, Levine, & Goldin-Meadow, 2006; Frick, Daum, Walser, & Mast, 2009; Frick, Daum, Wilson, & Wilkening, 2009) and adults (e.g., Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998). Furthermore, neuroimaging data suggest that the parietal lobe plays an essential part in mental spatial transformation (see, e.g., Jäncke & Jordan, 2007; Mast, Bamert, & Newby, 2007, for reviews). The parietal lobe has been associated with transforming sensory input into motor output; most notably, it is thought to be responsible for visuo-spatial processing and manipulation of objects (Fogassi & Luppino, 2005). Taken together, behavioral and neuroimaging data from children and adults support the notion that mental spatial transformation of objects is linked to manual experience.

Studies that investigated infants' understanding of rotational object movements have so far shown that at 3–6 months of age, infants differentiate a familiar object from a new object (i.e., its mirror version) in a novel orientation (Möhring & Frick, 2013; Moore & Johnson, 2008, 2011; Quinn & Liben, 2008). In addition, at 4–8 months of age, infants track and anticipate the orientation of an object that undergoes an invisible transformation (Hespos & Rochat, 1997; Rochat & Hespos, 1996). For example, in the research by Rochat and Hespos (1996), an object was rotated through a 120° arc and continued its trajectory for 60 more degrees behind a screen. When revealed at the end of the event, the object was in a probable or improbable orientation. The results showed that 4- to 8-month-olds looked reliably longer at the improbable than at the probable outcome, suggesting that they expected the object to be revealed in the probable orientation and detected the violation in the improbable outcome.

Taken together, these findings suggest a fairly sophisticated understanding of rotational object transformations in infants. However, the development and the determinants of these early spatial skills remain still unclear. To fill these gaps, the present research investigated the development in infants' representation of rotational transformation events and examined the role of experience in this development. In three experiments, we examined infants' ability to form a mental representation of an object and update this representation during a spatial transformation, which is an important prerequisite for many spatial tasks. More specifically, we tested infants' ability to track the orientation of an object that underwent a hidden rotation. Furthermore, we investigated effects of manual and observational experience on infants' task performance. Infants watched events in which a toy sitting at the center of a turntable (a Lazy Susan) was fully covered and then rotated 90°. When revealed at the end of the event, the toy was in a probable (correct) or an improbable orientation. If infants successfully updated their initial representation of the toy during the hidden rotation, they should respond with prolonged looking at the improbable outcome because it violated their expectation.

The present research extends previous research that investigated infants' understanding of rotational object movements in at least three ways. First, most of the previous tasks presented a single object (e.g., Hespos & Rochat, 1997; Möhring & Frick, 2013; Moore & Johnson, 2008, 2011; Rochat & Hespos, 1996). Our task, on the contrary, involved multiple objects: the toy and the turntable, as well as the cover. It required infants to make use of information about the spatial relations between these items when they mentally tracked the orientation of the toy. Second, in the above-mentioned studies, objects were mostly presented as isolated stimuli, whereas everyday events typically provide richer spatial cues, but are also far more cluttered. In this study, infants saw live presentations with increased complexity involving multiple objects and a human hand acting upon them. Third, in most of the previous studies, the test object was shown in motion (e.g., Hespos & Rochat, 1997; Moore & Johnson, 2008, 2011; Rochat & Hespos, 1996) or in multiple orientations (Quinn & Liben, 2008) before the test, to prompt infants to expect a rotation of the object. Research with adults has shown that it is easier to recognize an object when it is presented in orientations between familiarized views, or in extension of familiarized views, than to recognize an object when it is rotated in a completely novel, orthogonal plane (Bülthoff & Edelman, 1992). In our task, the movement of the toy was concealed by a cover, and infants were required to initiate the rotation of the toy in their minds based on one static view of the object.

Based on the above differences in task demands, we expected infants to succeed in our task at an older age than in the previous research. The literatures on motor development and tool use suggested that our task might be appropriate for infants in their first months of the 2nd year. First, a comparison of the norms of various motor development assessments (Noller & Ingrisano, 1984) showed that the ability to place two objects in a specific spatial arrangement, such as stacking a tower of two cubes, does not emerge until infants are between 12 and 17 months old. Consistent with these results, Fenson, Kagan, Kearsley, and Zelazo (1976) found that infants at 13 months and older successfully arrange objects in an appropriate or functional spatial relation (e.g., putting a lid *on* a pot, a spoon *in* a cup, etc.), whereas infants at 9 months fail to do so. Second, complex forms of tool use that require processing information about spatial orientation still seem to develop in the 2nd year of life. For example, even though infants as young as 7 months produce certain means-end behavior such as pulling a cloth to retrieve a toy (e.g., Willatts, 1999), it is not until they are about 14 months that infants would turn a spoon to the correct orientation before bringing it to their mouth (McCarty, Clifton, & Collard, 1999) and would grasp tools in a useful orientation (McCarty, Clifton, & Collard, 2001). In line with this developmental pattern, our pilot data indicated that it was around the first 4 months of the 2nd year that infants began to detect the improbable outcome in our task, which likewise involved multiple objects in a functional spatial relation and required infants to consider spatial orientations. Thus, this age range was chosen for the present experiments.

Experiment 1

In Experiment 1, we examined 13- to 16-month-olds' ability to infer the orientation of an object after a hidden rotation. We prompted infants to expect a toy to undergo a rotation by placing it in the center of a turntable and rotating it after it was fully hidden. When revealed at the end of the event, the toy was in a probable or an improbable orientation. If infants anticipated the outcome of the hidden rotational transformation, they should respond with prolonged looking at the improbable outcome because it violated their expectation.

Method

Participants. Twenty-eight healthy full-term infants participated in Experiment 1. For most of the analyses, participants were divided into two groups according to their age (see the Results section):

The younger age group was 13–14 months old (M = 13 months 24 days, range = 13 months 1 day to 14 months 29 days; 6 girls, 8 boys), and the older age group was 15–16 months old (M = 15 months 24 days, range = 15 months 0 days to 16 months 25 days; 6 girls, 8 boys). For the sake of brevity, we will refer to these age groups as 14- and 16-month-olds, respectively. Eight additional infants were tested but excluded from analyses due to fussiness (n = 1), distraction, and inattentiveness (n = 5; see the Events section for exclusion criteria), or observer difficulties in following infants' gaze (n = 2).

In this and the following experiments, participants were recruited from birth announcements and local hospitals; they were primarily Caucasian from middle-class backgrounds. Parents were offered travel reimbursement or a small gift but were otherwise not compensated for their participation.

Apparatus. The apparatus consisted of a wooden stage (70 cm high × 102 cm wide × 58 cm deep) that was mounted 96 cm above the room floor. The sidewalls were painted white, and the floor and back wall were covered with white foam boards. In the front of the stage was a large opening (41 cm high × 95 cm wide); between trials, a fabric-covered wooden frame (61 cm × 99.5 cm) was lowered in front of this opening. In the back wall was a small opening (16 cm × 22 cm), located 18 cm from the left wall and extending from the bottom of the back wall, through which the experimenter introduced her left hand into the apparatus. A flap (7 cm × 14 cm) in the back wall allowed the experimenter to monitor her movement while concealing her from the infant's view.

A Lazy Susan (30 cm in diameter) with a gray surface and a white rim was used as a turntable and placed 40 cm from the left wall and 15 cm from the front of the stage. A black cover, made of identical thin slates of cardboard and shaped like a lampshade (17 cm high, 28 cm in diameter at the lower rim, 9 cm at the top rim), was used to hide the toy during the second familiarization trial and during test trials. The cover had a slight texture of connected slates, making it easy for infants to see the movement when the cover rotated with the turntable, without providing distinct visual cues.

One of two stuffed animals was placed on the turntable: A turtle (10 cm high × 24 cm long) was used in the familiarization trials and a duck (14 cm × 15 cm) in the test trials. For one infant, who had the same toy duck at home, the duck was used for the familiarization trials and the turtle for the test trials. However, to simplify matters, we will subsequently refer to the toy used in test trials as "duck." The turtle or duck was affixed at the center of the turntable so that when the turntable was rotated, the location of the toy stayed the same. A rod connected the duck to a handle through a hole in the turntable and apparatus floor, allowing the experimenter to control the orientation of the duck from underneath the apparatus, independent of the movement of the turntable.

Events. Each infant watched two familiarization events and two test events (see Figure 1). In the following sections, the numbers in parentheses indicate the time taken to perform each component. A metronome beat softly once per second to help the experimenter follow the scripts of events. At the beginning of each trial, the fabric-covered frame in the front of the apparatus was lifted, and the event proper began after the infant had looked at the initial display for 2 cumulative seconds.

The first familiarization trial introduced the lampshade-shaped cover, the turntable, and the toy turtle. At the beginning of the trial, the experimenter's left hand rested on the cover; to its left (from the infant's point of view) was the turtle sitting on the turntable facing the infant. When the event began, the experimenter lifted the cover 18 cm, lowered it over the turntable fully hiding the turtle (4 s), lifted it again and returned it to its starting position (4 s).

In the second familiarization trial, the turtle sat uncovered on the turntable, and the experimenter rotated the turntable showing the movement of both the turtle and turntable. The experimenter started with her hand resting on the stage floor to the right of the turntable. She grasped (1 s) the front rim of the turntable and turned it to the right (i.e., counterclockwise if seen from above) at a speed of 30° per s (3 s). After every 90°, the experimenter shifted her grip to the front of the turntable and continued turning. The shifting of the grip served to prevent infants from learning an association between the experiment's hand position and the orientation of the turtle. The above movements were repeated until the trial ended.

These familiarization events provided opportunities for infants to inspect the apparatus and movements involved in the test events, so that they could focus on the crucial aspects in the test trials. In addition, the second familiarization trial demonstrated the movement of the turtle during rotation, to prompt infants to generate an expectation about the spatial transformation of the test object. Therefore, we chose a toy with a clear spatial axis for the

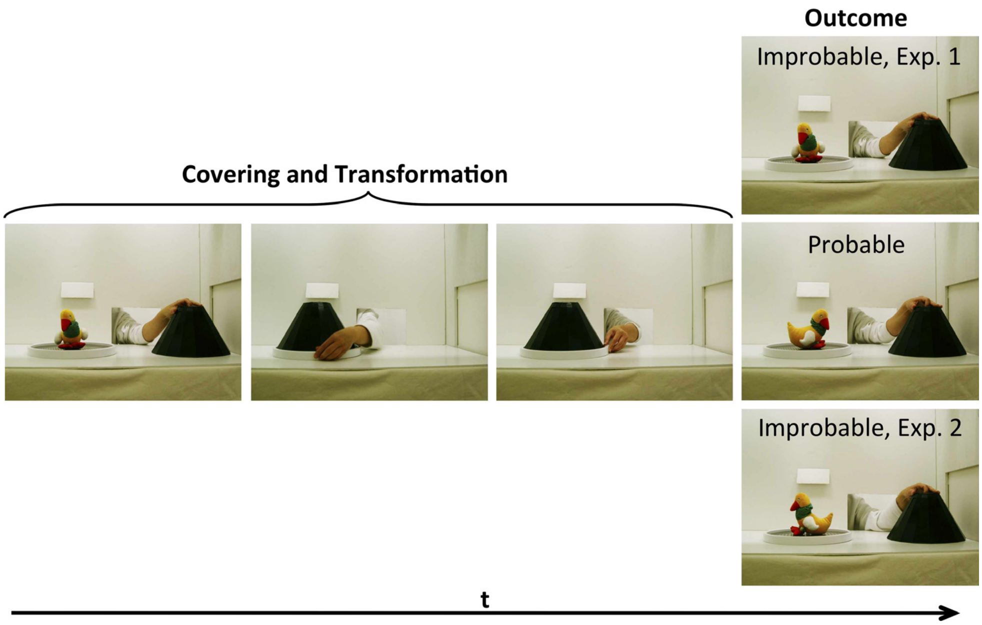

Figure 1. Event sequence in the test trials of Experiments 1 and 2: In the probable event, the duck turned 90° with the turntable; in the improbable event of Experiment 1, the duck remained in its initial orientation; in the improbable event of Experiment 2, the duck turned 90° to the opposite side.

familiarization trial, to visually highlight that it would rotate the same amount as the turntable. To ensure that infants received sufficient exposure to the familiarization events, those who watched the first or second familiarization trial for less than 12 s were coded as "inattentive" and excluded from analysis. The 12-s minimal exposure was chosen so that infants would have the opportunity to see the turtle (a) become fully covered at least twice in the first familiarization trial and (b) rotate a three-quarter turn (showing the orientation of facing left and right at least once) in the second familiarization trial.

Next, each infant received two test trials. Prior to the test trials and out of the infant's view, the experimenter replaced the turtle with the duck and connected it through to the handle below the stage. Thus, the infant never saw the duck rotating with the turntable. This design prevented the infant from learning what the duck should look like after rotation of the turntable and ensured that the responses were not derived from prior exposure. At the beginning of each test trial, the duck faced the infant, the experimenter's left hand rested on the cover and her right hand held the handle from underneath the stage, out of the infant's view, to control the duck's orientation. When the event proper began, the experimenter lowered the cover over the duck (4 s), turned the turntable 90° counterclockwise (4 s), and lifted the cover and placed it at its starting position (4 s). When revealed, the duck had either turned 90° with the turntable (probable event, see Figure 1) or remained in its starting orientation (improbable event). The infant watched the final paused scene with the experimenter's hand resting on the cover until the test trial ended (see below).

Procedure. Each infant sat on a parent's lap approximately 90 cm from the lowered fabric-covered frame. The infant's eye level was about 15 cm above the apparatus floor and centered in front of the turntable. Parents were instructed to remain neutral and quiet and to close their eyes during the test trials.

After the infant was seated, the experimenter showed the turtle and the duck in a forward-facing orientation, one after the other, for about 2 s each. The familiarization trials were the same for every infant and were shown in a fixed order. Each familiarization trial ended when the infant looked away for 2 consecutive seconds after having looked at the event for at least 8 s, or until the infant had looked for 60 cumulative seconds. The test trials presented a probable or an improbable outcome; the order of test trials (i.e., whether infants saw the improbable or the probable event first) was counterbalanced across infants. Each test trial ended when the infant looked away for 2 consecutive seconds after having looked at the final paused scene for 5 cumulative seconds, or when the infant had looked for 60 cumulative seconds.

Looking time was measured by two observers who were naive to the hypothesis and the order of the test trials. Each observer monitored the infant's gaze through a small hole in a fabric-covered door hinged to the left or right of the stage, and pressed a button linked to a computer whenever the infant was looking at the event area. To assess interobserver agreement, each trial was divided into 100-ms intervals. Percent agreement was calculated by dividing the number of intervals in which the observers agreed by the total number of intervals in the trial. Agreement was measured for all infants and averaged 95% in the test trials of Experiment 1.

Results

Test trials. To examine the development of infants' ability to anticipate the final outcome of a rotational object transformation, we analyzed the infants' looking times at the final paused scene of the probable and improbable test events. A difference score was calculated by subtracting the looking times at the probable event from the looking times at the improbable event for each infant. A linear regression analysis revealed a significant correlation between the difference scores and infants' age in days ($R = .47$), and a linear model explained a significant proportion of variance, $R^2 = .22$, $F(1, 26) = 7.52$, $p = .01$. Figure 2 shows that above 15 months of age (456 days) most infants looked longer at the improbable event and showed positive difference scores, whereas only 3 of 14 infants showed negative scores. Below 15 months of age, on the contrary, most infants looked longer at the probable event, with only 4 of 14 infants showing positive scores. Fisher's exact test showed that this difference was significant ($p = .02$). Therefore, infants were divided into two age groups (below or above 15 months of age) for subsequent analysis of variance (ANOVA).

Preliminary analyses of the test data yielded no significant effects involving order, all Fs < 2.78, all ps > .11. Therefore, this variable was excluded from subsequent analyses. The infants' looking times at the final paused scene of the test events were analyzed by a 2 × 2 × 2 mixed model ANOVA, with event (improbable or probable) as a within-subject variable and with age (14 or 16 months) and sex as between-subjects variables. The analysis yielded a significant Age × Event interaction, assuming an α level of .05, $F(1, 24) = 7.48$, $p = .01$, $\eta^2 = .24$. There was no interaction of sex and event, $F < 1$, and no other effects or interactions were statistically significant, all Fs < 1.05, all ps > .31. Separate pairwise t tests indicated that the 16-month-olds looked reliably longer at the improbable ($M = 18.16$, $SE = 2.60$) than at the probable ($M = 12.38$, $SE = 1.12$) event, $t(13) = 2.82$, $p = .01$, $d_z = .75$, whereas the 14-month-olds' looking times at the two test events did not differ significantly,

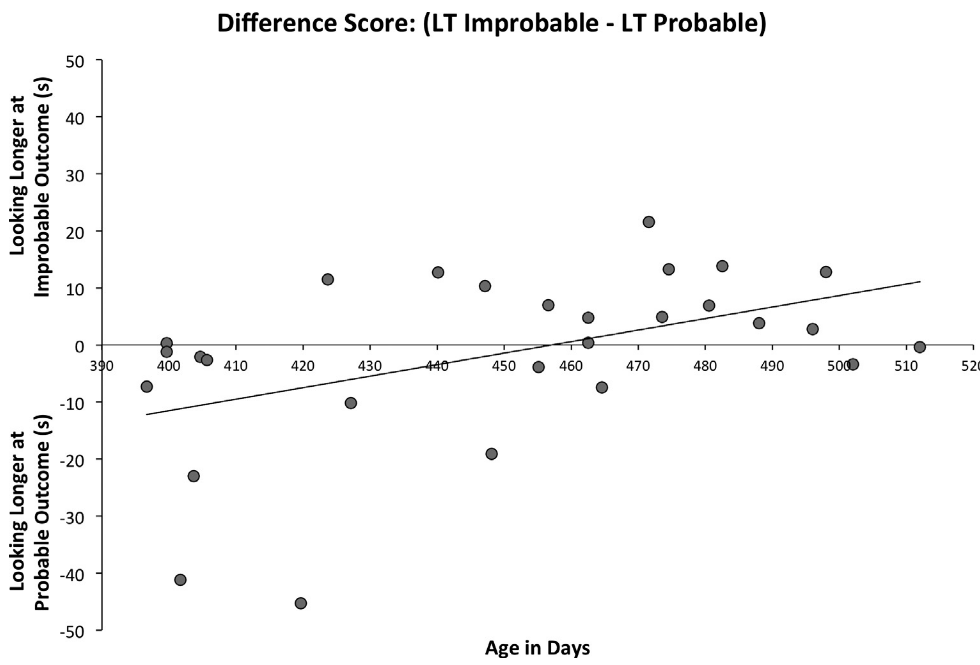

Figure 2. Difference score of infants' mean looking times (LTs) during the improbable test trial minus those during the probable test trial in Experiment 1. Positive values indicate longer looking at the improbable than at the probable event.

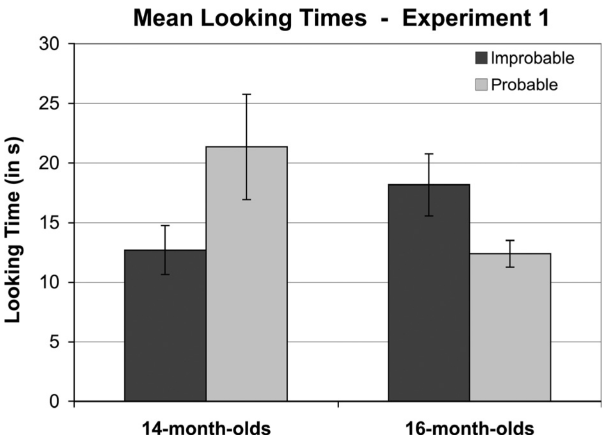

Figure 3. Infants' mean looking times at the improbable and probable events in Experiment 1. Error bars represent standard error.

$t(13) = -1.81$, $p = .09$, $d_z = -.48$ (see Figure 3). Indeed, the 14-month-olds had a tendency to look longer at the probable ($M = 21.34$, $SE = 4.42$) than at the improbable event ($M = 12.69$, $SE = 2.06$). The same results were obtained with an adjusted α-level of .025 to account for multiple comparisons. Nonparametric Wilcoxon signed-ranks tests also confirmed these results (16-month-olds: $T = 15.5$, $p = .02$; 14-month-olds: $T = 28$, $p = .12$).

Familiarization trials. The infants' looking times at the two familiarization trials were analyzed by two separate 2 × 2 mixed model ANOVAs, with age and sex as between-subjects variables. Neither of the two analyses yielded any significant results, all Fs < 1.80, ps > .19. The two groups of infants did not differ in their looking times at the first (14-month-olds: $M = 51.19$, $SE = 3.43$; 16-month-olds: $M = 56.15$, $SE = 1.35$) or the second (14-month-olds: $M = 41.14$, $SE = 4.81$; 16-month-olds: $M = 37.89$, $SE = 3.94$) familiarization event. Thus, their differential looking times in the test trials were not a result of different visual exposure in the familiarization trials.

Discussion

The analyses of infants' looking behavior in the test trials revealed a significant correlation between age and infants' inclination to look longer at the improbable event, in which the object did not turn with the turntable. These results suggest a developmental progression in the ability to mentally track a rotational transformation of an object between 13 and 16 months of age. Although this developmental progression appears to be rather continuous, there was a clear difference between infants below and above 15 months of age: The majority of the infants above 15 months tended to look longer at the improbable than the probable event, whereas the majority of infants below 15 months displayed an opposite looking pattern. Therefore, for further analyses infants were separated into two groups (referred to as "16-month-olds" and "14-month-olds"), with one group anticipating such spatial transformation more readily than the other group.

The ANOVA results confirmed that 16-month-olds looked reliably longer at the improbable than at the probable event. This looking pattern suggests that they expected the duck to turn with the turntable and spent more time processing an event in which the duck remained in its starting orientation. This result extends previous findings (e.g., Hespos & Rochat, 1997) by showing that 16-month-olds are capable of anticipating the final outcome of a rotational event, even with live presentations that involve multiple objects. Furthermore, the 16-month-olds succeeded even though they never saw the turntable move with the duck sitting on it and had no prior information about what the duck would look like in an orientation other than the starting one. In contrast, the 14-month-olds did not show a reliable difference in their looking times at the two test events and even displayed a tendency to look longer at the probable outcome. We suspected that this tendency might reflect the 14-month-olds' slight preference for the appearance of the duck in a novel orientation. Together, these results suggest that infants at about 15–16 months but not younger are able to anticipate the outcome orientation of an object after a hidden rotation without having seen the object in different orientations beforehand.

However, three alternative interpretations needed to be considered before conclusions could be drawn. First, the 16-month-olds' looking pattern could reflect their intrinsic preference for the appearance of the duck shown at the end of the improbable event. That is, the 16-month-olds might have looked longer, not because they detected the violation, but because the duck was visually more appealing to them when it was facing the infants, as opposed to facing to the side. If this were the case, infants should fail to differentiate between the probable and improbable events when the duck faced to the side at the end of both events. Second, the 16-month-olds might have looked longer at the improbable event in which the duck remained in its starting orientation because they knew that the orientation had to change when the turntable was moved but were not sure what the change should be. If this were the case, infants should not look longer at an improbable event that presented a change. Third, the 14-month-olds might have also differentiated the probable and improbable events, as did the 16-month-olds, but looked longer at the probable outcome because it matched their expectation. In this case, we would expect infants to look longer at the probable event even if it was paired with a different improbable event. Experiment 2 tested these alternatives.

Experiment 2

Recall that in Experiment 1, when revealed at the end of the probable test event, the duck was in the correct orientation (facing to the right, from the infant's point of view), whereas in the improbable event it remained in its starting orientation (facing the infant). In Experiment 2, the improbable event was modified so that the duck ended up in an incorrect orientation, facing to the left. Thus, at the end of both test events, the orientation of the duck differed from its starting orientation, and the duck was always shown in a side view. This important modification allowed us to gain additional insight into infants' cognitive processing of rotational object transformations, and to test the three alternative interpretations noted above.

First, if the 16-month-olds in Experiment 1 looked longer at the improbable event because the duck was shown in a forward-facing orientation at the end, the infants in Experiment 2 should look about equally at the two events, now that the duck was shown in a side-facing orientation at the end of both events. Second, if the 16-month-olds in Experiment 1 knew *that* the orientation of the duck had to change, but did not know *how* it should change, the infants in Experiment 2 should look about equally at the two events, now that the duck was shown in a novel orientation at the end of both events. In contrast, if the 16-month-olds knew *how* the orientation should change, they should still look longer at the improbable than at the probable event in Experiment 2. Third, if the 14-month-olds in Experiment 1 had correctly expected the duck to turn with the turntable but looked longer at the probable event because it matched their expectation, the 14-month-olds in Experiment 2 should show the same tendency and look longer at the probable outcome. In contrast (and consistent with our interpretation), if the 14-month-olds' tendency to look longer at the probable event in Experiment 1 was due to their preference for a novel view of the duck, the 14-month-olds in Experiment 2 should look about equally at the two events now that the duck was shown in a novel orientation at the end of both events.

In Experiment 1, a general tendency to look at a novel view could have competed with infants' tendency to look longer at the improbable (but familiar) event. In Experiment 2, however, no such competing effects were expected, as the impossible event did not present a familiar view. Thus, we expected the 14-month-olds in Experiment 2 to perform slightly better than those in Experiment 1.

Method

Twenty-eight healthy full-term infants, who had not taken part in Experiment 1, participated. Half of them were 13–14 months old (M = 14 months 9 days, range = 13 months 11 days to 14 months 29 days; 4 girls), and half were 15–16 months old (M = 15 months 21 days, range = 15 months 2 days to 16 months 15 days; 7 girls). Data from six additional infants were excluded due to distraction and inattentiveness ($n = 2$), or observer difficulties ($n = 4$).

The infants saw the same events as in Experiment 1, except that at the end of the improbable test event, the duck had turned 90° in the opposite direction (rather than remaining in its starting orientation). Thus, the orientation of the duck changed in both test events: 90° to the right from the infant's point of view in the probable event, and 90° to the left in the improbable event. Interobserver agreement was measured for 26 infants (only one observer was present for 2 infants) and averaged 94% in the test trials of Experiment 2.

Results

Test trials. The infants' looking times at the final paused scene of the test events were analyzed by a 2 × 2 × 2 ANOVA, with event (improbable or probable) as a within-subject variable and with age (14 or 16 months) and sex as between-subjects variables. The analysis yielded a significant effect of event, $F(1, 24) = 5.02$, $p = .04$, $\eta^2 = .17$, but no interaction of age and event, $F(1, 24) = 1.70$, $p = .20$, $\eta^2 = .07$. As we have outlined above, a higher performance level of younger infants in Experiment 2 was expected, and therefore the nonsignificant age difference is not surprising.

The primary goal of Experiment 2 was to test the alternative interpretations for the results in Experiment 1, as outlined earlier. Thus, it was crucial to compare across the two experiments. The infants' looking times at the final paused scene of the test events in Experiments 1 and 2 were analyzed by a 2 × 2 × 2 × 2 ANOVA with event (improbable or probable) as a within-subject variable, and with experiment (1 or 2), age (14 or 16 months), and sex as between-subjects variables. The analysis yielded a significant interaction of event and age, $F(1, 48) = 8.72$, $p = .01$, $\eta^2 = .15$. Importantly, the analysis yielded no statistically reliable effects of experiment or any other effects or interactions, all Fs < 3.20, ps > .08.

Separate pairwise t tests were conducted to examine the performance of each age group in test trials of Experiment 2. The analyses yielded similar results as in Experiment 1. Specifically, the 16-month-olds in Experiment 2 looked reliably longer at the improbable ($M = 18.38$, $SE = 3.02$) than at the probable ($M = 11.21$, $SE = 1.50$) event, $t(13) = 2.68$, $p = .02$, $d_z = 0.72$, whereas the 14-month-olds in Experiment 2 looked equally at the improbable ($M = 14.00$, $SE = 2.57$) and the probable ($M = 12.26$, $SE = 1.32$) event, $t(13) = .67$, $p = .52$, $d_z = 0.18$ (see Figure 4). Note that adjusting the α level to .025 to account for multiple comparisons did not change the results. Nonparametric Wilcoxon signed-ranks tests confirmed these results (16-month-olds: $T = 18$, $p = .03$; 14-month-olds: $T = 48$, $p = .78$). Fisher's exact tests showed that the number infants who looked longer at the improbable event (14-month-olds: 5 of 14; 16-month-olds: 10 of 14) did not differ significantly from Experiment 1 (ps = 1.0).

Familiarization trials. Infants' looking times at the two familiarization events were analyzed by two separate 2 × 2 ANOVAs with age and sex as between-subjects variables. The analyses yielded no significant effects, all Fs < 1.90, ps > .18. The younger and older infants did not differ in their looking times at the first (14-month-olds: $M = 46.59$, $SE = 4.32$; 16-month-olds: $M = 54.40$, $SE = 2.85$) and the second (14-month-olds: $M = 37.92$, $SE = 4.55$; 16-month-olds: $M = 38.16$, $SE = 4.13$) familiarization event.

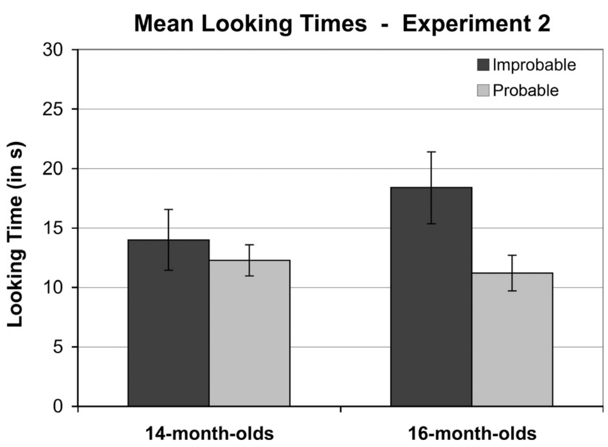

Figure 4. Infants' mean looking times at the improbable and probable events in Experiment 2. Error bars represent standard error.

Discussion

The 16-month-olds still detected the violation when the duck was revealed facing to the side at the end of the improbable event in Experiment 2. Even though the orientation of the duck changed in both test events, the infants still responded with a similar looking-time pattern as in Experiment 1, in which the duck remained forward facing in the improbable event. This suggests that the longer looking times at the improbable event in Experiment 1 were not due to infants' intrinsic preference for a particular orientation (e.g., forward facing) of the duck or their preference for a familiar view. Furthermore, the results in Experiment 2 suggest that the 16-month-olds not only knew *that* the duck had to change its orientation when the turntable was rotated, they also formed a correct expectation about which side the duck should turn to after the rotation.

The 14-month-olds looked about equally at the probable and improbable events in Experiment 2, suggesting that they again failed to detect the violation. Whereas the 14-month-olds in Experiment 1 had shown a (nonsignificant) tendency to look longer at the probable event in which the duck's orientation changed, no such tendency was observed in Experiment 2 when the duck's orientation changed in both the probable and improbable events. The present result thus ruled out the alterative interpretation that the 14-month-olds tended to look longer at the probable event in Experiment 1 because it matched their expectation. If this were the case, the 14-month-olds in Experiment 2 should have displayed the same tendency, but they did not. The results thus supported our interpretation that the 14-month-olds generally failed to anticipate the correct orientation of the duck after the rotation, and that the tendency observed in Experiment 1 was likely due to their preference for a new view of the duck in the probable event.

Taken together, the results of Experiments 1 and 2 provided converging evidence for a developmental progression between 14 and 16 months of age in infants' ability to mentally track the orientation of an object during an invisible rotation. The infants who succeeded in our tasks were older than those in the previous research (Hespos & Rochat, 1997; Möhring & Frick, 2013; Moore & Johnson, 2008, 2011; Quinn & Liben, 2008; Rochat & Hespos, 1996). The discrepancy between young infants' success and older infants' failure is not surprising, given that task demands differed profoundly between the present and previous research, as summarized in the Introduction. Most prominently, our task involved two objects, and spatial changes of one object (i.e., the duck) had to be inferred from information about spatial changes of the other object (i.e., the turntable). Based on research on infants' sensitivity to spatial or functional relations when playing with multiple objects (Fenson et al., 1976) and their sensitivity to spatial orientation when using tools (McCarty et al., 1999, 2001), such sophisticated spatial reasoning involving multiple objects was not likely to be expected before 13 or 14 months of age.

Along these lines, the developmental progression shown in Experiments 1 and 2 may be a result of infants' improved manipulative skills and their increased experience with handling multiple objects (McCarty et al., 1999, 2001; Fenson et al., 1976; Noller & Ingrisano, 1984). Such action experience may enhance infants' sensitivity to information about spatial object properties, thereby enabling them to consider spatial relations of objects not only in reference to themselves but also in reference to other objects (cf. Lockman, 2000; Pick & Lockman, 1981). In other words, action experience may enable infants to link the movement of the toy with the movement of the turntable. In Experiment 3, we thus examined whether 14-month-old infants' ability to mentally track a rotational transformation of an object could be improved by experience with the turntable and a different toy in a short training session.

Experiment 3

The same procedure as in Experiment 1 was administered to two separate groups of 14-month-olds, except that prior to the familiarization and test trials, the infants received a training session in which they either acted upon the turntable themselves (self-turning condition) or watched an experimenter do so (other-turning condition).

In the self-turning condition, the turntable and the toy turtle used in the familiarization trials of Experiment 1 were placed on a table, and each infant had the opportunity to turn the turntable for a maximum of 3 min. If active experience rotating the turntable facilitated infants' understanding of rotational object transformations, the 14-month-olds in Experiment 3 should be more likely to detect the violation and look longer at the improbable than at the probable event.

Infants in the other-turning condition received a training session in which they watched the experimenter rotate the turntable for a similar amount of time, but were not allowed to touch the turntable themselves. Based on previous research showing that passive visual experience is less helpful than active movement for comprehending spatial transformations (e.g., Acredolo et al., 1984; Benson & Uzgiris, 1985; Frick, Daum, Wilson, et al., 2009), one could expect mere observational experience to have a less profound effect than action experience. However, other research suggested that infants could also benefit from observational experience. For example, similar activation patterns were found in the sensorimotor cortex when adults executed an action, to when 7-month-old infants and adults observed a live person perform the same action (Shimada & Hiraki, 2006). Furthermore, research on infants' action imitation has shown that observing actions of others can increase 9-month-old infants' knowledge about objects (Meltzoff, 1988). By 12 months of age, infants not only predict goal-directed actions of others but also infer unseen aspects of the actions (Csibra, Biró, Koós, & Gergely, 2003). These findings provided initial support for a matching mechanism in infants that allows them to link action execution and observation, which could be instrumental for observational learning.

The design of the two types of training sessions in Experiment 3 allowed us to examine whether infants' ability to mentally track the orientation of an object during a hidden rotation would benefit from (a) additional action experience and (b) observational experience. These two training conditions were administered between subjects, and the looking times in the test trials were compared with those of the infants in Experiment 1 who did not receive any training.

Method

Participants. Participants were 28 healthy full-term 14-month-old infants who had not participated in Experiment 1 or 2. Half of these infants were assigned to the self-turning condition (M = 14 months 10 days, range = 13 months 13 days to 14 months 27 days; 6 girls), and half to the other-turning condition (M = 13 months 26 days, range = 13 months 0 days to 14 months 26 days; 6 girls). Data from six additional infants were excluded due to fussiness (n = 2), distraction (n = 1), or noncompliance during the training session (n = 3).

Apparatus. During the training phase, the toy turtle was placed on the turntable, which was mounted on a heavy wooden board for stability. The board was painted white and placed on a table with a U-shaped cutout where the infant was seated. In the self-turning condition, the turntable was positioned centered in front of the cutout and 6 cm away from the infant, well within his or her reach. In the other-turning condition, the turntable was positioned 62 cm away from the infant, out of reach; the experimenter who sat across the table from the infant handled the turntable. A white cover was placed on the turntable to prevent the infant from seeing the setup before the training phase started. The apparatus used in the test phase was the same as in Experiments 1 and 2.

Procedure. The training and test phases took place in separate rooms. Training was administered in a room equipped with a one-way mirror that allowed an observer to monitor the duration of infants' action (see below). During the training phase, the infant sat on the parent's lap in the cutout of the table and against the front edge, and the experimenter sat on the opposite side. In the self-turning condition, each parent was instructed beforehand to guide the child's hand to turn the turntable if the child did not initiate any action within the first few seconds. In addition, parents were specifically instructed never to turn the turntable on their own and to let go of the children's hand after a few turns so that they could act on the turntable independently. Using a turntable, we were able to naturally constrain the type of object movement that infants would experience in the training phase (i.e., a rotation around the vertical axis), and allow infants to actively produce the movement by themselves. The observer behind a one-way mirror measured the time each infant spent turning the turntable. The training phase ended when the infant had turned the turntable for 90 cumulative seconds or when 3 min had elapsed.

The training sessions were recorded and coded offline. Coding indicated that infants in the self-turning condition rotated the turntable on their own for an average duration of 66.5 s (range = 31.9 s to 125.0 s, SD = 28.5 s) or 89.4 s (range = 53.7 s to 130.0 s, SD = 24.3 s) if parent-assisted action was included (i.e., the time parents guided infants' hand to turn or spin the turntable). With regard to visual experience, the infants in the self-turning condition saw the turntable spinning for an average duration of 84.2 s (range = 50.0 s to 122.4 s, SD = 21.1 s). Interobserver agreements on the coding of *unassisted* turning and *parent-assisted* turning were analyzed for all infants in the self-turning condition and yielded r = .99 and r = .97, respectively.

The procedure in the other-turning condition was similar to the self-turning condition, except for the training phase in which the infants watched the experimenter act on the turntable. To make the visual experience comparable with that in the self-turning condition, the experimenter's action followed a script designed to reflect two main actions produced by the infants in the self-turning condition: (a) turning and (b) spinning. Specifically, the experimenter would "turn" the turntable by grasping it in the front (from the infant's point of view), moving it 90°, and returning it to the starting orientation, at a speed of 30° per s. In addition, the experimenter would "spin" the turntable by setting off and letting go of the turntable, and repeating the same action after it came to a halt. Half of the infants in the other-turning condition saw the sequence of turning counterclockwise, spinning clockwise, spinning counterclockwise, and turning clockwise, for 30 s each. Half of the infants saw the sequence of spinning clockwise, turning counterclockwise, turning clockwise, and spinning counterclockwise. The observer behind the one-way mirror measured the time each infant spent looking at the moving turntable or at the experimenter's hand. The training phase in the other-turning condition ended when the infant had looked for 120 cumulative seconds, or when the 4 min had elapsed. A minimal exposure of 120 s was chosen to match the range of the duration that the self-turning group saw the turntable rotating, thus ensuring that the other-turning group received the same amount (if not more) of visual experience as the self-turning group.

After the training phase, the infants in both conditions were brought to the testing room and watched the same familiarization and test events as in Experiment 1. The delay between the training and test phases lasted about 3 min. Interobserver agreement was measured during the test trials for 26 infants (only one observer was present for two infants) and averaged 95% per trial per infant.

Results

Test trials. In a first overall analysis, and most crucial to our research question, we examined whether the training experience enhanced infants' performance in our task. We compared the two training groups of Experiment 3 with the 14-month-olds of Experiment 1 who had no training by a 2 × 2 × 3 ANOVA with event (improbable or probable) as a within-subject variable and with sex and condition (no-training, self-turning, other-turning) as between-subjects variables. The analysis showed a significant interaction of Event × Condition, $F(2, 36) = 3.31$, $p = .048$, $\eta^2 = .16$. There were no other significant effects or interactions, all *F*s < 1.91, all *p*s > .16.

To interpret the above effect of Event × Condition interaction, pairwise comparisons were conducted. First, a 2 × 2 × 2 ANOVA, with event (improbable or probable) as a within-subject variable and with condition (self-turning or other-turning) and sex as between-subjects variables yielded no significant results, all *F*s < 2.69, *p*s > .11, suggesting that infants' performance after action and observational experience did not differ significantly.

Second, the looking times of the self-turning group were compared with those of the 14-month-olds in Experiment 1 who did not receive any action experience, by a 2 × 2 × 2 ANOVA with event (probable vs. improbable) as a within-subject variable and with condition (self-turning vs. no-training) and sex as between-subjects variables. This analysis yielded a significant Event × Condition interaction, $F(1, 24) = 7.49$, $p = .01$, $\eta^2 = .24$. There was no interaction of event and sex, $F < 1$, and no other effects were significant, all *F*s < 2.92, all *p*s > .10. Inspection of the response patterns (see Figure 5) showed that whereas the no-training group had shown a slight tendency to look longer at the probable (perceptually novel) outcome than at the improbable outcome, the self-turning group looked significantly longer at the improbable ($M = 21.06$, $SE = 3.45$) than at the probable ($M = 14.94$, $SE = 2.69$) event, $t(13) = 2.95$, $p = .01$, $d_z = .79$. This result remained the same if an α level of .025 was assumed to adjust for multiple comparisons, and nonparametric Wilcoxon signed-ranks tests confirmed the result ($T = 15$, $p = .02$). In the self-turning group, a significantly greater number of infants (12 of 14) looked longer at the improbable event than at the probable event as compared to the no-training group (Fisher's exact test: $p = .006$).

An analogous ANOVA was calculated to compare the looking times of the 14-month-olds in the self-turning condition with those of the 16-month-olds in Experiment 1. The analysis yielded a significant main effect of event, $F(1, 24) = 15.12$, $p = .001$, $\eta^2 = .39$, but no significant Event × Condition interaction, $F < 1$, suggesting that the 14-month-olds in the self-turning condition performed similar to the 16-month-olds without training. Together, these results suggested that action experience enhanced the 14-month-olds' performance in our task, to the level of the 16-month-olds' performance.

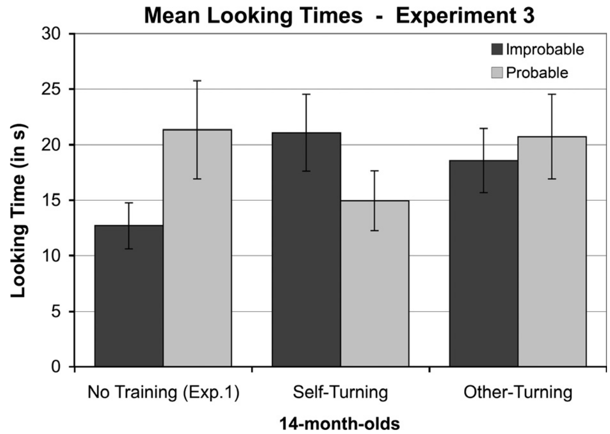

Figure 5. Fourteen-month-olds' mean looking times at the improbable and probable events in the self-turning and other-turning conditions of Experiment 3, compared to the 14-month-olds in Experiment 1 who received no training. Error bars represent *SE*.

Finally, the looking times of the other-turning group during the test trials were compared with those of the no-training group from Experiment 1, by a 2 × 2 × 2 ANOVA with event (probable vs. improbable) as a within-subject variable and with condition (other-turning vs. no-training) and sex as between-subjects variables. The analysis yielded no interaction of event and condition, $F(1, 24) = 1.26$, $p = .27$, $\eta^2 = .05$, suggesting that the responses of the two groups did not differ significantly. There was no interaction of event and sex, $F < 1$, and no other effects were significant, all *F*s < 2.41, all *p*s > .13. Inspection of the response patterns showed that the other-turning group looked about equally at the improbable ($M = 18.55$, $SE = 2.90$) and the probable ($M = 20.71$, $SE = 3.80$) event, $t(13) = -.48$, $p = .64$, $d_z = -0.13$, and a Wilcoxon signed-ranks test confirmed this result ($T = 48.5$, $p = .80$). Thus, observational experience alone was not sufficient to help 14-month-olds to discriminate the improbable and probable event in our task. The number of individual infants who looked longer at the improbable event (8 of 14) did not differ significantly from the no-training group (Fisher's exact test: $p = .25$).

Familiarization trials. The infants' looking times at the two familiarization events were analyzed by two separate 3 × 2 ANOVAs with condition (no-training, self-turning, or other-turning) and sex as between-subjects variables. The analyses yielded no significant effects, all Fs < 1.43, all ps > .25. The infants in the training conditions did not differ in terms of their looking times at the first (self: $M = 52.54$, $SE = 2.94$; other: $M = 52.61$, $SE = 2.60$) and the second (self: $M = 35.74$, $SE = 3.61$; other: $M = 31.48$, $SE = 3.52$) familiarization event.

Discussion

The results of the self-turning condition indicated that when provided with action experience, the 14-month-olds looked reliably longer at the improbable than at the probable event, just like the 16-month-olds did without training. This suggests that action experience enhanced the younger infants' ability to mentally track the rotational transformation of the object, making it possible for them to detect the wrong orientation of the object in the improbable event.

The results of the other-turning condition showed that with observational experience only, the 14-month-olds looked about equally at the probable and improbable events. In addition, there was no significant difference in the responses of the other-turning group and the no-training group, suggesting that observational experience alone was not sufficient to help infants detect the violation in the improbable event. However, the tendency to prefer the probable event shown in the no-training group was not observed in the other-turning group. In addition, the direct comparison between the self-turning and the other-turning condition yielded no significant interaction involving event and condition. Thus, it is likely that observational experience alone might have had *some* effect, but it was not strong enough to help infants pass our task. Moreover, effect sizes (of the Event × Experience interactions) showed that, as compared to no experience, the benefits of observational experience ($\eta^2 = .05$) were considerably smaller than those of action experience ($\eta^2 = .24$). This finding bears important practical implications for education and learning, as it suggests that watching others perform an action does not have the same beneficial effect as performing the action oneself (see also Newcombe & Frick, 2010). However, because this difference did not reach significance, it should be interpreted with caution.

Two explanations may account for the benefits of action experience. First, action experience provides multisensory information through visual and tactile senses. Prior research has shown that exploring objects through more than one sense requires mapping information from one modality to another, and thus helps infants direct their attention to relevant information in perception and object individuation tasks (e.g., Bahrick, Lickliter, & Flom, 2004; Wilcox, Woods, Chapa, & McCurry, 2007). Hands-on experience with the turntable might have enabled the infants in the self-turning condition to map haptically perceived information to visually observed spatial changes (i.e., changes in the orientation of the toy sitting on the turntable) during the training phase. Such mapping could have facilitated their ability to correctly infer the resulting orientation of another toy in the test phase.

Second, action experience allows infants to take an active role to control the spatial transformation of an object. Active control has been argued to account for the effect of motor experience on object perception in infants (e.g., Soska et al., 2010). Thus, experience with active control in the training phase of Experiment 3 might have increased the likelihood that infants learned to relate their actively executed movement of the turntable to visual feedback on the movement of the toy, enabling them to anticipate another toy's orientation in the test phase. This interpretation that infants might have profited from active movement with concurrent perceptual feedback is also consistent with an ecological view of perceptual development (Gibson & Pick, 2000). Future research can test this hypothesis by providing infants with adult-assisted action experience only (thus removing the component of active control) and examining the effect of such training.

A possible alternative interpretation could be that infants might have generated an expectation about the duck's postrotation orientation by associating the observed transformation of the experimenter's hand or the turtle in the training session and the familiarization trials with the expected transformation of the duck in the test trials. However, the results of the other-turning condition rendered such an explanation unlikely. If this were the case, we should have observed a stronger effect in the other-turning condition than we did, because this associative information was also available. In fact, compared to the self-turning condition, the visual information provided in the other-turning condition was more similar to the test trials, and thus it should have been easier for the other-turning group than for the self-turning group to form the above association. For example, the experimenter's hand was visible in the other-turning condition, and moved the turntable in a similar manner as during the subsequent test trials. In the self-turning condition, however, the infants only saw their own hands and often just wiggled the turntable back and forth a few centimeters, or jolted the turntable and then let it spin for a while. Even though the other-turning condition was designed to also present various kinds of turning and spinning motions to match the self-turning condition to a certain extent, the experimenter's movements were standardized and thus visually less complex than the infants' movements. Nevertheless, these clear hand movements apparently were not sufficient to help the infants succeed in the other-turning condition. Thus, infants must have benefited from something other than—or in addition to—visual cues and movement information.

General Discussion

The results of Experiment 1 suggested that infants are able to infer an orientation change to an object that undergoes a hidden rotational transformation at the age of 15–16 months, but not younger. These results extend previous findings by showing that at 15 months of age, infants become able to infer the outcome of a rotational event when shown live presentations that involve multiple objects whose spatial relations have to be considered. Thus, infants succeeded in a more naturalistic setting, in which objects were not presented in isolation. Furthermore, infants succeeded even if the to-be-rotated object was never shown in motion or multiple views before the test events. This implies that infants do not need to store multiple views of an object to anticipate its appearance in a novel orientation, and that seeing an object in motion is not a necessary precondition for infants to be able to anticipate its movement.

Experiment 2 ruled out alternative interpretations that infants' looking times were due to a preference for a familiar view, a probable view, or a view that showed a forward-facing object. Furthermore, the fact that 15- to 16-month-olds still looked longer at the improbable event outcome, in which the object that was turned to the opposite side, suggested that they not only knew *that* the orientation of an object had to change during a hidden rotation, but also *how* (in which direction) it had to change. These results demonstrate a quite sophisticated ability in 15- to 16-month-olds that goes beyond merely recognizing that something "is wrong" in the improbable event. Instead, the present findings suggest that at this age, infants are able to form fairly specific expectations about spatial relations that result from movements of multiple objects.

Experiment 3 showed that, 14-month-olds' ability to understand the rotational transformation of an object was enhanced by action experience. These results underscore the importance of motor experience for the development of spatial abilities, consistent with previous research (e.g., Acredolo et al., 1984; Benson & Uzgiris, 1985; Campos et al., 2000; Frick, Daum, Walser, et al., 2009; Frick, Daum, Wilson, et al., 2009) and early theories of cognitive development (e.g., Bruner et al., 1966; Gibson, 1988; Piaget, 1936/1952; Piaget & Inhelder, 1948/1956, 1966/1971). Experience with rotating a turntable for less than 2 min enhanced infants' ability to update their mental representation of a hidden toy, as compared to the no-training group. Specifically, the 14-month-olds initially displayed a slight preference for a conceptually plausible but perceptually novel outcome; however, after brief hands-on training, their looking pattern reversed to resemble that of the 16-month-olds. Thus, the present findings showed that even a small amount of action experience sufficed to increase infants' sensitivity to spatial changes, and enhanced their ability to anticipate an orientation change of an object brought about by the movement of another object. These results are consistent with earlier studies that found effects of brief manual experience with objects on performance in cognitive tasks (Möhring & Frick, 2013; Sommerville et al., 2005; Sommerville et al., 2008), suggesting that these early cognitive skills are highly malleable and that there is a close link between cognition and action.

Our results extend previous research by showing that action experience not only enhances infants' ability to update spatial information during perspective changes (Acredolo et al., 1984; Bai & Bertenthal, 1992; Benson & Uzgiris, 1985) but also facilitates their ability to update a mental spatial representation when changes are brought about by object movements. This suggests that, just as experience with self-initiated movement enables infants to overcome an egocentric response tendency in perspective-change tasks, experience with manipulating multiple objects may help infants to consider spatial relations between objects in a more objective way, promoting a shift from egocentric to allocentric spatial thinking in the 2nd year of life (cf. Pick & Lockman, 1981).

Finally, it is worth noting that the present results showed no effects of sex, which is consistent with some previous studies (Hespos & Rochat, 1997; Möhring & Frick, 2013; Rochat & Hespos, 1996), but stands in contrast with others (Moore & Johnson, 2008, 2011; Quinn & Liben, 2008) that found that only male infants appeared to recognize a familiar object in a novel orientation. A possible explanation of these conflicting results regarding sex differences may lie in the differences of the stimulus presentation. Previous studies that found sex differences had used computer-generated 3D stimuli on a black background (Moore & Johnson, 2008, 2011) or 2D letters on white posterboards (Quinn & Liben, 2008). The studies that found no sex differences in infants (Hespos & Rochat, 1997; Rochat & Hespos, 1996), including this study, had used 3D live presentations, or videos thereof (Möhring & Frick, 2013), which might have provided richer spatial information. Thus, female infants' ability to mentally track spatial properties of an object during a rotation may depend on sufficient 3D information about the object and its spatial environment.

To sum up, the present research demonstrates a developmental progression between 14 and 16 months of age in infants' sensitivity to spatial object relations and their ability to track the orientation of an object that undergoes a hidden rotation. The present findings also suggest that this developmental progression is likely related to increased manipulative experience involving multiple objects, which may enhance infants' perception of spatial relations between objects. This notion was corroborated by the finding that a small amount of active experience in rotating a turntable with a different object on it sufficed to enhance the performance of 14-month-old infants, who did not succeed in our task without any training. The present findings thus highlight the role of hands-on experience for the development of spatial cognitive abilities.

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