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COGNITION

Dynamic mental representation in infancy[1]

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Abstract

Recent research indicates that 4- to 8-month-old infants can track and anticipate the final orientation of an object following different invisible spatial transformations (Rochat, P., Hespos, S.J. (1996). Cognitive Development, 11, 3–17). Six experiments were designed to specify further the nature and development of early expectation for a set of dynamic events. A violation of expectation method was used to assess infants' reactions to probable and improbable outcomes of an objects' orientation following an invisible transformation. The availability of orientation cues, the path of motion, and the amount of invisible spatial transformation was systematically varied. The studies indicate that infants as young as 4 months of age detect orientation-specific cues for objects undergoing invisible spatial transformations. Developmental differences in this ability between 4 and 6 months of age lend insight to the nature and limitations of this early representational ability. These findings provide evidence for dynamic mental representation in infancy. © 1997 Elsevier Science B.V.

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1. Introduction

We are always making assumptions about objects beyond the information given by perception. For example, we assume that occluded objects continue to exist (out of sight does not mean out of mind), that unsupported objects fall down (they rarely float in midair), and that two solid objects cannot pass through one another. This ability implies that we represent information about objects even when they are not perceptually present. However, empirical evidence suggests that object representa-

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tion is linked to the way perceptual information is processed. Mental rotation studies with adults suggest that there is a temporal spatial isomorphism between an object rotation and its imagined rotation (Shepard and Metzler, 1971; Shepard, 1984). These studies imply that certain spatial and temporal attributes intrinsic to physical events may also be intrinsic to the mental representation of such events. Given any physical dynamic event, the temporal quality is intrinsic and necessary. Similarly, our representation of dynamic events may have an intrinsic and necessary temporal quality. For example, temporal constraints in physical events have directionality (i.e., in that time goes forward), and continuity (i.e., time does not stop and start) (Freyd, 1987). We suggest that representation of dynamic events shares the intrinsic qualities of directionality and continuity and that these constraints are evident in infancy.

Traditional theories of perception (e.g., Goldmeier, 1937, 1972; Koffka, 1935; Wertheimer, 1938; Rock, 1973) have focused primarily on static, two-dimensional stimuli, overlooking the importance of dynamic information. Motion was considered an additional, independent variable in an already complex system. In contrast, more recent theories of perception suggest that dynamic information is fundamental to the perceptual process (Johansson, 1973, 1986; Gibson, 1979). Gibson (1966) suggested that invariants, aspects of the environment that stay the same across a changing perceptual array, are fundamental to perception because they are most reliable in specifying properties of objects in the optic array. He emphasized that our visual system has evolved to register change and to detect invariance in the optic array as opposed to reconstructing dynamic events from static visual information. The spatial relationships between objects in the perceptual array are often in flux: perceivers move and objects move. Change in the perceptual array resulting from motion carries information about the structure of a particular object and spatial relationships between objects (Neisser, 1989).

Kellman (1993) proposed that the ability to detect motion-carried information is fundamental to the development of perceptual systems. From birth, infants are attracted to objects that are in motion more than stationary ones (Banks and Salapatek, 1981; Slater et al., 1985; Yonas and Granrud, 1983). Some forms of motion-produced information are picked up very early in life. For example, newborn infants perceive that a visual image whose projection expands symmetrically in the field of view specifies an imminent collision (Bower et al., 1970; Ball and Tronick, 1971; Gibson, 1982). Common motion may also influence the perceived unity of objects. Experiments on 4- to 6-month-old infants using looking paradigms (Kellman and Spelke, 1983) and reaching paradigms (Hofsten and von Spelke, 1985) have demonstrated that common motion leads to perceived unity of objects and that relative motion leads to the perception of separate objects. Kellman et al. (1987) showed that 5-month-old infants can distinguish between their own motion around a stationary object, object motion around them while stationary, and conjoint motion of themselves and of the object. These studies suggest that prelocomotor infants detect subtle cues specifying different types of movement.

Examples of detected looming, perceived unity, and discrimination of object versus observer motion are all demonstrations of the ability to detect invariant structure from motion. There are a variety of dynamic cues that specify properties of objects. Kellman (1993) suggested that spatial-temporal invariant patterns are the basis of initial concepts about objects. More specifically, motion-carried information may specify object properties better than purely static spatial information. An empirical question that has not been fully addressed by infancy researchers pertains to the developmental change in an infant's flexibility in using different perceptual cues. For example, when a piece of paper slides off the table and floats down to the floor. Even though my view of the paper's trajectory is occluded, I develop expectations about the transformation based on the dynamic information perceived before occlusion. I anticipate that the paper will come to rest on the floor, that it will probably not land balanced on its edge but will land flat. Furthermore, I expect the words on the page to have the same spatial arrangement as they did before the fall. The question addressed here is, when and how do these expectations develop?

At the level of representation, Piaget and Inhelder (1971), provided a useful classification of mental imagery, making a basic distinction between static and kinetic mental images. According to Piaget and Inhelder, static images correspond to the mental representation of an object, independent of any transformation. Kinetic images, on the other hand, correspond to the mental representation of the object's transformation. Based on a series of studies evaluating children's drawings, Piaget and collaborators suggested that static images develop first. By 7 to 8 years of age, children start to describe and interpret invisible transformations per se, beyond the mere static mental representation of the start and end points of a transformation. Piaget concluded that this development corresponds to children's growing ability to manipulate mental images. An analogous progression was suggested by Piaget (1952, 1954) regarding the development of object permanence. In the context of manual search tasks, Piaget observed that infants first can recover a hidden object at a single location (Stage 4 of the sensorimotor period) and are eventually capable of representing its invisible displacements in a final stage achieved by 18 months (Stage 6 of the sensorimotor period). Bower (1974) suggested that infants' failure to perform search tasks could be due to the difficulties involved with manual search not a lack of object permanence. A series of studies with infants as young as 7 weeks of age (Bower, 1967, 1974; Bower et al., 1971) suggested that infants did indeed demonstrate object permanence earlier than Piaget claimed in a context that does not require a manual search (for reviews see Gratch, 1975, 1976; Harris, 1987; Baillargeon, 1993). Research in the last decade has provided further evidence of object permanence by young infants who are shown to represent static characteristics of objects such as height (Baillargeon and Graber, 1987), width (Aguiar, 1994), and position (Baillargeon and DeVos, 1992). Only recently have researchers investigated kinetic imagery in infancy in the context of preferential looking paradigms.

Rochat and Hespos (1996) investigated young infants' ability to represent an object's invisible spatial transformation (i.e., kinetic mental imagery according to Piaget and Inhelder (1971)). They tested infants in a situation where an object disappeared behind an occluder. Infants were familiarized to an object disappearing behind an occluder following either a translation (vertical fall), or a rotational motion (180° arc). The final third of both motions was occluded by a screen so that the final orientation of the object was not visible. Following familiarization, infants were shown six test trials. In the test trials, infants saw the object disappearing behind the occluder, then the occluder was removed. On alternating test trials, infants were presented with the object in the appropriate orientation outcome (probable orientation), or rotated by 180° (improbable orientation). Looking time at the revealed object was measured. Results showed that infants look significantly longer at the improbable orientation outcome. Based on these results Rochat and Hespos (1996) concluded that infants are capable of mentally tracking invisible transformations and anticipating the final orientation outcome. However, the object used was rich in orientation cues and the invisible transformation was short. Furthermore, Rochat and Hespos (1996) did not find any developmental trends in this ability. As it stands, it is still unclear what the relevant cues are that infants use to anticipate the final orientation outcome of the transformation. If there are developmental differences in this ability then what are the determinants of young infants' mental tracking of invisible spatial transformations? The present research was designed to address these questions. In particular, there were four specific aims guiding the research.

The first aim was to verify the original phenomenon reported by Rochat and Hespos (1996) while further controlling for possible perceptual cues inadvertently provided by either the experimenter (Experiment 1), or by the background of the display (Experiment 2). In Experiment 1, we attempted an exact replication of Rochat and Hespos (1996), using a double-blind procedure. In Experiment 2, we replicated the original phenomenon with the same object but used a different display that eliminated possible perceptual cues on the background of the display that might be used by the infant, independent of any dynamic representation.

The second aim was to investigate young infants' ability to anticipate the orientation outcome of an object within the context of a different, potentially more complex path of motion: a rotation in depth. Using the same object and procedure, 4- and 6-month-old infants were presented with two events where the object moved in the sagittal (*zy*) plane before disappearing behind the occluder. In the Ferris event, the object maintained the same upright orientation with respect to the stage throughout the transformation, much like a seat on a Ferris wheel with respect to the ground. In the rotation event, the object orientation changed 180° from the start orientation with respect to the stage. The rotation event, in contrast to the previous experiments, had an object orientation and appearance at the moment of occlusion that was markedly different from what it looked like at the end of the transformation.

The third aim was to assess the performance of 4- and 6-month-olds when we extended the amount of rotation that occurred in the invisible transformation. Infants were presented with an object identical to the one used in the former studies, but rotating behind a larger screen that increased the occluded portion of the transformation by 90° (i.e., from 60° of occluded rotational motion in the original experiment to 150°).

Finally, the fourth aim was to establish the relative role played by intrafigural orientation cues on the object as potential determinants of young infants' ability to track invisible spatial transformations. Four- and 6-month-old infants were tested with an object that had fewer orientation cues. This novel object provided only intrafigural orientation cues, rather than both intra- and extrafigural cues. In Experiment 5, we attempted to replicate the original findings using this novel object in translation and rotation conditions. In Experiment 6, we repeated Experiment 5 but we provided additional perceptual cues on the background of the stage to determine the extent to which this manipulation might affect the differential pattern of response we observed in 4- and 6-month-old infants.

Overall, six experiments confirm the original phenomenon reported by Rochat and Hespos (1996) with more stringent control conditions. Furthermore, they capture determinants of young infants' ability to track and anticipate the final orientation outcome of an invisible transformation. More specifically, these experiments demonstrate some of the developmental features of dynamic representation in infancy.

2. Experiment 1

Infants were familiarized with an object either vertically translating or rotating behind an occluder. During test trials, the screen was lowered following the transformation and revealed either in a probable or improbable orientation outcome. Half of the infants were tested in an additional new control condition where the displayed object did not provide any orientation cues. The experimenter was blind to both the type of object and the orientation (probable versus improbable) outcome. The double blind procedure ensured that the experimenter was not implicitly cueing the infant to influence his/her looking duration. Infants were randomly assigned to the experimental or control condition. The two objects used in the experimental and control conditions are illustrated in Fig. 1.

In the experimental condition, the display object was the same horizontally asymmetric object used in Rochat and Hespos (1996). There were extrafigural and intrafigural perceptual cues (the overall shape and colors) that specified a change in orientation. In the control condition, the object was horizontally symmetric; thus, not providing any cues that distinguished upright from a 180°, inverted orientation. Within the violation of expectation paradigm, the prediction was that infants in the experimental condition would look significantly longer at the improbable compared to the probable orientation outcome and that infants in the control condition would not discriminate between the two outcomes. Thus, different looking patterns would emerge from the experimental and control conditions. Alternatively, if infants'

Object for Experimental Condition

Object for Control Condition

Fig. 1. Schematic depiction of the objects used in Experiment 1.

behavior was a result of some perceptual aspect (e.g., timing or noise of the object) then similar results should be observed in the two conditions. All other aspects of the experiment were constant across the two conditions.

2.1. Method

2.1.1. Participants

Fifteen full-term healthy infants (4 females, 11 males) participated in the experiment. The infants were 4- to 8-months-old. This large age range was used because Rochat and Hespos (1996) showed no developmental differences in this task across 4 to 8 months using the same procedure and object as in the experimental condition. Parents in all of the studies were contacted at the hospital nursery when the infant was born and through follow-up phone calls. Infants were given an Emory Infant Lab T-shirt after the experiment. They were randomly assigned to the control or experimental condition. Eight infants between 4- to 8-months-old (mean 5 months, 22 days; range 4 months, 12 days, to 8 months 5 days) were tested in the control condition. Seven infants between 4- to 7-months-old (mean 6 months, 6 days; range 4 months, 12 days to 7 months, 10 days) were tested in the experimental condition. Three additional infants were excluded from the sample due to fussiness (2) or experimenter's error (1).

2.1.2. Apparatus

In the experimental condition, the object was made of two pieces of hard foam blocks glued together. These pieces were: a bright red rectangular shape 16 cm tall, 8 cm wide, 4 cm deep with a semi-circle (8 cm in diameter) cut out of the long side, and a bright yellow rectangular solid 16 cm tall, 4 cm wide, 4 cm deep (see Fig. 1). The entire object was 24 cm long. In the control condition, the object was made of a single rectangular solid that was red in color made out of the same material as the other object. The object was 16 cm tall, 8 cm wide, 4 cm deep.

The events were presented on a three-sided puppet stage (115 cm high, 120 cm wide, and 36 cm deep). The walls and floor of the stage were covered with black felt. The lower part of the backdrop consisted of a trap door made of the same material, giving the experimenter access to the object on stage. On the front edge of the stage was a white 52 cm wide by 36 cm tall opaque occluder made of Styrofoam board. From behind the stage, via a system of pulleys, the occluder could be raised to occlude the lower portion of the stage, or be lowered to reveal it. When the occluder was raised, the experimenter could surreptitiously change the orientation of the object from behind the occluder, through the trap door.

The room was lit by a clamp lamp located behind and 1 m above the infant's head. The stage was illuminated by two 60 W lamps clamped to the top left and right front corners. The lamps were concealed from the infant's view by a black curtain hanging from the ceiling (120 cm wide and 40 cm tall). Both room and stage lighting were controlled by a dimmer switch accessible to the experimenter from behind the stage. A small peep hole was cut in the backdrop of the stage so the experimenter could see the infant during familiarization trials and to ensure that the infant fixated the object for at least 1 s before the transformation began. Two cameras provided video recording of the testing sessions: one was placed behind the stage, and the other was placed above and behind the infant. The lens of the camera behind the stage was placed against a 5 cm diameter hole in the black backdrop at the infant's line of gaze. When the screen was lowered, this camera provided a view of the infants' face while they were looking at the display. The other camera provided a view of the object on stage as seen from the front of the stage. This camera was positioned high above the infant's head so that it was possible to see behind the occluding screen to record whether it was a probable or improbable orientation outcome. Images from both cameras appeared on either side of a split-screen (Pelco model US100DT). In addition, a digital clock (Video Timer SMPTE Time Code TC-3) was superimposed on the image. The split-screen images were recorded. The half of the screen showing the infant's face was monitored on-line on a small TV monitor behind the stage so the experimenter could observe the infant during test trials and monitor when the infant looked away from the display for longer than 2 s (see Section 2.1.4). The half of the screen showing the view of the object on stage was covered so that the experimenter could not see whether they were using the control or experimental object.

For the translation condition, a long vertical slot was cut into the felt backdrop of the stage in order to guide the object in its vertical trajectory from the top to the bottom of the stage. An 8 cm screw (0.4 cm in diameter) came out the back of the object (invisible to the infant) through the vertical slot. The screw protruded through the backdrop and was attached to a wooden block held by the experimenter behind the stage. This allowed the experimenter to control the object motion and final orientation.

In the rotation condition, a radial arm made of a black round metal rod (0.5 cm diameter) was used to move the object in the rotation condition (see Section 2.1.4). The rod protruded from the backdrop by 6 cm, and extended parallel to the backdrop to form a 40 cm radial arm. A round, 73 cm diameter disk held by Velcro strips was placed in front of the radial arm to hide it. The disk was covered with the same black felt used for the backdrop. The experimenter controlled the radial movement of the arm from behind the stage. When moved, the extremity of the arm where the object was attached described a 180° arc from 1200 to 1800 h. The object appeared to be orbiting around the edge of the disk.

2.1.3. Design

Infants were randomly assigned to the experimental or control condition. The only difference between these conditions was that the objects were different (see Section 2.1.4). All infants were tested in the translation and rotation events. The order of event (i.e., translation first or rotation first), starting orientation (i.e., Y-shaped object or inverted Y for the experimental condition), and test order (i.e., probable outcome first or improbable outcome first) were counterbalanced across infants within the experimental and the control conditions.

2.1.4. Procedure

During the experiment the infant sat on the parent's lap facing the stage. The infant's head was approximately 64 cm from the front edge of the stage and 1 m from the back of the apparatus. The parent was instructed not to interact with the infant and to close her eyes with head oriented towards the floor during the trials. Pilot observations indicated that blindfolding the parents perturbed and distracted most infants.

Each infant was tested in succession in both translation and rotation events (see description below). The events had two-phases consisting of six familiarization trials followed by six test trials. The infants were given a short break between events while changes were made on the apparatus. In the translation event, infants were shown an object moving at a constant velocity (a count of 5 s from start to end) and disappearing behind an occluder. The last third of the trajectory was hidden. In the rotation event, infants were shown an object attached to the extremity of a radial arm rotating through a 180° arc from 1200 to 1800 h and disappearing behind the occluder at 1600 h (see Fig. 2). The constant velocity and duration of the transformation in the translation event matched the motion characteristic of the transforma-

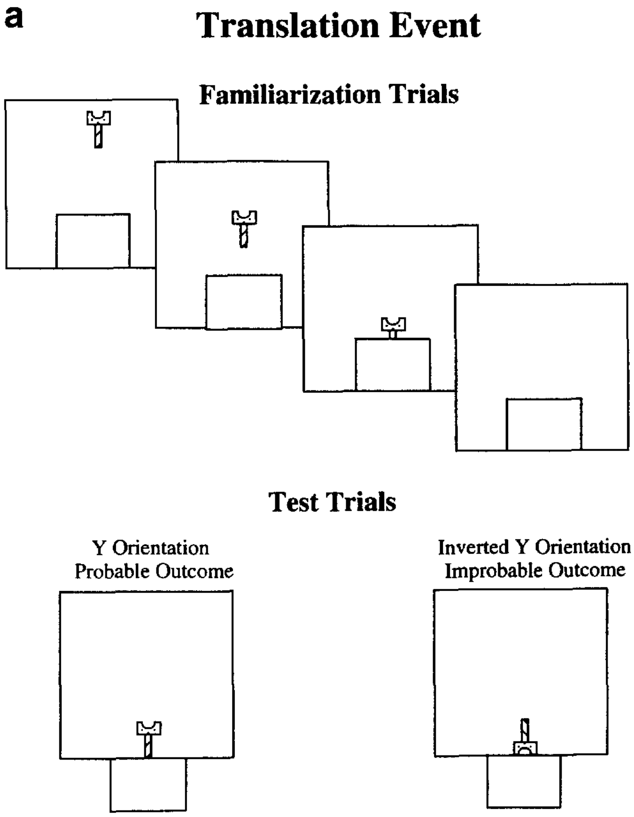

Fig. 2a.

tion in the rotation event. In both, the object was visible for two-thirds of the event. The order of events was counterbalanced across subjects.

Two experimenters worked together to produce the events: Experimenter 1 controlled the lights, raised and lowered the occluder screen, and looked through the peek hole to see if the infant had fixated the object (see below), Experimenter 2 moved the objects through their trajectories and surreptitiously adjusted the orientation of the objects behind the occluder before they were revealed in the test trials.

The familiarization trials served to acquaint the infants with the object and its trajectory with the final orientation being occluded. There was a blackout before each trial began so that Experimenter 2 could move the object into position. At the start of the event, Experimenter 1 turned on the lights revealing the object at the top of the stage. Experimenter 2 waved the object until Experimenter 1 signaled that it had attracted the infant's visual attention. Once the infant had fixated the object for approximately 1 s Experimenter 2 moved the object through the trajectory and behind the occluding screen. This procedure was repeated six times. Following familiarization, infants were presented with six successive test trials. In the test trials there was a blackout where the object was moved into position. At the start of the event the lights were turned on revealing the object at the top of the stage.

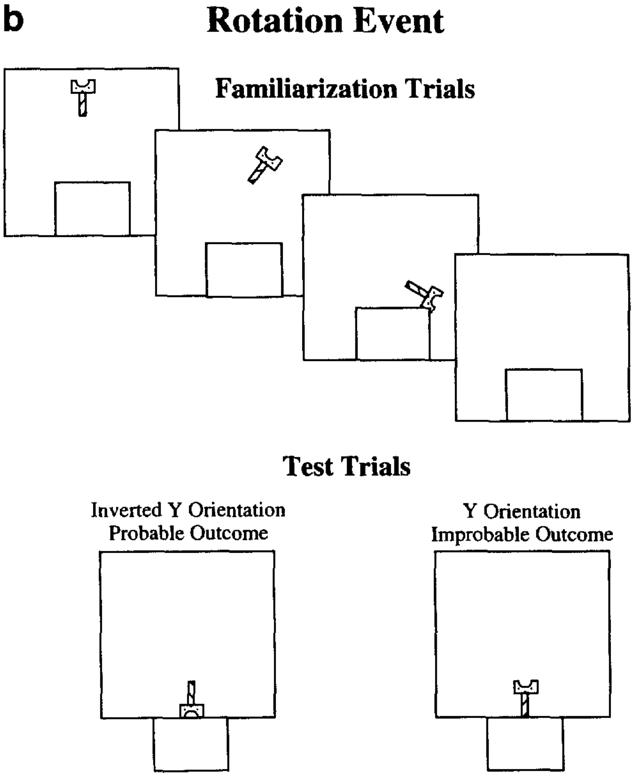

Fig. 2. (a,b) Schematic depiction of the translation and rotation events seen by the infants in Experiment 1.

After the infant had fixated the object, it moved through the trajectory and behind the occluder. Then, Experimenter 1 lowered the occluder screen revealing the object in either a probable or improbable orientation outcome. Prior to lowering the screen, Experimenter 2 surreptitiously adjusted the orientation of the object through the trap door behind the occluder (see apparatus, above). On trials with the improbable orientation outcome, Experimenter 2 rotated the object 180°. On trials with the probable orientation outcome, Experimenter 2 rotated the object 90° back and forth to equate time and potential noise across outcomes.

From the moment the screen was lowered, looking time at the revealed object was measured based on a close up video recording of the infant's face. When the infant looked away from the object for 2 consecutive s, the screen was raised and a new test trial began. During the six test trials, infants were presented with three probable and three improbable orientation outcomes presented in alternating order. The inter-trial interval (the time between the screen coming up, and the object being presented at the top of the stage) was 3 s. The intra-trial interval (the time after the object goes behind the occluder until the screen is lowered) was on average 3.5 s.

2.1.5. Scoring

Two independent coders analyzed the video recordings of infants' looking during the test trials, from the moment the screen was lowered and until the infant looked away for 2 s. Coding was based on a viewing of the video recording. While viewing the video recording, coders recorded infant's looking at the display by pressing a button which activated one channel of a computerized event recorder. While scoring, an opaque sheet covered the portion of the split image on the TV monitor depicting the event on stage. Coders were blind to whether the infants were tested in the experimental or control condition and to what display the infant was presented with (e.g., whether they were looking at a probable or improbable orientation outcome). Based on the methodology established by researchers using a similar experimental paradigm, looking time was operationally defined as the first look at the

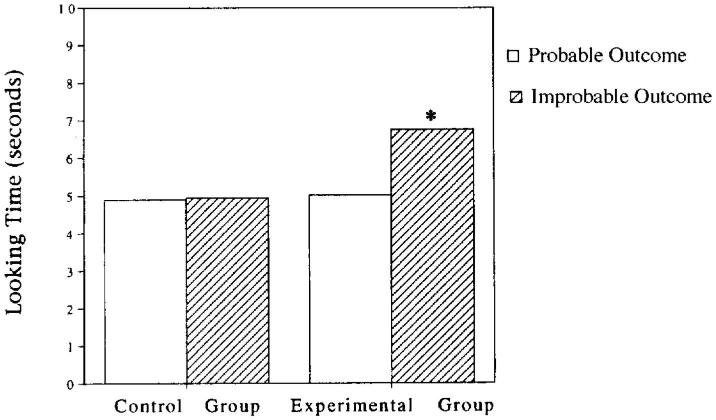

Fig. 3. Mean looking times of the infants in test trials for Experiment 1.

display that was longer than 1 s and ending when the infant looked away from the display for longer than 2 continuous s. This operational definition is directly borrowed from current research on infant cognition (see for example, Kellman and Spelke, 1983; Baillargeon et al., 1985; Spelke et al., 1992; Baillargeon, 1993, 1995). Inter-coder reliability was assessed on one-half of all test trials that were included in the analysis (four control participants and three experimental participants). When there was a large discrepancy in the coding (e.g., larger than 3 s), the single trial was re-coded by both experimenters until agreement was obtained. This occurred on less than 2% of the data. Percent agreement between coders was greater than 0.93.

2.2. *Results*

Overall, analysis of the looking time revealed that infants in the experimental condition looked significantly longer at the improbable compared to the probable orientation outcome, and infants in the control condition looked equally at the two events. An overall 2 (condition: experimental or control) ×2 (event: translation or rotation) ×3 (test order: 1st, 2nd, or 3rd test trial pair) ×2 (orientation: probable or improbable outcome) mixed design analysis of variance (ANOVA) yielded a significant main effect of orientation $F(1,13) = 5.822$, $P < 0.03$. There was a significant interaction between experimental/control and orientation $F(1,13) = 6.471$, $P < 0.02$. A graph of the means illustrating this interaction is shown in Fig. 3. The average looking times for the control condition were similar for probable (4.90 s) and improbable (4.95 s) events. In contrast, the average looking times for the experimental condition were different for probable (5.02 s) and improbable (6.76 s) events. In subsequent analyses we performed separate ANOVAs for the infants in the experimental and control conditions[2]. A 2 (event: translation or rotation) ×3(test order: 1st, 2nd, or 3rd test trial pair) ×2 (orientation: probable or improbable outcome) within subject ANOVA performed on the experimental condition data yielded a main effect of orientation $F(1,6) = 7.398$, $P < 0.03$. A 2 (event: translation or rotation) ×3(test order: 1st, 2nd, or 3rd test trial) ×2(orientation: probable or improbable outcome) within subject ANOVA performed on the control condition data yielded no significant main of orientation ($F(1,7) < 1$). Note that no significant interactions between orientation outcome and sex ($F(1,13) < 1$), event order ($F(1,13) < 1$), starting orientation ($F(1,13) < 1$), or test order ($F(1,16) < 1$) were found.

Non-parametric tests confirmed the main findings. In the control condition, four out of eight infants looked on average longer at the improbable compared to the probable orientation outcome. In contrast, for the experimental condition, six out of seven infants looked on average longer at the improbable compared to the probable orientation outcome. Wilcoxon sign ranked tests performed on the difference scores

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[2] Keppel (1982) suggests that when there is a between-subject variable comparing two repeated measure designs, it is possible to perform separate repeated measures ANOVAs instead of simple effects on the significant interaction. The large variance on the control group increases the overall variance of the sample and may hide the main effect of the experimental group.

for each infant confirmed that infants in the experimental condition looked longer at the improbable orientation outcome ($T = 26$, $P < 0.0468$ (two-tailed)), and infants in the control condition did not show a significant difference in looking at the two outcomes ($T = 12$, $P > 0.52$). A Wilcoxon-Mann–Whitney test confirmed that the difference scores from the two conditions differed from each other ($W = 37$, $P < 0.0145$).

2.3. Discussion

In this first experiment, the only difference between the experimental and control condition was the display object. The display object for the experimental condition had perceptual cues that afforded tracking orientation change, and in the control condition, the object was devoid of such cues. As predicted, we found a significant difference in looking behavior between the control and experimental conditions. Infants in the experimental condition looked longer at the improbable compared to the probable orientation outcome for both the translation and rotation transformations. In contrast, the infants in the control condition looked equally at both outcomes. Thus, the effect disappeared when the orientation cues were removed. This suggests that looking was indeed dependent on the orientation cues provided by the object, and not dependent upon biasing from either the experimenter or the coders. This study confirmed and replicated the original findings reported by Rochat and Hespos (1996) controlling for potential inadvertent cues from the experimental environment.

3. Experiment 2

In the second experiment, we considered the possibility that infants could use local referents on the background of the display (e.g., the vertical slot in backdrop of the stage, or the edge of the disk that the object rotated around) to track and anticipate orientation independent of any dynamic representation. Indeed, it is possible that the longer look at the improbable outcome is a result of the novel relation between the object and its support at the end of the transformation compared to this relation at the beginning. For example, on probable outcomes in the rotation event, a particular portion of the Y-shaped object maintained a consistent relation to the circular disk on the backdrop of the stage. This relationship was inconsistent in the improbable orientation outcome. To test whether infants were influenced by this aspect of the display, we created a new display where the movement of the object was controlled by magnets so that there were no visible perceptual cues that could serve as a landmark.

We presented infants with a procedure and object identical to the one used in Rochat and Hespos (1996). The only difference was that we used a display that eliminated all local perceptual cues specifying the relation of the object to the background that infants might have used, independent of any dynamic mental representation.

3.1. Method

3.1.1. Participants

Twenty-one full-term infants (9 males and 12 females) participated in the experiment. They were divided into two age groups: 11 4-month-olds (mean 4 months, 10 days; range 3 months 21 days to 5 months 2 days). Ten 6-month-olds (mean 6 months, 13 days; range 6 months, 7 days to 6 months, 21 days). Three additional babies were excluded from the sample due to fussiness.

3.1.2. Apparatus

Infants were placed 1 m in front of a stage. The stage measured 88 cm high, 111 cm wide and 28 cm deep. It was positioned in the wall 1 m from the floor. Both the sides and the floor of the stage were covered with black felt. The rear of the stage, which was formerly an observation window, was completely covered with a black opaque lamination (Frisk Coverseal). Near the middle of the display, a small hole measuring 5 mm in diameter was cut into the lamination so the experimenters could see the child at all times from the adjacent room. Additionally, another hole, measuring 2 cm in diameter, was cut into the lamination at the bottom of the display to videotape the infants. The experimental room was dark so that the observation holes were not noticeable and matched the coloring of the black lamination. Similar to Experiment 1, on the front edge of the stage was a white opaque occluder that measured 111.5 cm wide and 35.5 cm tall. The screen could be raised or lowered by the experimenter. The lighting and camera set up were the same as Experiment 1.

The display object looked the same as Experiment 1 except the object was hollowed out to minimize the weight of the object. Four small magnets (1.8 cm in diameter) were glued to the back of the object. Next to each of the magnets, a circular Teflon furniture slide measuring 2 cm in diameter was glued onto the rear of the object. The Teflon slides were set slightly higher than the magnets to minimize surface friction and ensure stable and silent movement of the object. The display object was moved by magnetic force with a second identical (control) object located behind the rear of the window display. When the display and control object were magnetically aligned, any movement of the control object from behind the stage was mirrored by the display object in front of the stage. For the translation condition, the path of the object and the screen height were marked on the backside of the window by white tape so that the experimenter had a reference for moving the object in a stable and rigid fashion. For the rotation condition a string (32 cm long) was attached to the center of the control object and used as a compass to rotate the object smoothly around a point located in the center of the display.

3.1.3. Procedure and scoring

During the experiment the infant sat on the parent's lap facing the stage. The infant's head was approximately 1 m from the stage/window. The parent was asked not to interact with the infant and to close her eyes and oriented her head towards the

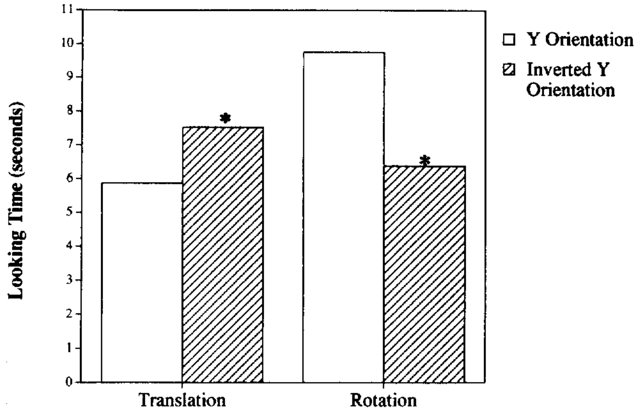

Fig. 4. Mean looking times of the infants in test trials for Experiment 2.

floor and away from the stage during the trials. The procedure was the same as Experiment 1 except there were four familiarization trials instead of six[3]. The infants were given a short break between events. All other aspects of the events were the same as Experiment 1.

Again, two experimenters worked together to produce the events: Experimenter 1 looked through the peek hole to see if the infant had fixated the object. Then, Experimenter 1 moved the object through its trajectory and surreptitiously changed the orientation of the object when it was behind the occluder. Experimenter 2 controlled the lights and raised and lowered the occluder screen.

Intercoder reliability was assessed on one-third of all the test trials that were included in the analysis. Percent agreement between the coders was greater than 0.92.

3.2. Results

Overall, analysis of the looking time revealed that infants in both age groups looked significantly longer at the improbable compared to the probable orientation outcome. An overall 2 (age: 4- or 6-month-old) ×2 (event: translation or rotation) ×3 (test order: 1st, 2nd, 3rd test trial pair) ×2 (orientation: probable or improbable outcome) mixed design ANOVA yielded a significant main effect of orientation $F(1,20) = 21.21$, $P < 0.001$. This pattern was upheld for translation and rotation separately as well, $F(1,20) = 4.058$, $P = 0.0576$, $F(1,20) = 14.080$, $P = 0.0013$, respectively. A graph of the means is shown in Fig. 4. The average looking time in the translation event for Y-orientation (probable) outcome (5.95 s) was shorter

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[3] Earlier experiments that used a magnet controlled object on the stage/window (Plotkin, 1996) revealed that infants became bored and frustrated with six familiarization trials, and four familiarization trials worked better. We have no explanation why this particular stage incurred boredom whereas the other stage did not. However, due to the high attrition rate in the other study using this stage, we decided to use four familiarization trials instead of six.

than the average looking time for the inverted-Y (improbable) outcome (7.52 s). The opposite looking pattern was found for the rotation event. The average looking time for the inverted-Y orientation (probable) outcome (6.38 s) was shorter than the average looking time for the Y orientation (improbable) outcome (9.75 s). No significant effect of age was found ($F(1,19) = 1.205$, $P < 0.2861$). There was a significant main effect of test order, $F(2,20) = 8.17$, $P < 0.001$. The means show that there was a decrease in mean looking time across test trials (1st = 8.31, 2nd = 6.49, 3rd = 5.74). No significant interactions of orientation with sex ($F(1,19) < 1$), event order ($F(1,19) < 1$), starting orientation ($F(1,19) < 1$), or test order ($F(1,19) < 1$) were found.

Non-parametric tests confirmed the main findings. Eighteen out of 20 infants looked on average longer at the improbable compared to the probable orientation outcome. Wilcoxon signed ranked tests performed on the difference scores for each infant confirmed that infants in both age groups looked longer at the improbable orientation outcome (4-month-olds: $T = 58$, $P < 0.0244$; 6-month-olds: $T = 52$, $P < 0.0098$). A Wilcoxon-Mann–Whitney test confirmed that the difference scores from the two age groups were not different from each other ($z = 0.3872$, $P > 0.3520$).

3.3. Discussion

Parametric and non-parametric analyses demonstrated that both 4- and 6-month-old infants discriminated the probable from the less probable orientation outcomes of the object. This phenomenon did not appear to depend on age, sex, event order, test order, or starting orientation. From 4 months of age, infants were capable of tracking an object undergoing invisible spatial transformations and anticipating the outcome of these transformations. The absence of local perceptual cues did not influence the pattern of responses. These findings confirm that 4- and 6-month-old infants are capable of anticipating the probable orientation outcome, tracking the invisible transformation based solely on the motion information that takes places prior to occlusion, and not on the relative change of relation between the object and its support.

4. Experiment 3

In Experiment 3, we tested infants' ability to track the orientation of an object moving behind the screen in depth. Infants were familiarized with two events. In one, the object maintained the start orientation through the transformation (Ferris event, see Fig. 5a). In the other, the object rotated 180° from the start orientation (rotation event, see Fig. 5b). Similar to the other experiments, during test trials, the screen was lowered following the transformation and revealed in either a probable or an improbable orientation outcome. The movement in depth provided different orientation cues compared to movement in the fronto-parallel plane (Experiments 1 and 2).

Experiment 3 entertained an alternative account of the results reported in the preceding experiments. It is possible that instead of mentally tracking the object moving behind the occluder, infants might have compared the final orientation outcome of the object with how it appeared just before the occlusion. Accordingly, infants would use a perceptual matching strategy rather than dynamic representation to detect the improbable orientation outcome. This alternative hypothesis was put to test in the rotation event. The object orientation just prior to occlusion was radically different from final orientation of both the probable and improbable outcomes (e.g., the last view was of the top of the object see Fig. 5b). In contrast, during the Ferris event the orientation with respect to the stage was the same throughout the entire transformation.

The predicted outcomes for both events were opposite. In the Ferris event, the probable outcome matched the start orientation and the improbable orientation outcome was inverted with respect to the start orientation. In the rotation event, the opposite was true: the probable orientation outcome was inverted compared to the start orientation as the improbable orientation outcome matched the start orientation. Infants were tested in both events, in a counterbalanced order across age groups.

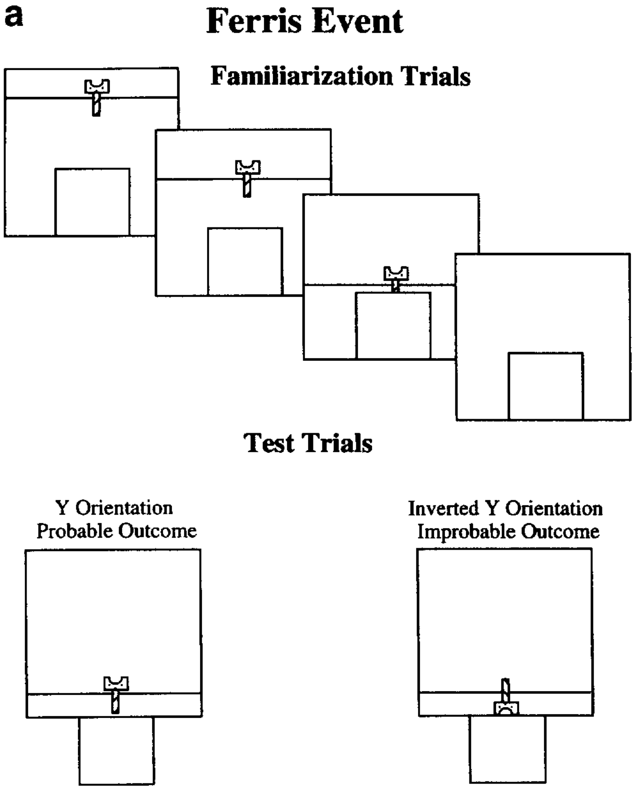

Fig. 5a.

4.1. Method

4.1.1. Participants

Nineteen full-term healthy infants (8 females, 11 males) participated in the experiment. They were divided into two age groups: nine 4-month-old infants (mean 4 months, 20 days; range 4 months, 0 days to 5 months, 2 days); 10 6-month-old infants (mean 6 months, 11 days; range 6 months, 2 days to 6 months, 28 days). Three additional babies were excluded from the sample due to fussiness.

4.1.2. Apparatus

The object was the same one used in Experiment 1. A black metal horizontal rod passed through the center of the object and extended off stage on either side. The rod was made of screw stock, which was 58 cm long and 5/8 inches in diameter with ridges like a screw on its surface.

A new stage was built to accommodate the new path of motion for the object. The dimensions of the stage were 122 cm tall, 78 cm wide, 58 cm deep. The walls and floor of the stage were covered with black felt. A slot in the side curtain of the stage

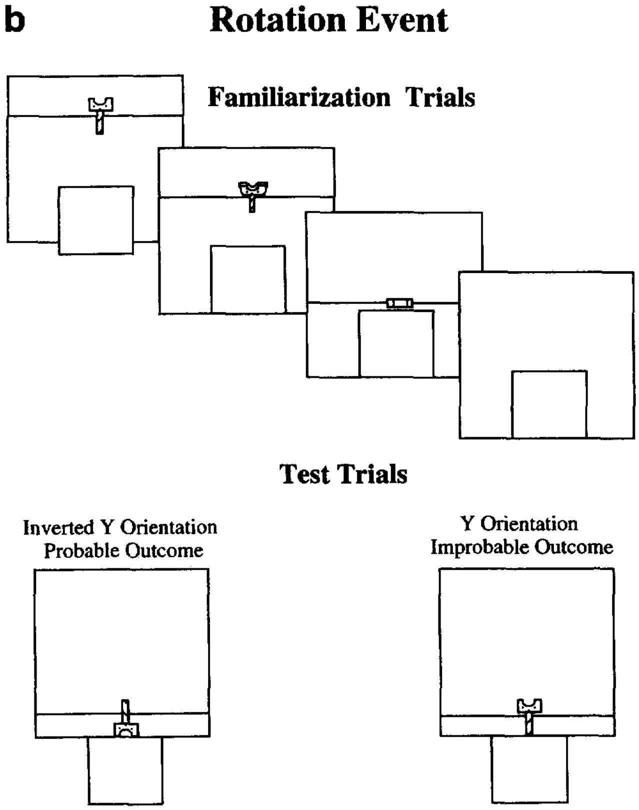

Fig. 5. (a,b) Schematic depiction of the Ferris and rotation events seen by the infants in Experiment 3.

gave the experimenter's assistant access to the object on stage. On the front edge of the stage was a white opaque occluder screen (76 cm wide and 40 cm tall) made of Styrofoam board. From behind the stage, via a system of pulleys, the occluder could be raised to occlude the lower portion of the stage, or lowered to reveal it. Similar to Experiment 1, two experimenters worked together to produce the events: Experimenter 1 raised and lowered the occluder screen, looked through the peek hole to see if the infant had fixated the object, and moved the object through its trajectory. Experimenter 2 controlled the lights and surreptitiously adjusted the orientation of the object from behind the occluder, through the side of the stage. There were black curtains hanging in front of the stage to prevent the infants from seeing the apparatus that moved the object on the sides of the stage. The curtains formed a window that was 73 cm high and 29 cm wide. The lighting and camera set up were the same as Experiment 1.

For the rotation event, the metal rod screwed into 30 cm long wooden arms on either side of the stage. The wooden arms were attached to vertical supports which consisted 45 cm high by 10 cm wide boards attached to either side of the stage. A 7 cm long metal screw held the wooden arms to the boards, which enabled the wooden arms to rotate 180° in depth. At the beginning of a trial the object was presented at the 1200 h position. From behind the stage, the experimenter could rotate the object through a 180° arc in the zy-plane to the 1800 h position by moving the wooden arms on either side of the stage.

For the control condition, a weight (invisible to the subject) was attached to the metal rod that caused the object to maintain the start orientation throughout the transformation as in a Ferris wheel.

4.1.3. Procedure and scoring

The procedure and scoring were the same as Experiment 1. Intercoder reliability was assessed on one-third of all test trials that were included in the analysis. Percent agreement between two coders was greater than 0.98.

4.2. Results

Overall, analysis of looking time revealed that infants in both age groups looked significantly longer at the improbable compared to the probable orientation outcome. An overall 2 (age: 4- or 6-month-old) ×2 (event: Ferris or rotation) ×3 (test order: 1st, 2nd, or 3rd test trial pair) ×2 (orientation: probable or improbable outcome) mixed design ANOVA yielded a significant main effect of orientation $F(1,17) = 14.5$, $P < 0.002$. This pattern was upheld for translation and rotation separately as well, $F(1,17) = 9.673$, $P = 0.006$, $F(1,17) = 6.579$, $P = 0.0195$, respectively. A graph of the means is shown in Fig. 6. The average looking time in the Ferris event for Y orientation (probable) outcome (4.73 s) was shorter than the average looking time for the inverted-Y (improbable) outcome (7.01 s). The opposite looking pattern was found for the rotation event. The average looking time for the inverted-Y orientation (probable) outcome (5.17 s) was shorter than the average looking time for the Y orientation (improbable) outcome (6.94 s). There were no

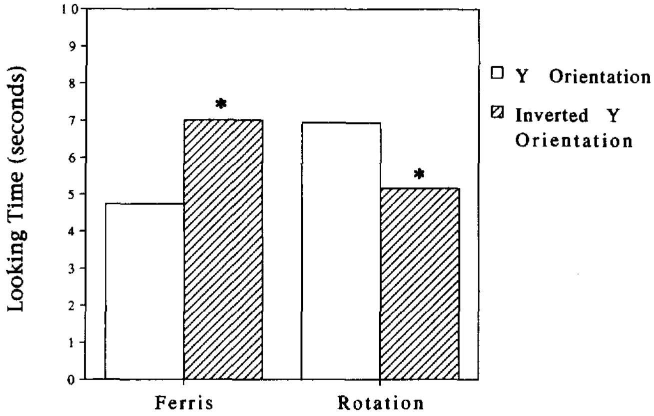

Fig. 6. Mean looking times of the infants in test trials for Experiment 3.

significant interactions of orientation with age ($F(1,17) < 1$), sex ($F(1,17) < 1$), event order ($F(1,17) < 1$), starting orientation ($F(1,17) < 1$), or test order ($F(1,17) < 1$).

Non-parametric tests confirmed the main findings. Seventeen out of 19 infants looked on average longer at the improbable compared to the probable orientation outcome. Wilcoxon signed ranked tests performed on the difference scores for each infant confirmed that infants in both age groups looked longer at the improbable orientation outcome (4-month-olds: $T = 44$, $P < 0.0078$; 6-month-olds: $T = 53$, $P < 0.0058$). A Wilcoxon-Mann-Whitney test confirmed that the difference scores from the two age groups were not different from each other ($W = 93$, $P > 0.3019$).

4.3. Discussion

Infants looked significantly longer at improbable compared to probable orientation outcomes for both the Ferris and rotational events. This phenomenon did not appear to depend on age, sex, event order, test order, or starting orientation. From 4 months of age, infants showed that based on motion-specific information (e.g., Ferris versus rotational), they are capable of mentally tracking an object undergoing invisible spatial transformations and anticipating the outcome of these transformations.

Note that the path of motion in both conditions was exactly the same, the only difference was the orientation prior to occlusion. The differential response to the two events supports the hypothesis that the infants detect the difference in orientation characteristics throughout the motion that took place prior to occlusion rather than making a perceptual match between the final orientation outcome and how it appeared just before occlusion. These results unambiguously dismiss the perceptual matching hypothesis to account for the basic phenomenon reported here.

5. Experiment 4

In this experiment, we investigated the limitations of infants ability to mentally track the orientation by extending the amount of rotation that occurred in the invisible transformation. In Experiments 1 and 2, only one-third of the entire transformation occurred behind the occluder. In this experiment we increased the invisible transformation to half of the total movement, testing whether infants' ability to track the invisible transformation depends on relatively short invisible transformations.

Similar to the Experiments 1 and 2 infants saw 120° of rotation in the fronto parallel plane before the object became occluded. The object rotated in a counterclockwise direction from 1500 to 1100 h (see Fig. 7). The object then disappeared behind an occluder and continued to rotate to 1800 h. During test trials, the occluding screen was lowered and the object was revealed in the probable or improbable (inverted 180°) orientation outcome. Note that compared to the previous experiments, there was a 90° increase in the amount of invisible transformation (60° in Experiments 1 and 2 versus 150° in the present experiment). The rationale for using this trajectory was that the start orientation was midway between the probable and

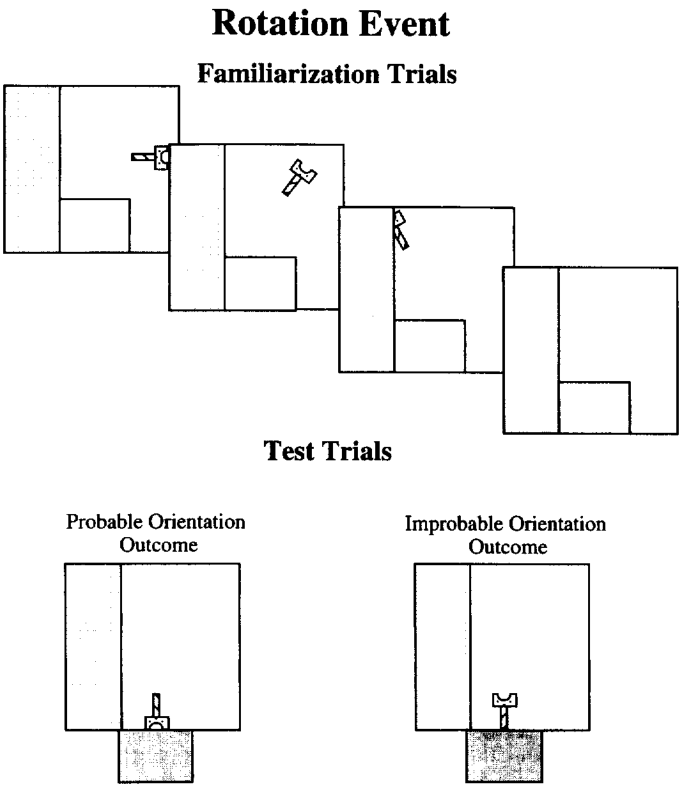

Fig. 7. Schematic depiction of the rotation with extended occlusion event seen by the infants in Experiment 4. Note that the motion was in the counterclockwise direction.

improbable orientation outcomes and the orientation of the object at the moment of occlusion was maximally different from the probable orientation outcome. Infants were tested in the rotation condition only. This experiment was a test of infants' ability to extend the amount of invisible transformation, not an extension of the retention time. The duration of occlusion time was the same as in the previous experiments. The intratrial interval, measured from the time the object became occluded until the screen is lowered was on average 3.5 s in all experiments. The time necessary to move the object the extra 90° was negligible compared to the time that Experimenter 2 needed to surreptitiously flip or touch the object behind the occluder (see Section 2.1.4 for Experiment 1).

5.1. Method

5.1.1. Participants

Nineteen full-term healthy infants (6 females, 14 males) participated in the experiment. They were divided into two groups: 10 4-month-old infants (mean 4 months, 13 days; range 4 months, 2 days to 4 months, 28 days); nine 6-month-old infants (mean 6 months, 3 days; range 5 months, 15 days to 6 months, 28 days). Four additional babies were excluded from the sample due to experimenter's error.

5.1.2. Materials and apparatus

The same apparatus and scoring from Experiment 1 were used, except for three changes. (1) The start orientation of the object was horizontal (e.g., 1500 h, midway between the probable and improbable orientation outcomes). (2) We put a second white opaque occluder between the rotating object and the original screen to increase the occlusion. (3) The motion direction in this study was counter clockwise, not clockwise as in the other experiment. This change was necessary because the structure of the stage and the room in which the study was run made it impossible to do a clockwise motion without rebuilding the entire stage. Also, we changed the direction of motion so that the radial arm, the stage, and background could remain consistent across experiments.

5.1.3. Procedure and scoring

The procedure and scoring were the same as in Experiment 1. Intercoder reliability was assessed on one-third of all test trials that were included in the analysis. Percent agreement between two coders was greater than 0.95.

5.2. Results

Overall, analysis of looking duration revealed that during test trials 6-month-old infants but not 4-month-old infants looked significantly longer at the improbable compared to the probable orientation outcome. An overall 2 (age: 4- or 6-month-old) ×3 (test order: 1st, 2nd, or 3rd test trial pair) ×2 (orientation: probable or improbable outcome) mixed design ANOVA yielded a significant main effect of orientation $F(1,17) = 4.753$, $P < 0.04$. There was no significant age by orientation interaction

$F(1,17) = 1.2$, $P < 0.28$. Fig. 8 presents a graph of the mean looking times for the different age groups for probable and improbable outcomes. The average looking times for the 4-month-old infants were similar for probable (7.0 s) and improbable (7.6 s) outcomes. In contrast, the average looking time for the 6-month-old infants was different for probable (7.51 s) and improbable (9.4 s) outcomes. Separate ANOVAs run on the 4- and 6-month-old infants revealed a main effect of orientation for the 6-month-olds ($F(1,8) = 6.801$, $P < 0.0312$) but not the 4-month-olds ($F(1,9) = 0.5$, $P < 0.49$). There were no significant interactions of orientation with sex ($F(1,17) < 1$), starting orientation ($F(1,17) = 2.719$, $P < 0.11$), or test order ($F(1,17) < 1$).

Non-parametric tests confirmed the main findings. Eight out of nine of the 6-month-old infants looked on average longer at the improbable compared to the probable orientation outcome. In contrast, six out of 10 of the 4-month-old infants looked on average longer at the improbable compared to the probable orientation outcome. Wilcoxon signed ranked tests performed on the difference scores for each infant confirmed that 4-month-old infants did not show a significant difference in looking at the two orientation outcomes ($T = 29$, $P < 0.9218$). In contrast, 6-month-old infants looked longer at the improbable orientation outcome, $T = 39$, $P < 0.0546$). Although a Wilcoxon-Mann–Whitney test showed that the difference scores from the two age groups were not significantly different from each other ($W = 75$, $P > 0.1214$).

5.3. Discussion

There is a trend toward a developmental difference between the two age groups in this experiment. Although the age by orientation outcome interaction was not significant, the parametric and non-parametric test show that 6-month-old, but not 4-month-old infants looked significantly longer at the improbable orientation outcome. These findings suggest that extending the invisible transformation did not influence the 6-month-old infants' ability to track and anticipate the orientation

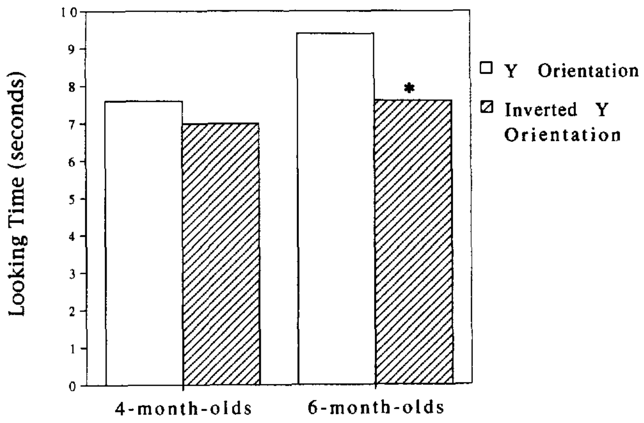

Fig. 8. Mean looking times of the infants in test trials for Experiment 4.

outcome, but did affect performance for 4-month-old infants. Because the duration of the intratrial interval was comparable with the previous experiments, these results cannot be accounted for by an increased load on memory demand. It thus appears that 4-month-old's ability to track an invisible transformation is constrained by the amount of invisible rotation, per se.

6. Experiment 5

The goal of Experiment 5 was to extend the findings of the previous experiment by investigating the perceptual cues on the object that infants use to track orientation. Orientation cues are often based on an object's symmetry (Rock, 1973). Bornstein et al. (1981) showed that infants as young as 4-months-old are sensitive to object symmetry. Kellman (1993) proposed that the salience of certain perceptual cues and flexibility in using different perceptual cues changes through development. We addressed the question of whether infants depend on an object that is rich in orientation-specific perceptual cues in order to track its invisible transformation. In the experimental condition for Experiment 1, it was possible to discriminate the probable from the improbable event by tracking either the shape of the object (extrafigural cues) and/or its intrinsic color pattern (intrafigural cues). In this experiment, we tested whether infants' behavior changed when an object with fewer orientation-specific cues was used (see Fig. 9). We created a condition where the shape of the object did not provide any orientation cues from which the infant could discriminate between the probable and improbable outcome. In order to discriminate between these events, infants had to track intrafigural cues, in particular the asymmetric color pattern on the object. We tested whether infants could use intrafigural cues alone to anticipate the orientation outcome.

As in Experiments 1 and 2, infants were shown both translation and rotation events with probable and improbable outcomes during test trials.

6.1. Method

6.1.1. Participants

Twenty full-term healthy infants (9 females, 11 males) participated in the experiment. They were divided into two groups: 10 4-month-old infants (mean 4 months, 19 days; range 4 months, 11 days to 4 months, 27 days); 10 6-month-old infants (mean 6 months, 17 days; range 5 months, 23 days to 6 months, 27 days). Two additional babies were excluded from the sample due to experimenter's error.

6.1.2. Apparatus

The same apparatus from Experiment 1 was used, except that the object was different. The Y-shaped object was replaced with a rectangular object (see Fig. 9). The object was made out of two pieces of hard foam blocks glued together. One was a bright yellow rectangular shape, 16 cm tall, 8 cm wide, 4 cm deep with a

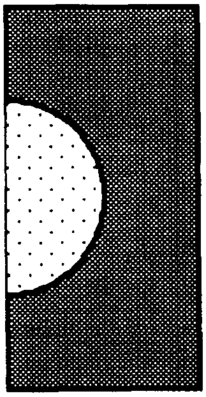

Fig. 9. Schematic depiction of object seen by the infants in Experiments 5 and 6 (darker gray was red, the semi-circle was yellow).

semi-circle (8 cm in diameter) cut out of the long side, and a bright red semi-circle shape filled the cut out.

6.1.3. Procedure and scoring

The procedure and scoring were the same as Experiment 1. Intercoder reliability was assessed on one-third of all test trials that were included in the analyses. Percent agreement between three coders was greater than 0.94.

6.2. Results

Overall, analysis of looking time revealed that during test trials 6-month-old, but not 4-month-old infants looked significantly longer at the improbable compared to the probable orientation outcomes. This trend was found in both the translation and the rotation events (see Fig. 10). An overall 2 (age: 4- or 6-month-old) ×2 (events: translation or rotation) ×3 (test order: 1st, 2nd, or 3rd test trial pair) ×2 (orientation: probable or improbable outcome) mixed design ANOVA yielded a significant main effect of orientation $F(1,18) = 6.38$, $P < 0.02$, and a significant age by orientation interaction $F(1,18) = 7.99$, $P < 0.01$. Fig. 10 presents a graph of the mean looking times for the different age groups for the probable and improbable outcomes. The average looking times for the 4-month-old infants were similar for the probable and improbable outcomes in both translation and rotation events (Translation – start orientation: 9.04 s, inverted orientation 7.92; Rotation – start orientation: 8.74 s, inverted orientation: 8.01 s). In contrast, the average looking times for the 6-month-old infants were longer for improbable compared to probable outcomes (Translation – start orientation: 6.62 s, inverted orientation: 9.41; Rotation – start orientation: 6.97 s, inverted orientation: 4.48 s). This interaction suggests that there is a developmental progression in the ability to detect improbable orientation outcomes of an object providing only intrafigural cues. Separate ANOVAs on the different age groups revealed that for the 6-month-olds there was a main effect of orientation

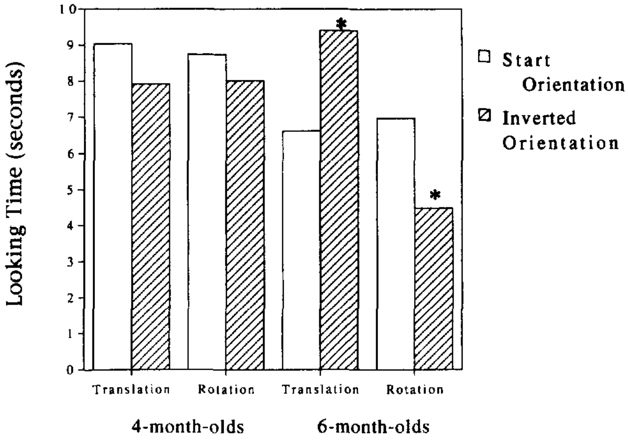

Fig. 10. Mean looking times of the infants in test trials for Experiment 5.

outcome ($F(1,9) = 14.322$, $P < 0.001$), but this effect was not significant for the 4-month-old infants $F(1,9) < 1$. For the 6-month-old infants there was a significant main effect of orientation in translation (marginal) and rotation events separately, $F(1,9) = 4.620$, $P = 0.0601$, $F(1,9) = 7.252$, $P = 0.0247$. In the overall analysis, there were no significant interactions between orientation outcome and sex ($F(1,16) < 1$), event order ($F(1,16) < 1$), starting orientation ($F(1,16) < 1$), or test order ($F(1,16) < 1$).

Non-parametric tests confirmed the main findings. Nine out of 10 of the 6-month-old infants looked on average longer at the improbable compared to the probable orientation outcome. In contrast, six out of 10 of the 4-month-old infants looked on average longer at the improbable compared to the probable orientation outcome. Wilcoxon signed ranked tests performed on the difference scores for each infant confirmed that 4-month-old infants did not show a significant difference in looking at the two outcomes ($T = 29$, $P > 0.9218$). In contrast, the 6-month-old infants looked longer at the improbable orientation outcome ($T = 52$, $P < 0.0098$). A Wilcoxon-Mann–Whitney test confirmed that the difference scores from the two age groups differed from each other ($W = 143$, $P < 0.0014$).

6.3. Discussion

We observed different responses between 4- and 6-month-old infants in this experiment. Parametric and non-parametric analyses showed that 6-month-old infants discriminated the probable from the improbable orientation outcomes in translation and rotation events. In contrast, 4-month-old infants looked equally at the probable and improbable outcomes in both events. These findings suggest that using an object with intrafigural orientation cues only, does not influence 6-month-old infants' ability to track and anticipate the orientation outcome, but it does affect performance for 4-month-old infants. The rationale for the last experiment was based on this developmental trend. We tried to assess further young infants relative dependence on rich perceptual cues to anticipate the outcome of invisible spatial transformations. The question was whether 4-month-olds might behave like 6-month-olds when provided with additional perceptual cues.

In particular, we tested both 4- and 6-month-olds with the same object but provided additional cues pertaining to the relationship of the object to its support (i.e., radial arm). The idea was that 4-month-olds would eventually behave like 6-month-olds when provided with additional perceptual cues accompanying the transformation of the object behind the occluder. This would suggest that as a function of development, infant's representation is increasingly inferential and detached from perceptual information indexing invisible outcomes.

7. Experiment 6

We replicated the conditions of Experiment 5 with the additional perceptual cue of a local referent. The same rectangular object was used but there were two changes in the background of the stage. In the rotation condition, the radial arm was uncovered thus the central portion of the arm was always visible to provide information about the object motion behind the occluder. In the translation condition, a Plexiglass vertical track was used to guide the object in a free-fall and the object made an audible impact noise behind the occluder. We were interested in testing whether a visible portion of the radial arm and the auditory cue from the translation condition would facilitate 4-month-old infants' ability to track and anticipate the invisible transformation for an object with fewer orientation cues.

7.1. Participants

Twenty full-term healthy infants (7 females, 13 males) participated in the experiment. They were divided into two groups: 10 4-month-olds (mean 4 months, 16 days; range 4 months 2 days to 5 months 10 days); 10 6-month-olds (mean 6 months, 17 days; range 6 months, 5 days to 7 months, 9 days). Three additional babies were excluded from the sample due to fussiness.

7.2. Apparatus

The same apparatus from Experiment 5 was used except for two changes. Two strips of Plexiglas (4 cm wide and 80 cm tall) with a 1 cm separation were attached to the backdrop of the stage. These served as a guide track for the object during the translation condition. The object was placed in the vertical track at the top of the stage and dropped to the bottom. Two popsicle sticks glued to the back of the object held the object on the track. In the rotation condition, the felt disk described in Experiment 1 was removed so that the radial arm was visible. The visible track in the translation condition and the visible arm in the rotation condition added cues regarding the relation of the object to its support.

7.3. Procedure and scoring

The procedure and scoring were the same as Experiment 1. Intercoder reliability was assessed on one-third of all test trials that were included in the analysis. Percent agreement between two coders was greater than 0.91.

7.4. Results

Overall, analysis of looking time revealed that during test trials 6- but not 4-month-old infants looked significantly longer at the improbable compared to the probable orientation outcomes. An overall 2 (age: 4-month-old or 6-month-old) ×2 (event: translation or rotation) ×3 (test order: 1st, 2nd, or 3rd test trial pair) ×2 (orientation: probable or improbable outcome) mixed design ANOVA yielded a significant interaction between age and orientation $F(1,18) = 7.504$, $P < 0.01$. Fig. 11 presents a graph of the mean looking times for the different age groups for the probable and improbable outcomes. The average looking times for the 4-month-old infants were similar for the probable and improbable outcomes in both translation and rotation events (Translation – start orientation: 5.01 s, inverted orientation: 4.44; Rotation – start orientation: 5.43 s, inverted orientation: 5.74 s). In contrast, the average looking times for the 6-month-old infants were longer for improbable compared to probable outcomes (Translation – start orientation: 6.46 s, inverted orientation: 8.05; Rotation – start orientation: 8.54 s, inverted orientation: 5.15 s). Separate ANOVAs run on the 4- and 6-month-old infants revealed a main effect of orientation for the 6-month-olds ($F(1,9) = 7.62$, $P < 0.05$) but not the 4-month-olds ($F(1,9) < 1$). For the 6-month-old infants there was a trend towards a main effect of orientation in translation and rotation events separately,

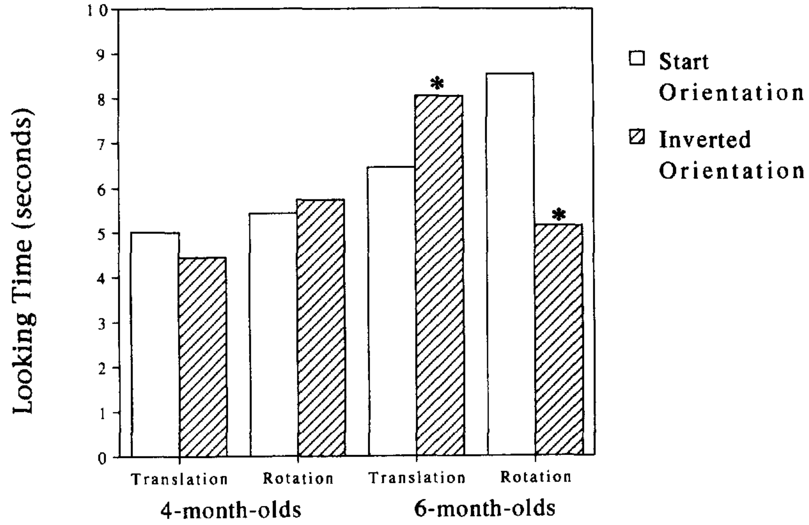

Fig. 11. Mean looking times of the infants in test trials for Experiment 6.

$F(1,9) = 2.830$, $P = 0.1268$, $F(1,9) = 8.789$, $P = 0.0158$. There were no significant interactions of orientation with sex ($F(1,16) < 1$), event order ($F(1,16) < 1$), starting orientation ($F(1,16) < 1$), or test order ($F(1,16) < 1$). A further comparison between the results obtained in Experiments 5 and 6 was performed. A 2 (Experiment: 5 or 6) ×2 (event: translation or rotation) ×3 (test order: 1st, 2nd, or 3rd test trial pair) ×2 (orientation: probable or improbable outcome) mixed design ANOVA yielded a significant main effect of test order $F(2,72) = 8.409$, $P < 0.0005$, orientation $F(1,36) = 9.58$, $P < 0.0038$, and a significant age by orientation interaction $F(1,36) = 15.38$, $P < 0.0004$. This analysis yielded no significant experiment by orientation outcome interaction ($F(1,36) < 1$).

Non-parametric tests confirmed the main findings. Nine out of 10 of the 6-month-old infants looked on average longer at the improbable compared to the probable orientation outcome. In contrast, three out of 10 of the 4-month-old infants looked on average longer at the improbable compared to the probable orientation outcome. Wilcoxon signed ranked tests performed on the difference scores for each infants confirmed that 4-month-old infants did not show a significant difference in looking at the two outcomes ($T = 36$, $P > 0.4316$). In contrast, the 6-month-old infants looked longer at the improbable orientation outcome ($T = 54$, $P < 0.0040$). A Wilcoxon-Mann–Whitney test confirmed that the difference scores from the two age groups differed from each other ($W = 140$, $P < 0.0034$).

7.5. Discussion

Similar to Experiment 5, we observed different responses between 4- and 6-month-old infants. Parametric and non-parametric analyses showed that 6-month-old infants only discriminated the probable from the improbable orientation outcomes in translation and rotation events. Again, 4-month-old infants looked equally at the probable and improbable events in both conditions hence the additional relational cues had no affect on performance.

8. General discussion

The objective of this research was to investigate the origins and early development of dynamic mental representation in infancy. Young infants' ability to track and anticipate the outcome of invisible spatial transformations was investigated in six experiments. First, we verified the original phenomenon reported in Rochat and Hespos (1996) in more controlled conditions. Results of Experiment 1 showed that infants' longer looking times at the improbable orientation outcome following an invisible transformation were not the result of implicit cues from the experimental situation. In the second experiment, we replicated the original phenomenon with the same object but used a magnetic display that eliminated possible perceptual cues infants might have used independent of dynamic representation.

In the third experiment, we investigated young infants' ability to anticipate the orientation outcome of an object moving in depth. Infants were presented with two events (Ferris and rotation). The results showed that both 4- and 6-month-old infants looked significantly longer at the improbable compared to the probable orientation outcome for both events. The significantly longer looks at the improbable outcome in the rotation event indicate that infants did not merely proceed by matching the start and end orientation outcome.

In the fourth experiment, we tested the performance of 4- and 6-month-olds when we extended the amount of rotation that occurred in the invisible transformation. Infants were presented with the Y-shaped object, but the object rotated behind a larger screen that increased the occluded portion of the transformation. The results showed that 6-, but not 4-month-old, infants looked significantly longer at the improbable compared to the probable orientation outcome. These results suggest that 6-month-olds were not affected by the extended occlusion, but 4-month-olds ability to track an invisible transformation is constrained by the amount of invisible rotation.

In Experiments 5 and 6, we investigated the salience of intrafigural orientation cues provided by the object as potential determinants of young infants' ability to track invisible spatial transformations. Four- and 6-month-old infants were tested with a display object providing only intrafigural orientation cues rather than both intra- and extrafigural cues. In Experiment 5, we attempted to replicate the original findings using this novel object in translation and rotation conditions. We found that 6-, but not 4-month-olds, discriminated between the probable and improbable outcomes. In Experiment 6, we repeated Experiment 5 but we provided additional perceptual cues on the background of the stage to determine the extent to which this manipulation might affect the differential pattern of response. Again, the results showed that only the older infants looked longer at the improbable compared to the probable orientation outcome. Thus, 4-month-old infants did not appear to use the cues provided by the apparatus to track and anticipate the orientation outcome of the invisible transformation. Thus, by 6 months infants develop specific representation abilities that do not depend on extrafigural cues. In contrast, 4-month-olds depend on rich extra- as well as intrafigural cues. (Experiments 1 and 2).

Overall, six experiments confirm the original phenomenon reported by Rochat and Hespos (1996) with more stringent control conditions. Furthermore, they capture determinants of young infants' ability to track and anticipate the final orientation outcome of an invisible transformation. These experiments demonstrate some of the developmental features of dynamic representation in infancy.

Taken together, these experiments lend insight to the potential constraints on young infants' ability to represent dynamic events in that there was a difference in how certain perceptual cues influenced performance. There were marked variations in the perceptual information between motion in the fronto-parallel plane (Experiments 1 and 2) and motion in the sagittal plane (Experiment 3). Nonetheless, these changes did not prevent 4-month-olds' ability to anticipate the orientation outcome of the object. In contrast, 4-month-old infants were capable of tracking and anticipating the orientation outcome of an invisible transformation of a 60° rotation (Experiments 1 and 2) but not a 150° rotation (Experiment 4). Furthermore, the absence of the extrafigural orientation cues on the object altered 4-month-olds performance (Experiments 5 and 6). In general, 6-month-old infants were able to track and anticipate the orientation outcome in a wide variety of situations whereas the 4-month-olds were not. The 4-month-old infant's ability to mentally track the transformation was limited and dependent on rich orientation cues and short invisible transformations. In contrast, 6-month-olds were more flexible and their behavior generalized to different situations.

A possible explanation of this developmental progression is that by 6 months, infants' repertoire of exploratory actions is linked to novel sensitivity regarding objects and their relative orientation. Between 4 and 6 months major postural development occurs. Four-month-old infants are usually cannot sit up by themselves whereas 6-month-old infants can (Uzgiris et al., 1975). Rochat and Goubet (1995) have demonstrated that perception, the development of sitting ability, and manual action are mutually dependent. When infants attain the ability to sit up, this development is linked with new levels of manual actions (Rochat, 1989, 1992). It is therefore possible that the onset of sitting ability interacts with infants' knowledge about object orientation.

Kellman (1993) suggests that within the domain of kinematic information there is variation in the validity of different perceptual cues. Some types of spatial temporal information may be more accurate in specifying the characteristics of an object in comparison to others. Studies on adult perception (Wallach and O'Connell, 1953; Gibson, 1966) suggest that when there are multiple information sources available, we rely on the optimal information. However, in circumstances where there are fewer perceptual cues, adults are flexible and rely on the information that is available. According to Kellman (1993), younger infants need rich cues from the environment, and the information must be redundant and converging to scaffold object reasoning. Over the developmental time course there is an increase in flexibility that manifests itself as a decrease in the dependence on redundant information. Kellman's theory is supported by the present data because we found no age effect when an object rich in orientation cues was used. However, the developmental differences were revealed in conditions where the object provided fewer perceptual cues. In Experiment 1, the object was rich in orientation cues and, it was possible to track the change in orientation through the intrafigural and/or extrafigural orientation cues provided by the object. In contrast, the object in Experiments 5 and 6 provided fewer orientation cues. It was necessary to track the change through the intrafigural cues alone. As mentioned above, only 6-month-olds were able to do so.

These studies show that infants can remember orientation information about an object undergoing an invisible transformation. The orientation has to be understood with respect to a referent. Referents can be the environment (e.g., gravity), a local reference frame (e.g., the wall of the room), or object-centered (e.g., the roof is the top of a car). Across experiments four different paths of motion were used: (1) translation that is vertical and linear (Experiment 1, translation condition), (2) translation in the zy-plane that describes a 180° arc (Experiment 3, Ferris event), (3) object rotation plus translation in the fronto parallel plane that describes a 180° arc (Experiment 1, rotation condition), and (4) object rotation plus translation in the zy-plane that describes a 180° arc (Experiment 3, rotation event). These different motion paths are listed in order of increasing geometric complexity. The linear displacement is relatively simple because the environmental, local, and object-centered reference frames are all in alignment. The translational motion in depth has all three reference frames in alignment but the path of motion is more complex because it is two-dimensional in contrast to the one-dimensional translation of the linear displacement. The other two paths of motion are complex because they describe motion in two-dimensions and the orientation with respect to the environment and the local reference frame changes but the object-centered orientation remains constant. It is interesting that the change in paths of motion did not hinder performance on this task even though they represent marked differences in geometric complexity of the motions. The conditions where a difference in performance occurred between 4- and 6-month-olds were those where there were fewer object-centered orientation cues or where the invisible transformation was extended, regardless of the path of motion. Taken together these findings suggest that the geometric complexity within the range of variation that we studied did not influence performance on this task.

In Experiment 3, we entertained an alternative interpretation of the data on the basis of the perceptual matching hypothesis. The perceptual matching hypothesis would suggest that the infants looked longer at the improbable orientation outcome because it differed drastically from the orientation of the object at the time of occlusion. Perceptual matching would explain the observed behavior in terms of a novelty response based on the comparison of the object's orientation as it disappears behind the screen and as it reappears during test trials. Infants were presented with a transformation where the orientation at the time of occlusion was drastically different from both the probable and the improbable outcome. Nevertheless, infants looked significantly longer at the improbable compared to the probable orientation outcome. If this was the case, then we would not have observed a differential response to the test outcomes across the Ferris and rotation events. Both the Ferris and rotation events have the same starting orientation; however, the probable and improbable outcomes are opposite. If infants were using a perceptual matching strategy, they would not have reacted differentially across conditions. Note that the results of Experiment 4 corroborate this interpretation.

One goal of these studies was to gather evidence supporting the argument that representation in infancy is potentially dynamic in nature. The findings suggest that certain spatial and temporal attributes that are intrinsic to the physical events may also be intrinsic to the mental representation of such events. More specifically, we suggest that representation of dynamic information is a necessary element to account for the observed results. Dynamic mental representation was introduced in the adult perception literature by Freyd (1987). Freyd's work has been limited to research on adults. The research presented here suggests that there is dynamic mental imagery in early infancy. There are interesting parallels between the two areas of research. The basic phenomenon in Freyd's work is called representational momentum. In their original study, Freyd and Finke (1985) show that memory for the final position of an object's motion that is abruptly occluded is distorted in the direction of the implied motion. The basic phenomenon described in these studies could be interpreted in terms of representational momentum as well. The infants were shown a moving object that became occluded, and they discriminated a probable from an improbable outcome of the implied transformation. Freyd and Finke (1985) demonstrated that the effect depended on a coherent implied motion. Kelly and Freyd (1987) showed that the momentum was attached to the represented object, not to an abstract frame of reference. They showed that minor fluctuations in the internal texture of the object weakened the momentum effect, and drastic changes in the object shape resulted in no momentum effect at all. In Experiments 5 and 6, we found that changes in the object shape lead to no discrimination between the probable and improbable events for the 4-month-old infants. The results from both Freyd (1987) and the studies presented here are interpreted as dependent on the subjects perceiving invariant information in the dynamic transformation that takes place prior to occlusion. Our findings coincide with Freyd's proposal that there is an intrinsic dynamic quality to our representation of invisible transformations. In addition, we extend her findings in that we reveal that not only is the dynamic quality intrinsic to adult representation but it is evident in early infancy as well.

A general finding from the research described here is that infants as young as 4 months of age have the ability to discriminate between a probable and an improbable orientation outcome following an invisible transformation. The sophistication of this ability seems striking when it is compared to recent findings on infants' inability to track the identity of an object in the context of partially occluded events. Xu and Carey (1996) showed 10-month-old infants a toy truck that was traversing back and forth, appearing briefly to the right and left of an occluding screen. After infants became habituated to this event, the occluding screen was lowered revealing either one truck or two trucks behind the screen. They found that infants looked significantly longer at the two-object outcome. They interpreted this findings as evidence that infants, like adults, anticipated that there would be a single object behind the screen moving back and forth. In a second condition, they habituated infants to the exact same spatial temporal event except a toy truck would emerge from the right side of the screen and a toy duck would emerge from the left side of the screen. After infants became habituated to this event, the occluding screen was lowered revealing either one truck or a truck and a duck behind the screen. They found that, unlike adults, the infants looked significantly longer at the two-object outcome. They interpreted these findings as evidence that the 10-month-old infants failed to track the identity information for this transformation. A similar finding was shown in Simon et al. (1995). Using a violation-of-expectation looking paradigm we found that 5-month-old infants reacted to a numerical violation but not an identity violation. Infants were shown a single Ernie doll on a puppet stage. Then a screen was raised occluding the doll from the infant's view. A second Ernie doll was shown to the infant and slowly lowered out of view behind the screen and placed next to the first doll. Finally, the screen was lowered, revealing either the possible outcome, two Ernie dolls ($1 + 1 = 2$) or the impossible outcome, one Ernie ($1 + 1 = 1$). Five-month-old infants looked significantly longer at the impossible outcome, suggesting that they reacted to a violation of numerosity. In contrast, the same 5-month-old infants did not react to a violation of identity in an impossible event where they were shown a Ernie + Ernie = Ernie and Elmo. Taken together, these studies suggest that infants can track orientation changes and changes in numerosity but not identity changes. It seems incongruous that 4- and 6-month-old infants in the present research discriminated between a probable and improbable orientation outcomes, yet 10-month-old infants in Xu and Carey's experiment do not detect the difference between a truck turning into a duck.

One way to reconcile these results is to posit that the infants may be encoding different types of information in these two experiments. In neurological studies, it has been postulated that there may be a functional distinction within the visual domain for identification and localization (Schneider, 1969; Ungerleider and Mishkin, 1982). Anatomical studies as well as behavioral studies involving monkeys with lesions show that there can be selective impairment of either recognition abilities or landmark detection abilities. Thus, in visual neuroscience a general distinction has been drawn between object identification: a 'what' system, and spatial localization: a 'where' system. More recently Goodale and Milner (1992) suggest that the distinction between 'what' and 'where' should be amended to a distinction between 'what' and 'how'. They have neuropsychological evidence that there could be separate visual pathways for perception and action. In particular, they show that there are human patients who cannot recognize or describe common objects but they can move around their environment efficiently. In contrast, there are patients that have difficulty reaching in the right direction or orienting their hand appropriately to grasp an object but they have no trouble with recognition. Neisser (1989) described a two-system theory that calls for similar distinctions between what and where in cognitive processes. Neisser suggested that direct perception systems may encode where objects are located in our perceptual environment and recognition systems identify what objects are and their category membership. Farah et al. (1988) apply this distinction to the domain of imagery. In particular, they draw a distinction between visual appearance representations and spatial location representations and support this dissociation with evidence from patients with neurological impairments of one or the other system.

Evidence from neuropsychological, cognitive, and clinical studies suggest that representing spatial temporal information might be different from representing identity information. The distinction between what and where/how types of representation applies to the nature of representation in studies on development. The studies presented here suggest that infants as young as 4 months of age track and anticipate the orientation outcome of invisible transformations. In these experiments, infants must detect spatial temporal invariants to track the object once it moved behind the occluder. In contrast, it appears that it is not until 12 months of age that infants track on the basis of a what system (Xu and Carey, 1996).

This is not meant to suggest that the what and where systems are mutually exclusive but rather, that one may be emphasized more in our particular task. It is important to consider the context in which this behavior is produced. When infants participate in violation of expectation experiments they are never given instructions, placed in front of a puppet stage, and presented with different events. We do not encourage them to attend to certain aspects of the events they see. However, there may be aspects of our experimental situation that encouraged infants to attend to spatial temporal information instead of identity information. Neisser (1989) points out that motion-carried information is critical to direct perception but it plays a small role in recognition. Experiments on looming and perceived unity from common motion demonstrate how dynamic information specifies spatial temporal properties of objects. In contrast, when we are trying to identify something we tend generally not to move it, we hold it still to study it. Similarly, in looking paradigms with dynamic events infants attend to the spatial temporal aspects of the objects. Thus, looking paradigms that use moving objects may emphasize attention to spatial temporal attributes for the infants. This is not to suggest that the what system is not implicated in the studies presented here. For example, the infants must use featural information to recognize that the object in the test trials is the same object that moved behind the occluder. We suggest that for this particular event the spatial temporal attributes appear to be more salient.

In summary, the studies presented here indicate that infants as young as 4 months of age are capable of representing orientation-specific information about invisible transformations. Developmental differences in this ability between 4 and 6 months of age lend insight to the nature of this representational ability. We propose that the research presented here supports the notion that there is dynamic mental imagery in early infancy and that the distinction between what and where/how types of representation applies to the nature of this early capacity.

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