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PAPER

Object representation and predictive action in infancy

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Abstract

Previous research has shown that 6-month-old infants extrapolate object motion on linear paths when they act predictively on fully visible moving objects but not when they observe partly occluded moving objects. The present research probed whether differences in the tasks presented to infants or in the visibility of the objects account for these findings, by investigating infants' predictive head tracking of a visible object that moves behind a small occluder. Six-month-old infants were presented with an object that moved repeatedly on linear or nonlinear paths, with an occluder covering the place where all the paths intersected. The first time infants viewed an object's motion, their head movements did not anticipate either linear or nonlinear motion, but they quickly learned to anticipate linear motion on successive trials. Infants also learned to anticipate nonlinear motion, but this learning was slower and less consistent. Learning in all cases concerned the trajectory of the object, not the specific locations at which the object appeared. These findings suggest that infants form object representations that are weakly biased toward inertial motion and that are influenced by learning. The findings accord with the thesis that a single system of representation underlies both predictive action and perception of object motion, and that occlusion reduces the precision of object representations.

Introduction

By 6 months of age, human infants represent objects and extrapolate their motions. Evidence for these abilities comes from studies using two different kinds of methods: studies of predictive actions such as reaching, head turning and visual tracking, and studies of preferential looking to novel or unexpected events. In predictive action studies (e.g. von Hofsten, 1980), infants are presented with a distant visible object that begins to move rapidly toward their reaching space, and their reaching and tracking movements are observed and measured. Under certain conditions, infants begin to reach for moving objects as early in development as they begin to reach for stationary objects, and from the start their reaching is predictive. Infants begin reaching for an object before it enters reaching space, aiming not for its current position but for a position further ahead on its path where the hand and the object will meet. Infants also show predictive head turning and visual tracking by following a moving object with no systematic lag (von Hofsten & Rosander, 1996, 1997; von Hofsten, Vishton, Spelke, Feng & Rosander, 1998). Predictive reaching and tracking therefore provide evidence that infants extrapolate future object positions.

In preferential looking studies (e.g. Spelke, Breinlinger, Macomber & Jacobson, 1992), infants are presented with a visible object that moves out of view behind a visible occluder, and the occluder is removed to reveal the object at one of several positions. Infants' looking time at the outcome displays is measured and compared with that of infants in a baseline condition who viewed the same outcome displays without the preceding motion. Under certain conditions, infants look systematically longer than baseline at outcome displays that present the object in a position that it would not have entered if it had continued to move naturally behind the occluder. Such preferential looking experiments provide evidence that infants make inferences about object motions behind occluders (Spelke *et al.*, 1992; Spelke, Katz, Purcell, Ehrlich & Breinlinger, 1994).

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From the above description, one might suppose that predictive action methods and preferential looking methods provide evidence for a single ability to represent objects and their motions. Differences emerge, however, when we consider the constraints on object motion that guide infants' representations in the two task contexts. In predictive action experiments, infants' anticipations of object motion appear to be guided primarily by a principle of inertia, or smoothness of motion (von Hofsten *et al.*, 1998). Predictive reaching, head tracking and eye tracking are most successful when an object moves at a constant speed on a linear or smoothly curved path. In preferential looking experiments, in contrast, infants' inferences about object motions appear to be guided primarily by a principle of continuity (Spelke *et al.*, 1992; Baillargeon, 1999). When an object disappears at one location and reappears at another location, infants look systematically longer if the two locations are separated by a barrier or by visibly empty space, as if the object had passed through the barrier or jumped discontinuously from one place to another. In a number of preferential looking experiments, however, infants' inferences failed to accord with inertia. For example, the 6-month-old infants in one series of experiments viewed an object moving on a straight line behind an occluder, and then the occluder was removed to reveal the object at rest in various positions. Infants looked reliably longer at an outcome display that presented the object on the far side of a barrier, providing evidence that they represented object motion on a connected, unobstructed path. In contrast, infants looked equally at outcome displays that presented the object at a position on the line of its visible motion and at a position far removed from that line. The latter finding suggests that infants failed to extrapolate object motion on a linear path (Spelke *et al.*, 1994; see also Spelke, Kestenbaum, Simons & Wein, 1995).

Predictive action and observation therefore appear to depend on anticipations in accord with different constraints on object motion, but what accounts for this difference? Some have suggested that infants have two distinct systems for representing objects, one that guides their perceptions and another that guides their actions (Spelke, Vishton & von Hofsten, 1995; Bertenthal, 1996). Like the multiple object representations found in human adults (e.g. Goodale & Milner, 1992) and in non-human primates (e.g. Ungerleider & Mishkin, 1982), the infants' two systems may represent objects in different ways for different purposes. The perception-oriented system may build object representations in accord with continuity, because continuity is fundamental to determining how many objects are present in a scene and how distinct appearances of objects relate to one another (see Kahneman, Treisman & Gibbs, 1992; Spelke *et al.*, 1992). The action-oriented system may build object representations in accord with inertia, because inertia is a critical factor in timing one's ongoing behavior to the positions and motions of objects (see Pavel, 1990; von Hofsten, 1995).

In contrast, others have argued that infants have a single system of object representation that behaves differently in different task contexts (e.g. Munakata, McClelland, Johnson & Siegler, 1997). A single system of object representation might show sensitivity to inertia in the above predictive action tasks but not in the above preferential looking tasks for two reasons. First, infants form more precise object representations when objects are visible than when they are hidden (see Baillargeon, 1993), as do adults. Because the predictive action experiments involved no occlusion, infants' object representations therefore may have been more precise in those experiments than in the preferential looking experiments. Sensitivity to inertia may require precise representations of object position, whereas sensitivity to continuity requires only an imprecise representation of an object's continued existence in some region of a scene.

Second, early-developing predictive actions on objects may depend on a simple mechanism that extrapolates upcoming motion based on the motion just seen (Pavel, 1990; von Hofsten & Rosander, 1997). Such a mechanism could not serve to extrapolate occluded object motions over any but the shortest distances, because the continuation of such motions does not reveal itself in any motion just seen. Sensitivity to inertia may therefore be evident only in situations involving no occlusion.

Experiments by van der Meer, van der Weel and Lee (1994) are consistent with the latter possibility. Infants aged 5 to 11 months were presented repeatedly with a linearly moving object that was occluded very briefly by a small screen before entering reaching space at the center of the field of view. At 11 months, infants reached to the central region where the object could be caught before the object even disappeared behind the screen, providing evidence for long-range extrapolations of object motion. At 5 months, in contrast, infants' reaching showed no evidence of such predictions. Because 5-month-old infants do reach predictively for moving objects that are continuously visible (von Hofsten, 1980), these findings are consistent with the view that a short-range, continuous extrapolation process guides their reaching. It is possible, however, that the reduction in reaching in van der Meer *et al.*'s (1994) experiment occurred because the occluder was placed within the baby's reaching space and so constrained the baby's reaching movements.[1]

The present experiment was undertaken, in part, to evaluate the nature and limitations on infants' extrapolations of object motion by investigating infants' predictive actions on moving objects whose paths are partially occluded. Infants were presented with the same moving objects as in the predictive reaching studies described above (von Hofsten *et al.*, 1998) with one exception: a small occluder was positioned in front of a portion of the object's path of motion just before the object entered the infant's optimal reaching space. Because the occluder did not intrude into optimal reaching space, it posed no barrier to obtaining the object. Because it was just at the border of that space, however, it occluded the object during the critical time when the infants in previous research initiated their predictive reaches. If separate systems guide predictive actions on objects versus perceptions of objects and only the action system is sensitive to inertia, then infants' predictive actions should show the same sensitivity to inertia in the present study as in previous studies. Moreover, the anticipations of upcoming motion that guide infants' actions should continue to differ from those revealed in preferential looking experiments. If a single system serves to represent objects in both reaching and preferential looking tasks and that system is perturbed by occlusion, in contrast, then infants should show less sensitivity to inertia in the present studies than in the previous studies of predictive action in which the moving object was fully visible. Infants should perform more similarly to the infants in previous preferential looking studies, who showed sensitivity to continuity but not inertia (Spelke *et al.*, 1994).

A second question raised by previous research concerns infants' ability to learn to anticipate upcoming object motions. In past predictive reaching experiments, infants have shown little change in their behavior over the course of an experiment, despite repeated encounters with an object that moved on a single trajectory. When infants reach repeatedly for an object that moves smoothly on a circular or linear path, their aiming for the object is as accurate on their first reach as on later reaches (von Hofsten, 1983; von Hofsten *et al.*, 1998). When infants are presented with an object that turns abruptly and repeatedly on the same path, they show no signs of learning to reach for it or to track it with their heads, even if they are presented with the same turning motion on six consecutive trials and the same type of turning motion on 12 trials (von Hofsten *et al.*, 1998). Only when infants were given a massive experience with a fully visible repetitive motion that turned abruptly at its endpoints (48 such turns over the course of the experiment) did 5-month-old infants show indirect evidence of learning, and even this evidence was obtained only from an analysis of eye movements (von Hofsten and Rosander, 1997). To date, there is no direct evidence that infants learn to anticipate abrupt turns in an object, and no evidence that such learning can guide predictive reaching or head turning.

Preferential looking experiments presenting partly occluded linear and nonlinear motions also provide no evidence for learning to anticipate object motions, either outside the laboratory or within it. Although 6-month-old infants have had a wealth of experience watching moving objects, and although all moving objects are influenced by inertia, such infants show no predisposition to extrapolate an occluded object's motion on a smooth path (Spelke *et al.*, 1994) or at a constant velocity (Spelke *et al.*, 1995). Moreover, infants who are presented repeatedly with an object that moves on a single linear path show no evidence of learning that the object will continue in linear motion. A dramatic example of the failure to learn to extrapolate linear motions was observed in one experiment by Spelke *et al.* (1994), in which 6-month-old infants repeatedly viewed an object that rolled on a straight line behind a screen and then was revealed at rest next to a barrier at the center of the display, on the same line as its previously visible path of motion. Although infants viewed this event on at least six and as many as 14 trials, they subsequently looked equally at test events in which the barrier was removed and the object appeared at two new, more distant positions: one on the same line of motion and one far removed from that line. Infants evidently failed to extrapolate linear motion in this situation, despite repeated experience with linear motion and no experience with any turning motion.

Predictive action studies and preferential looking studies therefore provide little evidence that infants learn to extrapolate object motions over periods of non-visibility. This finding is puzzling, however, in light of the wealth of evidence for rapid learning about objects in other contexts (see Haith and Bensen (1998), for a

[1] Van der Meer *et al.* (1994) also measured infants' predictive looking to the point of reappearance of the object. In contrast to reaching, they reported that infants looked predictively to the region in which the object reappeared as early as 5 months of age. This conclusion may be questioned, however, because the region of reappearance of the object was always at the center of the field of view, and because infants were given extensive experience with objects appearing in this central region over the course of the longitudinal study. It is not clear, therefore, whether looking to the central region was a predictive or a default strategy for the younger infants, and whether it occurred spontaneously or only after training. The present experiment addresses both these questions.

review). Do infants truly fail to learn to extrapolate object motions, or do they learn successfully but fail to show the fruits of this learning in their head-turning and reaching? Two features of the above studies might have hindered infants from exhibiting what they had learned. In the predictive action studies, infants were presented with an object that was continuously visible, and the effects of the current visual experience with the linearly moving object may have overpowered the effects of past experience with a turning object (see von Hofsten *et al.*, 1998). In the preferential looking experiments, infants may have learned to extrapolate linear motions, based either on their prior experience with objects or on their observations during the experiment. This learning, however, may have been too weak to guide extrapolations over the large regions of the scene that were occluded (see Munakata *et al.*, 1997). Learning to extrapolate object motion may be manifest only in a situation involving a moderate amount of occlusion, because effects of inertia on infants' extrapolations may be too strong when the path of object motion is fully visible and too weak when it is fully hidden.

The second purpose of the present experiment was to investigate infants' capacity to learn about both linear and nonlinear motions in a situation that might be more favorable to the expression of such learning. As in our past research, each infant was presented with linear and nonlinear motions on a series of trials that occurred in immediate succession. In contrast to our previous studies of predictive action, the object was occluded at the point at which it either continued to move straight or turned, thus eliminating any prepotent effects of a short-term extrapolation mechanism on infants' predictive actions. In contrast to our previous studies of preferential looking, the occluded region of the display was small, so that a learned but fragile predisposition to anticipate linear or nonlinear motion might better express itself. Predictive actions were measured on the first trial of each block, and changes in these actions were measured both across the trials within a block and across successive blocks. If infants learn to anticipate linear or nonlinear object motions, then their actions should accord better with those motions on later trials within a block and should further influence performance on the next block of trials.

Although both predictive reaching and predictive head turning were measured in this experiment, as in previous studies, reaching was found to be quite rare in the present study. Although this finding is of interest in itself and is the subject of another report (Spelke and von Hofsten, in preparation), the low frequency of reaching precluded any analysis of whether reaching was guided by inertia or affected by learning. In contrast, infants showed clear and robust patterns of head tracking in the present experiment, as they did in previous studies with fully visible objects. In studies presenting the same motions as the present research but no occlusion (von Hofsten *et al.*, 1998), infants' head tracking was predictive in two ways. First, it showed no lag in relation to the moving object. Second, it continued without any deceleration for 200 ms after the abrupt stopping of the object. In consequence, tracking was more accurate when the object moved linearly than when it stopped and turned. Here we focus on the same head turning measure and ask whether infants' head movements show the same patterns when they track an object that moves behind an occluder.

In the experiment, 6-month-old infants were presented with an object that moved along the diagonals of a large screen on four trajectories: two linear trajectories that intersected at the center of a display and two trajectories containing a sudden turn at the point of intersection (see Figure 1). An occluder was placed over the central part of the trajectories including the intersection between them. On each trial, the object began at one of the upper corners of the display, disappeared behind the occluder just before reaching the center of the display, reappeared just below the center of the display, and moved either to the diagonally opposite lower corner (i.e. on the extension of its linear path) or to the lower corner below its entrance point. The motions were presented in blocks of linear and nonlinear trials in an ABBA order, starting either with linear or with nonlinear motion. We

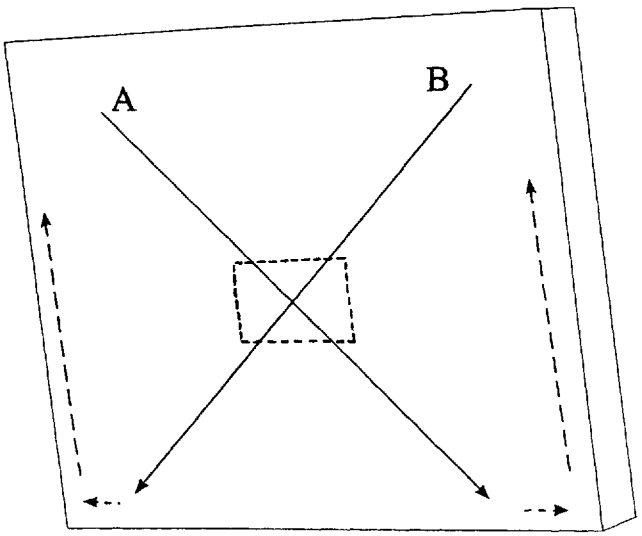

Figure 1 *A schematic view of the display screen showing the four different motion paths used in the experiments. The rectangle formed by broken lines indicates the position of the occluder in the experiment.*

asked, first, how infants anticipated the continuing object motion on the early trials of the experiment: were head movements guided by an expectation of linear object motion? Next, we asked how anticipations changed over the course of repeated exposure to each linear or nonlinear motion.

Method

Subjects

Participants were 33 full-term infants, aged 24–27 weeks (mean, 26 weeks). At the start of the experiment, the infants were recently fed and were assured to be in an alert state. Two infants were excluded because of fussing during the course of the experiment, however, and the testing of four infants was discontinued because we were unable to elicit sustained looking at the object at the start of each trial. Sixteen of the remaining infants showed high interest in the display, looking at the object both before and after its occlusion on at least four of the six trials in each block (see below). The remaining infants showed more variable interest in the object's motion and failed to meet the above criterion. Because we could not test meaningfully for learning effects in infants who failed to look at the object consistently, the present analyses focus only on the 16 infants who showed high and consistent visual attention.

Display and apparatus

Infants were tested with the same apparatus as in von Hofsten *et al.* (1998), with trajectories that were identical to those in Experiment 2 of von Hofsten *et al.* (1998). The object motions were produced by a large computer-controlled plane plotter (Roland DPX-4600), originally designed for producing precise technical drawings, whose pen was replaced with a small magnet. The 98 cm × 130 cm plotting area was topped with a sheet of aluminum that was painted white, coated with a silicone lubricant, and placed in a supporting structure such that it tilted 158° forward from the vertical. The aluminum sheet served as the background for an object, which was supported by a 12 cm wooden dowel rod firmly attached to a second magnet. When the magnet on the object's supporting rod was placed on the aluminum sheet directly over the plotter magnet, the combined attraction held the object in place and caused it to undergo whatever motion was produced by the plotter. By using the commands originally intended to direct the motion of the plotter pen, this apparatus enabled us to direct the motion of any small object very precisely, anywhere along the surface of the plotter.

A small stuffed teddy bear, 8 cm in length, served as the target object for most infants on most trials; if infants displayed no interest in reaching for this toy, a stuffed blue bird of approximately the same size was substituted. The object moved horizontally on the upper part of the aluminum surface for 13 cm before starting on its diagonal path (see Figure 1). During part of the motion, the velocity of the object increased in two steps. For the first 7.7 cm its velocity was 10 cm/s and for the remaining 5.3 cm its velocity was 20 cm/s. This part of the motion served to get the infant gradually used to the motion of the object and to attract the infant's attention to it. The diagonal motion paths were 115 cm long and measured 83 cm in the vertical dimension and 80 cm in the horizontal dimension. The paths intersected 47 cm from the lowest point of the diagonals. The target moved along these diagonal paths at a speed of 30 cm/s, producing an angular velocity (change in direction) that accelerated from approximately 13°/s at the start of the diagonal motion to approximately 65°/s as the target re-emerged from behind the occluder.

On any given trial, the object followed one of four paths of motion. It started either from the left or from the right, and either it moved linearly along the full length of the diagonal or it abruptly turned at the intersection of the two diagonals and continued along the other diagonal (see Figure 1). The infant chair was centered between the two diagonal paths, supported on a platform such that the bottom of the seat was 53 cm below the point of intersection of the paths.

Because of the nature of the hardware control unit, there was a delay of approximately 100 ms between the stopping of the first motion and the start of the second one on the nonlinear motion trials. During this delay, there was a brief change in the sound produced by the plotter motor. In order to eliminate the differential influence of the timing and the sound produced by this event, all four motions were interrupted at the intersection. Throughout the study, soft classical music provided a soothing background to the more abrupt, distinct sounds produced by the plotter.

During the experiment, a rectangular object was attached symmetrically over the intersection of the motion paths (see Figure 1). It measured 25 cm × 16 cm × 15 cm, had its longer sides oriented horizontally, and was covered with a white colored wool-like fabric. The occluder had two openings on its upper side and two on its lower side which each measured 6 cm × 13 cm. The object became occluded by entering one of the openings on the occluder's upper side, and it re-emerged through one of the openings on its lower side. The object was occluded for almost 0.9 s. Before the object disappeared behind the occluder it was out of reach, and when it reappeared it was within reach.

Design

Subjects were presented with four blocks of six to nine trials of each path of motion. Blocks of linear and nonlinear interrupted motions were presented in an ABBA order. The first two blocks started from one side and the last two blocks from the other side of the screen.

Procedure

The subjects were placed in a standard infant chair (Mothercare) and were given several minutes to become accustomed to their surroundings. During this time, they were allowed to play with the toy used in the experiment and were encouraged to reach for it as the experimenter held it in front of them. Subjects were then placed in position in front of the plotter screen with the occluder in place, directly below the intersection between the two diagonal motion paths. The subjects were encouraged to reach for the stationary toy in a location 7 cm below the occluder, and then to reach for the toy as it moved repeatedly 13.5 cm to the left and to the right of the center on a horizontal line. This warm-up procedure was intended to accustom the infant to the chair and the sounds of the apparatus, and to encourage looking at and reaching for the object. The warm-up period varied in duration depending on how quickly the infant began reaching for the object. During the warm-up period, the motions of the object appeared to violate the law of inertia, because the object abruptly stopped and changed direction at the ends and middle of each motion. These violations had no effect on infants' strong tendency to extrapolate linear motion in research with fully visible motion paths (von Hofsten *et al.*, 1998).

After the warm-up period, the toy was placed at the upper left or right corner of the screen. Then the infant's attention was called to it by the experimenter, who tapped the toy and/or the screen until the infant looked up at the starting point. The experimenter then stepped back and pressed a key on the computer to start the object's motion. The object moved downward past the infant along the pre-specified path. If it was not pulled from the screen by the infant, it continued to move along the edges of the screen to the starting position of the next trial. If the infant removed the object, it was gently taken away and manually repositioned at the next starting position.

If the infant made no contact with the toy over several trials, the toy was taken off the screen and held in front of the infant for her or him to handle. Motion trials were resumed when the infant's interest had been rekindled. The aim was to get six trials in each block in which the infant attended to the object. Therefore, if the experimenter judged the infant to be looking away at the start of a trial, it was repeated. However, no more than three extra trials per block were administered. At the end of the first two blocks of trials, the chair was turned around and the subject was given a short break. The experiment was usually completed within 10 minutes.

Data analysis

For a trial to be included in the analysis, the infant was required to look at the object before it disappeared behind the occluder and to regain fixation after it had reappeared. If more than six trials fulfilled the looking criteria in a single block, the first six trials were included. For an infant to be included in the analysis, he/she had to have at least four trials in each block fulfilling the looking criteria.

Eight of the infants included in the final sample began with a block of linear motion and eight began with a block of nonlinear motion. Of the infants who began with linear motion, five first saw the object arriving from the left and three first saw the object arriving from the right. Of the infants who started with nonlinear motion, four infants first saw the object arriving from each direction.

The data analysis was based on video recordings from two cameras, mixed onto a single screen. A video clock gave the time in milliseconds on each video frame. One camera was placed above the infant's head and was used to record head tracking of the moving target. The second camera provided a side view of the infant and was used to clarify any ambiguities in the top view. Both camera angles also served to indicate whether the infant was looking at the display. The video system was PAL, which produces 25 frames/s, in contrast to the 30 frames/s produced by NTSC.

A 17 in. video touch screen was used for coding head direction. It was activated when the coder touched it with a specially made fine pointer. The x and y location of the touch on the video screen (see Figure 2) was registered and stored on the hard disk drive of a 486 computer with a precision of approximately 0.25 mm in the vertical dimension and 0.33 mm in the horizontal dimension.

For a given trial, the coder first located the frame on which the object entered behind the occluder. He or she then rewound the videotape 1 s to begin the coding procedure. For a given frame, the coder touched the

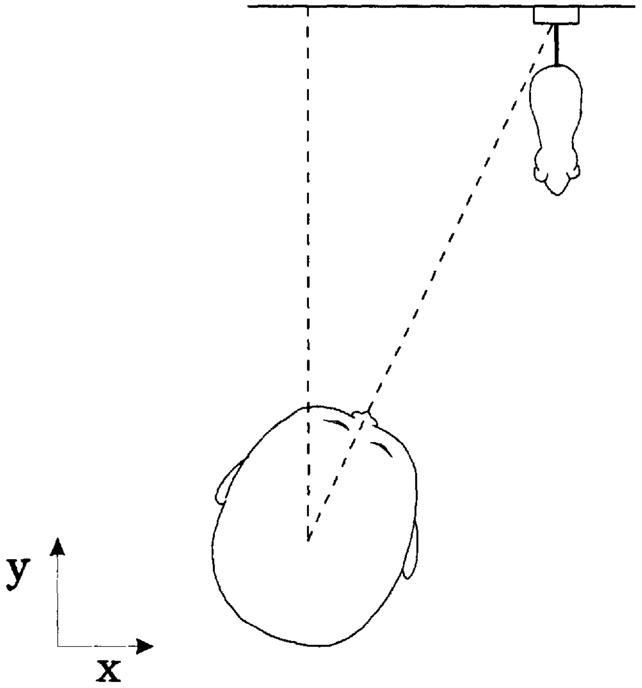

Figure 2 *A top view of a subject looking at the object showing the axes of the coordinate system used to analyze the results.*

location of the nose of the subject on the overhead video with the special pointer. This was repeated five times to improve coding precision. The median of these measurements was then calculated and used as the nose position for that specific video frame. If the nose was occluded, which sometimes happened towards the end of the coded sequence, the center of the forehead was used as the reference point. The videotape was then wound forward 200 ms (five frames) and the procedure was repeated. Altogether, the nose position was registered in this way 15 times for each trial, each separated by 200 ms, corresponding to a total of 2.8 s coding time.

The analysis of head turning was only based on the lateral position of the nose (the x axis in Figure 2). Before being subject to further analysis, the time series were manipulated in two ways. First, the zero point of each time series was set to the time when the object passed out of view. This was done by subtracting the measured value for that time frame from those of the other time frames. Second, all the trials in a certain block of a specific block sequence were analyzed as if the object always emerged from the left. To accomplish this, the data from the trials where the infants saw the object coming from the right were reversed. The unit of measurement is an arbitrary one corresponding to the unit used by the touch screen.

Prior to the main analysis of the data, a calculation was made of the ideal position of the head at the time of emergence of the object on a linear or nonlinear path. Because the object's point of emergence was equal to its point of disappearance on nonlinear trials, the ideal head position on those trials was zero, by definition. To estimate the ideal head position on linear trials, we observed all infants on those trials. For each infant and trial, the average head direction at two points of continuous tracking was determined, one at the point of disappearance of the object, where the head direction by definition had been set to zero, and the other at 1.0 s after the reappearance of the object, which was the last of the coded time frames. At that time all infants were once again consistently tracking the object with their head. The head direction at disappearance (zero) and the average head direction at the last of the coded time frames calculated over all infants and all trials were then entered into the cosine function describing the direction to the object over the trial. From this parameterized function the interpolated head direction at the re-entrance was determined to be 75 arbitrary units. Thus, if on a specific trial, the direction of the head was approaching 75 units at the reappearance point, it was concluded that the head had moved over to the point of the occluder where the object appeared on linear trials.

The actual position of the head at the time of reappearance of the object was coded for each infant and trial, and these positions were analyzed for the first block of trials to test for initial learning effects. The change over trials in head position was tested with a one-way repeated measures analysis of variance (ANOVA) and was further evaluated by t tests and binomial tests.

For a more detailed analysis of learning effects over the whole experiment, the change over trials of the change in head position over time was examined for all four time frames during which the object was fully occluded. Changes over trials and over trial blocks in these head movements were tested by separate two-way repeated measures ANOVAs for each of the two orders of trial blocks (linear first vs nonlinear first). If a missing trial occurred in the middle of a trial block, it was interpolated from the surrounding trials of that subject (eight cases); if it occurred at the end of a trial block, it was set equal to the last valid trial in that block for that subject (in six out of 64 cases Trial 5 was missing and in 21 out of 64 cases trial 6 was missing). This procedure tended to underestimate any learning effects for the final trials in a block.

Results

We begin by considering infants' anticipatory head movements on the first block of trials in the experiment. Figure 3 presents the mean head position at the time of

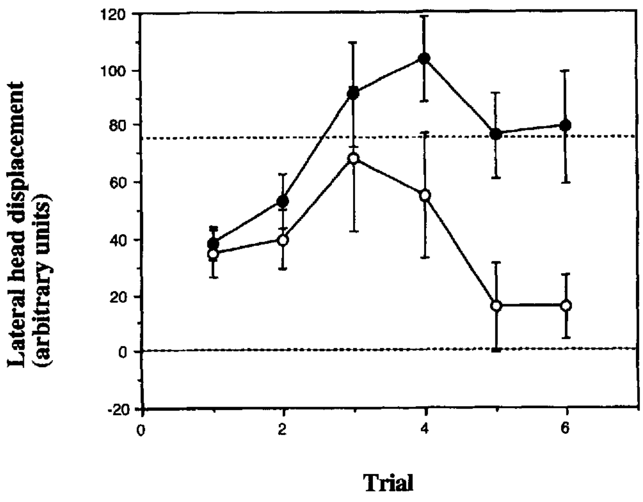

Figure 3 *Mean head position (and standard error) at reappearance for each of the six first trials of the experiment. Filled circles correspond to linear motion and unfilled circles correspond to nonlinear motion.*

the reappearance of the object, for each of the six trials. On the first trial, infants looked to a position midway between the points at which the object appeared, both on linear and on nonlinear trials. On subsequent trials of the linear condition, the infants came to look toward and beyond the far side of the occluder, where the object would reappear. This effect of trial on head position was significant ($F(5, 35) = 2.604$, $p < 0.05$). Infants turned their heads significantly more towards the far side of the occluder at reappearance on the third trial than on the first trial ($t = 2.771$, $p < 0.05$); by the fourth linear trial, all the subjects in the linear condition had increased their head turning toward the far side (binomial $p < 0.01$). In the nonlinear condition, in contrast, infants showed no consistent changes in head turning patterns over trials ($F(5, 35) = 1.515$, $p > 0.2$).

Infants' adaptation to the different motion patterns can be seen in more detail in Figures 4 and 5, which depict the head position during the ten coded time frames, from 500 ms before the object's disappearance to 600 ms after its reappearance, for the first, third and fifth trials of each condition. The vertical solid reference lines in these graphs depict the beginning (at 500 ms) and the end (slightly before 1400 ms) of the occlusion period. The horizontal broken reference lines depict the actual lateral head position at the time frame just before disappearance (zero by definition) and the ideal lateral head position at the time of reappearance (75 units). If the infants anticipate that the object will continue in linear motion behind the occluder, the head position curve should intersect the diametrically opposite corner of the rectangle formed by these reference lines. If infants anticipate the object to turn behind the occluder and appear below on the same side of it, the head position curve should intersect the lower adjacent corner of the rectangle. The figures reveal that on successive linear trials, infants consistently improved their predictions about the reappearance of the object. On nonlinear trials learning was more variable and less extensive but also showed improvement over trials.

The ANOVAs supported these findings. For infants who viewed the motion in the linear–nonlinear–nonlinear–linear sequence of blocks, head tracking changed towards the opposite side of the occluder in the first linear block ($F(15, 105) = 2.559$, $p < 0.01$), did not change in the first nonlinear block ($F < 1.0$), changed towards the same side in the second nonlinear block ($F(15, 105) = 1.795$, $p < 0.05$), and did not change in the final linear block ($F < 1.0$). For the remaining infants who viewed the motions in the opposite order, head tracking did not change toward the same side of the occluder on the first nonlinear block ($F(15, 105) = 1.699$), it did change towards the opposite side of the occluder on the first linear block ($F(15, 105) = 1.866$, $p < 0.05$), it did not show any further adjustment in that direction in the second linear block ($F < 1.0$), and it did not change in the final nonlinear block ($F < 1.0$).

Between blocks 2 and 3 of the experiment, there was a change in the direction of object motion (rightward vs leftward) but not in the kind of object motion (linear vs nonlinear). This change allows us to test whether the infants learned to predict the specific *place* where the object would appear or the specific *manner* of object motion. In the former case, performance should deteriorate at the transition between blocks 2 and 3, because the object appeared in a new place; in the latter case, performance should not deteriorate, because the object underwent the same type of linear or nonlinear motion.

When linear motions were shown in blocks 2 and 3, the infants looked for the object at its new reappearance point on the first trial of block 3. Analyzing the position of the head at re-entrance, there was a marginal improvement of linear prediction between the last trial of block 2 and the first trial of block 3 ($F(1, 7) = 4.014$, $p < 0.10$).

When nonlinear motions were shown in blocks 2 and 3, the average head position at reappearance on the first trial of block 3 was almost the same as on the previous trial. When considering the whole occlusion interval, however, changes were found between the last trial of block 2 and the first trial of block 3 ($F(3, 21) = 3.779$, $p < 0.05$), indicating that the head remained closer to the side at which the object disappeared on the trial

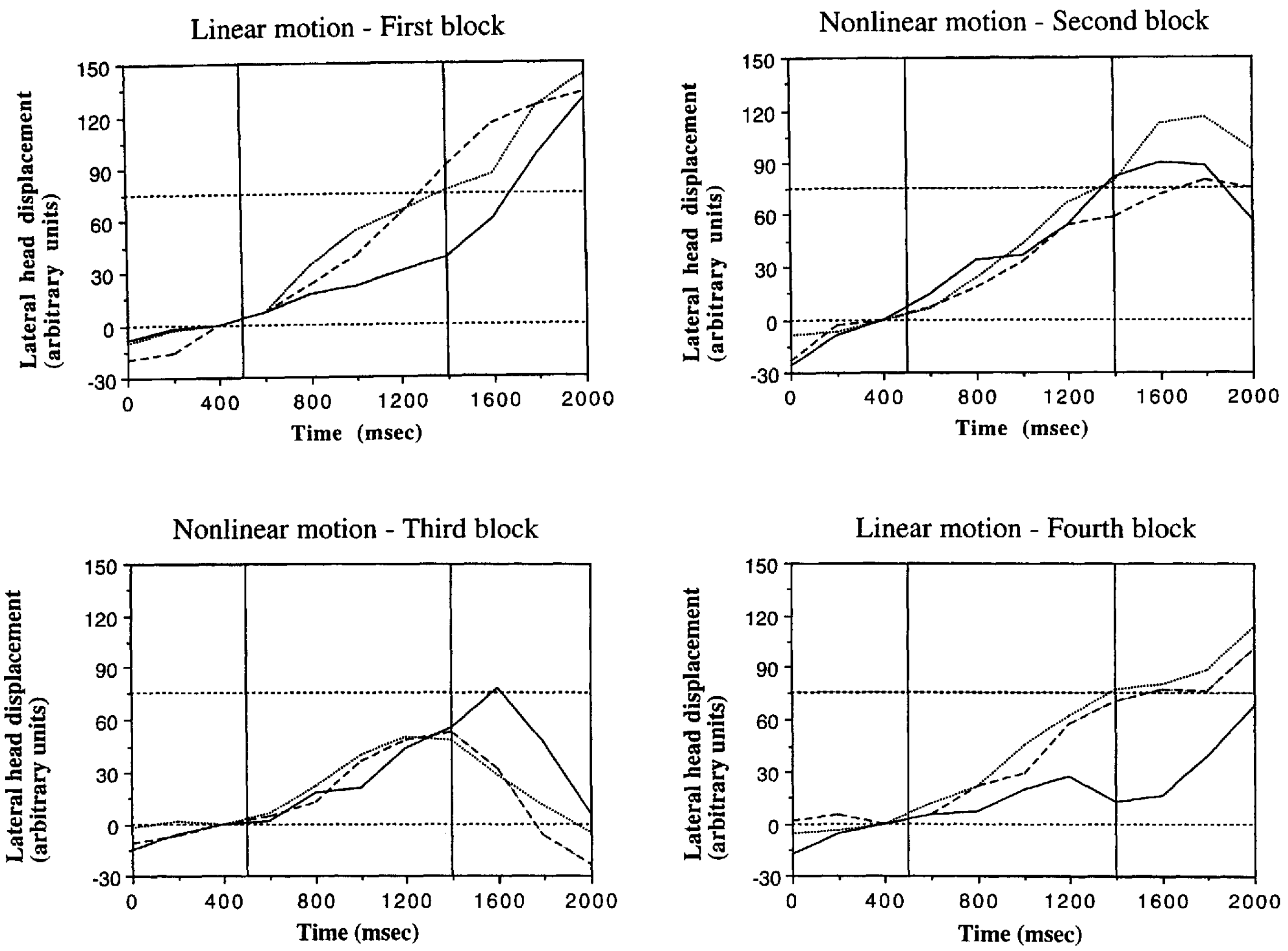

Figure 4 *Head tracking of the moving object at various stages of the linear–nonlinear–nonlinear–linear block sequence. Each graph shows the lateral head displacement over time for the first (solid curve), third (broken curve), and fifth (dotted curve) trial. The vertical lines in each graph denote the time of disappearance and reappearance and the horizontal broken lines show the head position at disappearance and the hypothetical head position at reappearance interpolated from head positions early and late in the trial (see text).*

following the change in object motion. This finding suggests that infants were learning to predict a nonlinear pattern of motion rather than a reappearance at a particular location.

Discussion

Four principal findings emerge from this experiment. First, infants do not accurately extrapolate the linear motion of an object behind an occluder the first time that they view the object's motion. After watching an object move linearly behind an occluder, infants looked for the object at a position intermediate between the far side at which a linearly moving object would reappear and the near side at which it had disappeared. In contrast to the findings of studies of predictive actions on fully visible objects (von Hofsten *et al.*, 1998), this finding provides no evidence that infants' head movements initially are guided by anticipations of linear motion of the occluded object.

Second, infants quickly learn to anticipate accurately a linear, occluded object motion. When the object moved on a straight line behind the occluder on repeated trials, the accuracy of infants' predictions had improved reliably by the third trial, and predictions were nearly perfect throughout successive linear trials of the study. Infants therefore learn rapidly to compensate for the hidden displacements of uniformly moving objects in this situation, in contrast to situations involving fully

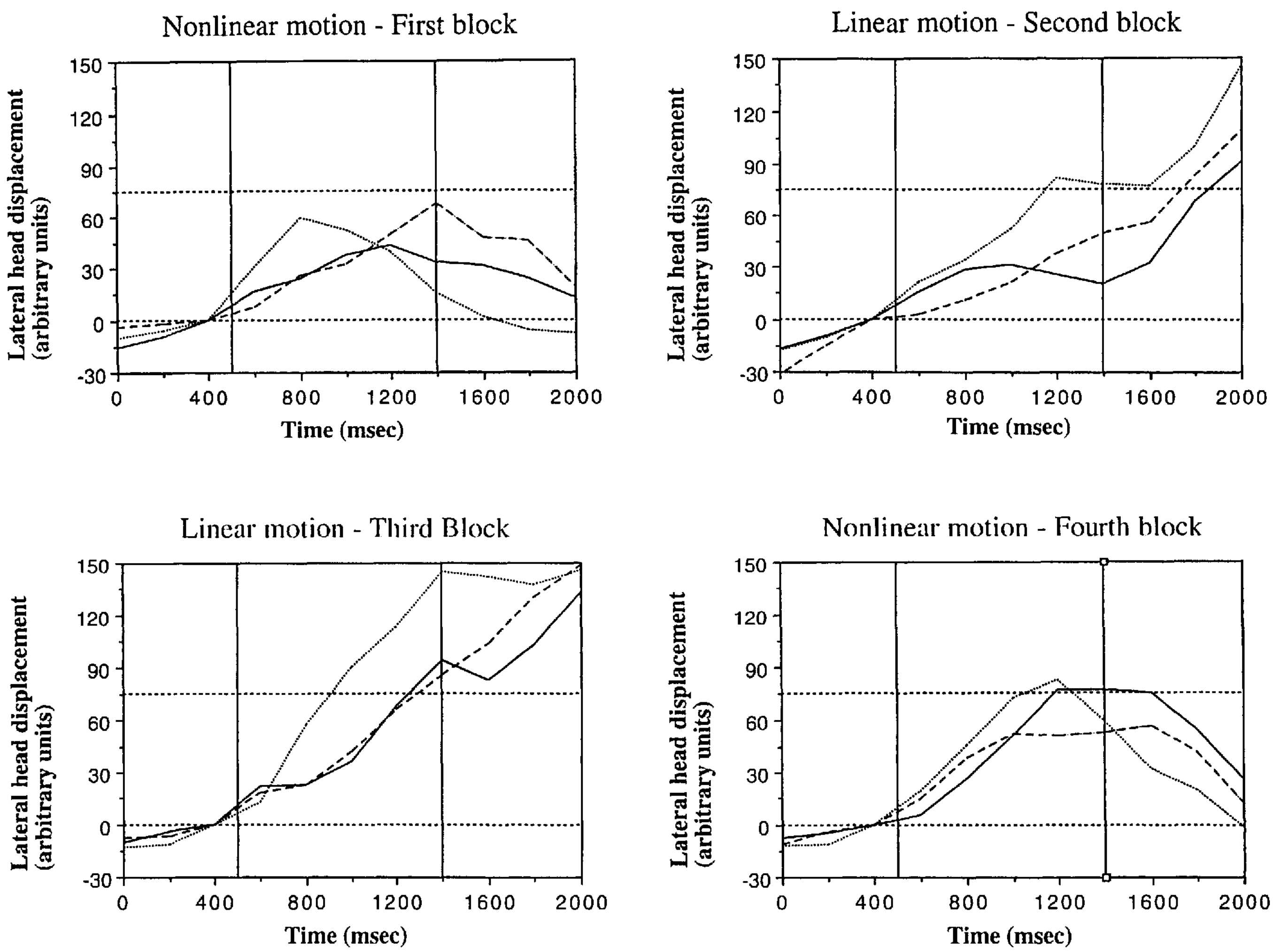

Figure 5 *Head tracking of the moving object at various stages of the nonlinear–linear–linear–nonlinear block sequence. Each graph shows the lateral head displacement over time for the first (solid curve), third (broken curve) and fifth (dotted curve) trial. The vertical lines in each graph denote the time of disappearance and reappearance and the horizontal broken lines show the head position at disappearance and the hypothetical head position at reappearance interpolated from head positions early and late in the trial.*

visible objects (von Hofsten *et al.*, 1998) or objects whose paths of motion are more fully occluded (Spelke *et al.*, 1994).

Third, infants presented with linear, temporarily occluded motion learn to predict *how* the object will move, not *where* it will appear. After six trials of linear motion in one direction, infants viewed the object moving in the opposite direction. On the very first test trial in which the object's direction changed, infants looked away from the place where the object previously reappeared and toward the opposite side of the occluder, where a linearly moving object would emerge. These findings provide an interesting contrast with studies of infants' search for stationary objects. When infants search on repeated trials for a stationary object, they tend to search in the location where the object has been retrieved previously (Piaget, 1954; Harris, 1983; Diamond, 1990). When infants search on repeated trials for a moving object that has become temporarily occluded, in contrast, their head movements suggest that they learn to predict the pattern of motion of the object rather than the location of its arrival. It has been argued that perseverative search for stationary objects reflects learning to reach to a particular place or to execute a particular response (Bremner & Bryant, 1977; Thelen & Smith, 1994). It is possible, however, that search for both moving and stationary objects reflects the operation of an inertia principle, whereby an object at rest remains at rest in a constant position and an object in uniform motion continues that motion.

Fourth, infants also learned to anticipate nonlinear occluded object motions, but learning was slower, less consistent and less complete than for the linear motions. No signs of learning were found during the first six trials of presentation of nonlinear motion, either for the infants who began with a block of nonlinear motions or for those who began with linear motions. Nevertheless, evidence for learning was obtained on the second block of nonlinear motion trials for those infants who received the two nonlinear blocks in immediate succession. On no trials, however, did infants' head movements predict with full accuracy the point of reappearance of the object, even though this point had the same horizontal position as the object's point of disappearance (see Figures 4 and 5). Learning about motions with an occluded change in path direction appears to be difficult but not impossible for infants. The difference in the ease by which infants learned to predict the reappearance of linearly and nonlinearly moving objects suggests that infants came to the experiment with a predisposition to learn to act predictively in accord with a linear extrapolation of object motion.

The present findings shed light on the nature of infants' representations of objects. Although such representations accorded with an inertia principle in past studies of predictive reaching and failed to accord with that principle in past studies of preferential looking, that difference appears to stem more from differences in the visibility of objects than from differences in the action demands on infants. When infants were given a task with the same action demands as previous studies of predictive action but with an object that was partly occluded, their tendency to anticipate the upcoming motion to be in accord with inertia was sharply diminished and did not exceed chance on the earliest trials. The present findings therefore fail to provide evidence for two distinct systems of object representation, one guiding infants' object-directed actions and the other guiding their perceptions. Although it remains possible that two such systems are present in infancy, they are not necessary to account for differences in infants' anticipations of object motions in the task contexts that have been investigated thus far.

In contrast, the present findings accord well with the view that task differences in infants' representations of objects stem from the graded nature of those representations. In the present studies, infants' patterns of learning provided evidence for a tendency to anticipate the upcoming motion in accord with inertia: infants learned more readily about linear than about nonlinear motions. Nevertheless, infants' initial reactions to the occluded motion of an object did not reveal this tendency. These findings suggest that a capacity to anticipate object motion in accord with inertia is present but weak in infancy. That suggestion is further supported by a comparison between the present research and previous studies using predictive action methods and preferential looking methods. When infants viewed a fully visible, linearly moving object in previous studies of predictive action, they showed a strong tendency to extrapolate motion on linear paths. When infants viewed a moving object that was briefly occluded in the present study and in previous research by van der Meer *et al.* (1994, but see footnote 1), they showed a diminished but still discernible tendency to anticipate continued motion on a linear path. When infants viewed a moving object that was visible during only a small portion of its trajectory in previous preferential looking studies, they showed no tendency to anticipate continued linear motion. The decrease in inertial extrapolations with decreasing perceptual support is characteristic of graded representations and is sufficient to account for the findings of diverse studies of object representation in infancy.

The present findings also shed light on infants' abilities to learn to extrapolate object motions. Although little evidence for learning was obtained in previous experiments, such evidence was strong and clear in the present study. Because the present study differed from previous predictive action studies only in one respect – the object's path of motion was partly occluded – occlusion again appears to influence the object representations involved in learning. When objects are fully visible, infants may fail to exhibit learning about their nonlinear motions because such learning is overpowered by a tendency to extrapolate visible object motions on linear paths. When objects are almost fully hidden, infants may fail to exhibit learning about any motions because infants' representations of hidden objects in this situation are too weak or imprecise. When objects are hidden only briefly, as in the present studies, infants appear to learn both about linear motions and, less readily, about abruptly turning motions. All these findings accord with the thesis that sensitivity to constraints on object motion is not all or none but graded.

Finally, the present study raises questions about the nature of the mechanism that accounts for anticipations of object motion in accord with inertia. We consider three possible characterizations of this mechanism. First, one might ask whether mechanical effects of inertia or peripheral factors such as muscle activation underlie infants' predictive actions in accord with inertia. In the present study, it is likely that such factors carry the head beyond the point of disappearance of the object. Note, however, that on the first trial of the experiment the head was turned to the midpoint of the display at the time the object re-emerged, halfway between the linear and the nonlinear points of reappearance. If the head moved passively after the object was occluded, then peripheral and mechanical factors would not appear to favor learning about either linear or nonlinear motions in this study. When the infants in the linear condition moved their heads to the far side of the occluder on later trials, they were not passively continuing the tracking begun before the object disappeared but speeding up their motion to relocate the object. When the infants in the nonlinear condition reversed the direction of their head motion to relocate the object, they similarly were acting against their own inertia. Because infants initially stop their heads at the middle of the display, equal forces may be needed to alter any mechanical and peripheral effects on the head movement system.

These considerations suggest that perceptual or cognitive systems underlie infants' anticipations of object motion, but understanding the nature of these systems requires further study. It is possible that infants' predisposition to extrapolate linear over abruptly turning object motions depends on a perceptual simplicity principle, like the principle of good continuation from Gestalt psychology (e.g. Wertheimer, 1923/1958) or the principle of non-accidentalness from computational vision (Witkin & Tenenbaum, 1983; Lowe, 1985). Linear motion exhibits a kind of good continuation over time; it is 'simpler' and 'more regular' than nonlinear motion and minimizes discontinuities and changes. Indeed, the present evidence for a graded tendency to extrapolate linear motions when objects are fully occluded resembles recent evidence for a graded tendency to extrapolate linear contours when objects are partly occluded. Although infants show no sensitivity to good continuation when viewing stationary, center-occluded objects (e.g. Kellman & Spelke, 1983), their perception of moving, center-occluded objects is reliably modulated by the alignment or misalignment of contours (Johnson & Aslin, 1996). It remains to be determined whether these similar findings reflect common mechanisms in the perception of object boundaries and object motions.

As a second possibility, infants' predisposition to perceive and learn about linear over nonlinear motions may reflect implicit sensitivity to mechanical constraints on the behavior of objects. Young infants have been found to be sensitive to a number of such constraints, including continuity (they extrapolate motion on connected paths), solidity (they extrapolate motion on unobstructed paths), contact (they extrapolate independent motions of distinct objects unless the objects come into contact) and support (they extrapolate downward motion in the absence of support) (for reviews, see Leslie, 1988; Spelke & van de Walle, 1993; Baillargeon, 1999). Like these other constraints, inertia is a basic constraint on the motions of objects that could be widely useful in extrapolating motions in the absence of specific knowledge about object kinds and object properties (Kellman & Arterberry, 1998). Distinguishing between [redacted]counts of the extrapolative mechanism [redacted] studies of the classes of motions that [redacted]te and the specific patterns of extra- [redacted]y show.

[redacted]ents

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