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COGNITION

Predictive action in infancy: tracking and reaching for moving objects

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Abstract

Because action plans must anticipate the states of the world which will be obtained when the actions take place, effective actions depend on predictions. The present experiments begin to explore the principles underlying early-developing predictions of object motion, by focusing on 6-month-old infants' head tracking and reaching for moving objects. Infants were presented with an object that moved into reaching space 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. In two studies, infants' tracking and reaching provided evidence for an extrapolation of the object motion on linear paths, in accord with the principle of inertia. This tendency was remarkably resistant to counter-evidence, for it was observed even after repeated presentations of an object that violated the principle of inertia by spontaneously stopping and then moving in a new direction. In contrast to the present findings, infants fail to extrapolate linear object motion in preferential looking experiments, suggesting that early-developing knowledge of object motion, like mature knowledge, is embedded in multiple systems of representation. © 1998 Elsevier Science B.V. All rights reserved

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1. Introduction

Although efforts to articulate the principles governing perceptible object motions challenged scientists for millennia, some sensitivity to constraints on object motion are evident in the simplest creature who tracks or intercepts a moving object. To reach for a moving object, for example, the brain must process incoming information about the object and its motion, plan the object-directed action, and transport the hand to a location in space where the object can be captured. Because these events may unfold over the course of a second or more, reaching must be guided by predictions of the object's future position and motion. The present research begins to investigate the system that generates these predictions.

Predictions of a moving object's future position are possible because object motion is subject to physical constraints. Objects move only on connected and unobstructed paths, and their motions are affected systematically by gravity and by collisions with other objects. In addition, object motion accords with Newton's law of inertia: objects continue in a state of rest or uniform motion unless acted upon by forces. Human adults appear to capitalize on many of these constraints in reaching for objects. Because reaching is a slowly developing skill, however, it is not clear whether mature predictive actions are shaped only by learning about specific patterns of object motion, or whether they rest on more general principles that emerge early in development. In an initial attempt to identify and characterize such core principles, we focus here on the predictive, object-directed actions of humans who have just begun to reach for objects effectively, i.e. 6-month-old infants.

Infants' sensitivity to constraints on object motion has been investigated by studies using preferential looking methods, focusing on infants' tendency to look longer at novel or unnatural events (Baillargeon, 1993; Spelke et al., 1995b). These studies suggest that infants are sensitive to the constraints of cohesion (objects maintain their connectedness as they move), continuity (objects move on connected, unobstructed paths), and contact (objects change their motion on contact with other objects or surfaces) (Spelke and Van de Walle, 1993). When infants are presented with a visible or occluded object that moves toward an obstacle, for example, they look longer at an event in which the object appears to interpenetrate the obstacle and reappears on its far side than at an event in which the object stops on contact with the obstacle (e.g. Baillargeon, 1986; Sitskoorn and Smitsman, 1995; but see also Cohen, 1995).

Similar studies suggest, in contrast, that young infants are not sensitive to inertial properties of object motion. Presented with an object out of reach that moves from view on a straight line, infants under 8 months look no longer if the object reappears at a position displaced far from the line of its visible motion than if it reappears on the original line of motion (Spelke et al., 1994, 1995a; but see also Baillargeon and Graber, 1987). None of these studies reveals, however, whether infants use constraints on object motion to guide predictive actions such as visual tracking and reaching.

The earliest appearing signs of predictive action have been found in eye tracking (Aslin, 1981; von Hofsten and Rosander, 1996; von Hofsten and Rosander, 1997).

Aslin observed that 3-month-old infants' smooth pursuit eye movements sometimes stayed on or were slightly ahead of a target they were tracking (Aslin, 1981). Von Hofsten and Rosander found that the smooth eye movements of 2-month-old infants predicted the smooth changes of a sinusoidal motion. In these studies, however, the infants viewed targets that moved back and forth repetitively. Because the infants who tracked these targets were familiar with their motions, the studies do not reveal how infants track a moving object viewed for the first time, and whether such tracking accords with any constraints on object motion.

Research by von Hofsten (1980, 1983) provides evidence that infants' object-directed reaching is predictive. As soon as infants begin catching stationary objects successfully (at about 18 weeks), they also begin to catch moving objects. Infants catch an object that approaches them by initiating arm and hand movements before the object is within reaching distance, aiming ahead of the object's current position toward a place where the paths of the object and the hand can intersect. In the experiment by von Hofsten (1980), aiming was accurate on the first attempted reach for a fast moving object (30 cm/s). These findings indicate that young infants can reach predictively without trial and error learning over the course of the experimental session. Nevertheless, the target objects in this study always traveled on the same circular path (albeit at variable speeds and distances and from variable starting positions), and infants tended to watch an object moving in its circular path before attempting their first reach. As subjects' reaches were well timed even the first time that they viewed an object moving at a given distance and velocity, infants evidently predicted that an object moving at a certain speed would maintain that speed. We do not know, however, how predictive reaching is guided by other spatio-temporal constraints on object motion.

In summary, studies of tracking and reaching for moving objects show that infants predict the future position of an object, but they reveal little about the nature or limits of infants' predictions. Systematic study of the principles guiding predictive actions requires manipulation of the spatial as well as the temporal properties of object motion. The present studies begin this effort.

In two experiments, we investigated how 6-month-old infants track and reach for visible objects whose motions either accord with, or appear to violate, the principle of inertia. In Experiment 1, infants viewed an object that either moved in a straight line at a constant speed ('constant linear motion') or underwent an abrupt stopping and turning at the midpoint of its trajectory in the absence of any visible cause ('interrupted non-linear motion'). The same kinds of motion paths were shown in Experiment 2, with the exception that objects moving on straight paths also stopped abruptly at the intersection before continuing ('interrupted linear motion'). Linear and non-linear motions starting from the upper left or upper right corners of the display, and intersecting at the midpoint of the display, were presented with equal frequency in each experiment, and infants' head tracking and reaching for the objects were observed. If tracking and reaching accord with the principle of inertia, then infants were expected to track the object more smoothly and to reach for it more effectively on the linear paths of motion. They were also expected to err systematically in their tracking and reaching for the turning object, by directing their head and hands away from its actual position toward a position that a linearly moving object would occupy.

2. Experiment 1

In the first study, infants were presented with four different paths of object motion on a nearly vertical, flat surface (Fig. 1). For two of the paths, the object started at the upper left corner of the surface and moved diagonally toward the center; for the other two paths, the object started at the upper right corner of the surface and moved diagonally toward the center. At the point of intersection of these paths, straight above and out of reach of the subject, the object either continued on a straight path or it abruptly stopped, changed direction, and continued on the other diagonal path. The constant linear and interrupted non-linear motions were presented in random order, such that the motion of the object at the midpoint was unpredictable. To track and to aim appropriate reaching movement for the object, however, infants' head and arm movements had to be based on an extrapolation of the object's motion beyond the center of the display. Infants' head turning and reaching were measured before, at, and after the object's arrival at the midpoint, in order to determine whether such extrapolations occurred and whether they were appropriate to the linear path of motion.

Because infants saw equal numbers of linear and non-linear motions in a random order, the motion of the object at the intersection point was inherently unpredictable in this experiment. Although it may seem contradictory to study predictive reaching

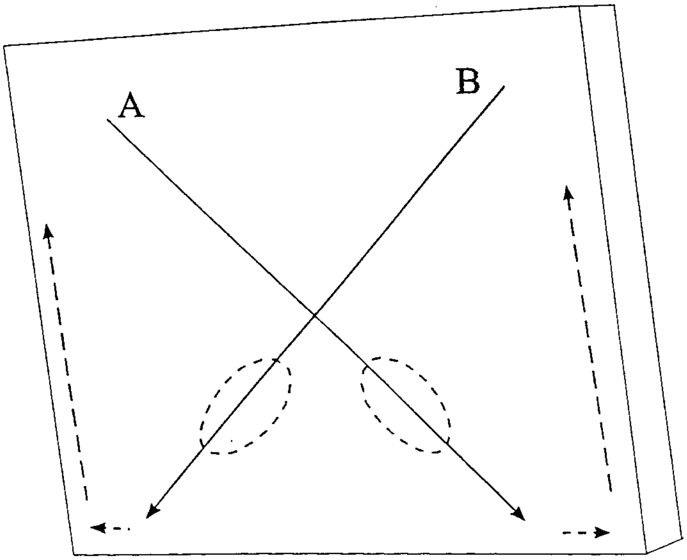

Fig. 1. A schematic view of the display screen showing the four different motion paths used in the experiments. The dashed ellipses indicate the reaching areas for each path.

in a situation in which successful predictions cannot be made, it is precisely this situation which allows us to assess how principled constraints guide infant behavior. If infants' predictive actions accord with the principle that a linearly moving object will continue moving on a straight path, we can be confident that this tendency reflects preexisting assumptions about object motion, rather than learning based on specific experience with the object during the experiment.

2.1. Method

2.1.1. Subjects

Fifteen infants, 23 to 26 weeks old, participated in the study. Two subjects did not complete the experimental procedure due to fussiness and therefore were eliminated from the sample. An additional two subjects never reached for the target and were excluded from the data treatment. All analyses therefore are based on the six female and five male subjects who completed the study and reached for the object.

2.1.2. Display and apparatus

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 (Fig. 2). The 98 × 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 15° 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, and at any velocity up to 60 cm/s.

A small stuffed teddy bear, 8 cm in length, served as the 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. Each object contained a small rattle to enable the experimenter to attract the infant's attention by tapping on it. The rattle was not activated during the motion of the object. In the present experiment, the objects always moved at the constant speed of 40 cm/s. At the initial starting distance from the subject (approximately 70 cm from the infant's eyes), this produced a retinal velocity of about 10°/s. As the object moved toward the position closest to the infant (approximately 25 cm from the eyes), the retinal velocity smoothly accelerated to a maximum of about 90°/s. Retinal velocity therefore varied about nine-fold during the course of each motion. This substantial increase in retinal velocity depends on the fact that the object moves on a plane. At the beginning of its trajectory most of its motion is directed towards the subject resulting in a fairly small lateral displacement but as it passes straight ahead all its motion is directed laterally.

On any given trial, the object followed one of four paths of motion: either constant linear or interrupted non-linear motion, beginning either from the left or from the right (see Fig. 1). Each motion path was 128 cm long and measured 83 cm in the vertical dimension and 97 cm in the horizontal dimension. The four paths intersected 36 cm from the lowest point of the diagonals. The infant chair was centered between the two diagonal paths, supported on a platform such that the bottom of the seat was 43 cm below the point of intersection.

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 non-linear motion trials. During this delay, there was a brief change in the sound produced by the plotter motor. The linear motions therefore passed the point

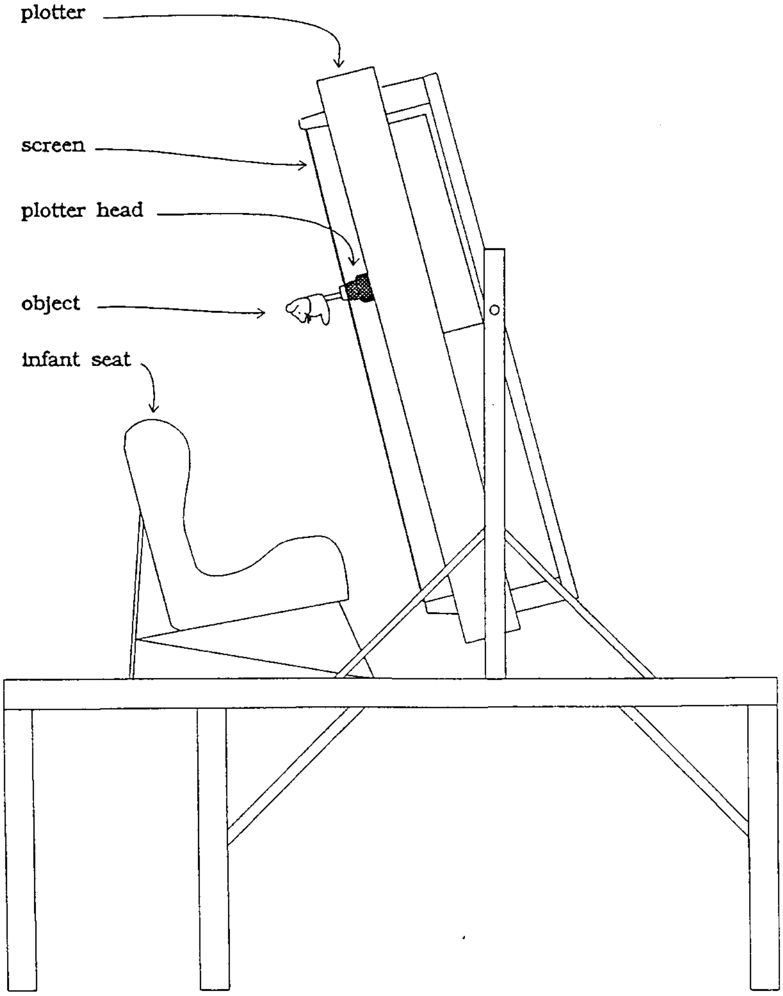

Fig. 2. A side view of the experimental apparatus.

of intersection undisturbed and accompanied by a continuous noise, whereas the non-linear motions first stopped for 100 ms and then moved along the other diagonal, accompanied by a brief change in noise. Throughout the study, soft classical music provided a soothing background to the more abrupt, distinct sounds produced by the plotter.

2.1.3. Design

Subjects were presented with a total of 24 trials in two blocks. Each trial block consisted of three presentations of each of the four paths of motion. All subjects viewed the motion paths in different random orders, with the restriction that no path be presented more than three times in succession across the experiment.

2.1.4. Procedure

The subjects were placed in a standard infant chair (Mothercare) and 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 then were placed in position in front of the plotter screen, directly below the intersection between the two diagonal motion paths. The subjects were encouraged to reach for the stationary toy in a location 5 cm directly below the intersection point, and then to reach for the toy as it moved repeatedly 13.5 cm to the left and to the right of 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 reaching for the object. The warm-up period varied in duration depending on how quickly the infant began reaching for the object. By the end of this period, all the infants (excepting the two who were eliminated from the sample for failure to reach) had reached for the object at least once. 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.

After the warm-up period, the toy was placed at the upper left or right corner of the screen, and 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 (see Fig. 1). If the infant successfully 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 three consecutive 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. At the end of the first block of 12 trials, the chair was turned around and the subject was given a short break. The experiment was usually completed within 10 min.

2.1.5. Data analysis

The data collection was based on video recordings from two cameras, mixed onto a single screen. One camera provided an overhead view of the infant and was used to record reaches for and 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.

The data from each infant were scored in two stages. First, judgments were made of whether or not each infant attended to the display during each of the trials. One coder operated a VCR and recorded the data, while a second coder judged whether the infant was looking at the display. The second coder was only permitted to view the first half of the object's path of motion, ending when the object arrived at the intersection point. Looking during that part of the trial could be judged from the overhead camera, because the infant could only look at the target by turning the face and eyes upward towards it. Since the linear and non-linear paths of motion were identical up to this point, the second coder remained blind to the experimental condition in making judgments of the infant's looking.

The second phase of the coding involved tracking the motions of the infant's head and hands during each trial. The paths of object motion were designed such that the object would come within reach shortly after moving through the point where the four motion paths intersected. At the beginning of the coding procedure, the first coder marked the location of the intersection point on the video screen by advancing the tape to the first non-linear perturbed motion trial. When the object stopped for 100 ms, it was located at the intersection point; this location on the video monitor was marked with a water-based pen, and the marking was used throughout the coding.

To determine where the infants oriented their heads and reached both before and during the time that the object was within reach, coders transcribed the position of the bridge and tip of the nose as well as the position of the base of the index finger of each hand from the video screen to a computer. This was done at nine points in time, defined relative to the moment of the object's arrival at the intersection point: –133, –67, 0, 67, 133, 200, 267, 333 and 400 ms. The transcribed movements were analyzed in a coordinate system with its axes parallel to the screen (horizontal, specifying the lateral position of the hand) and perpendicular to the screen (specifying the position of the hand in depth) (see Fig. 3). The units of this coordinate system were calibrated from known positions in a projection plane through the intersection point of the two paths of object motion. When the hand lay in this plane, 1 cm of recorded movement was equal to 1 cm of real movement. When the hand was at its lowest possible point (i.e. resting in the lap), the degree of recorded screen movement underestimated the degree of real movement by 25%.

In order to minimize possible effects of observer bias, the coder began to measure head and hand position at the latest point in time and worked backwards. (Throughout the trial, coders were focused on the task of recording head and hand position and reported no awareness of trial type.) Nose and hand positions of the subject were marked for each time frame, and were later entered into a computer by means of a digital drawing tablet. The use of a 40.5 × 30 cm video monitor (526 × 390 pixels)

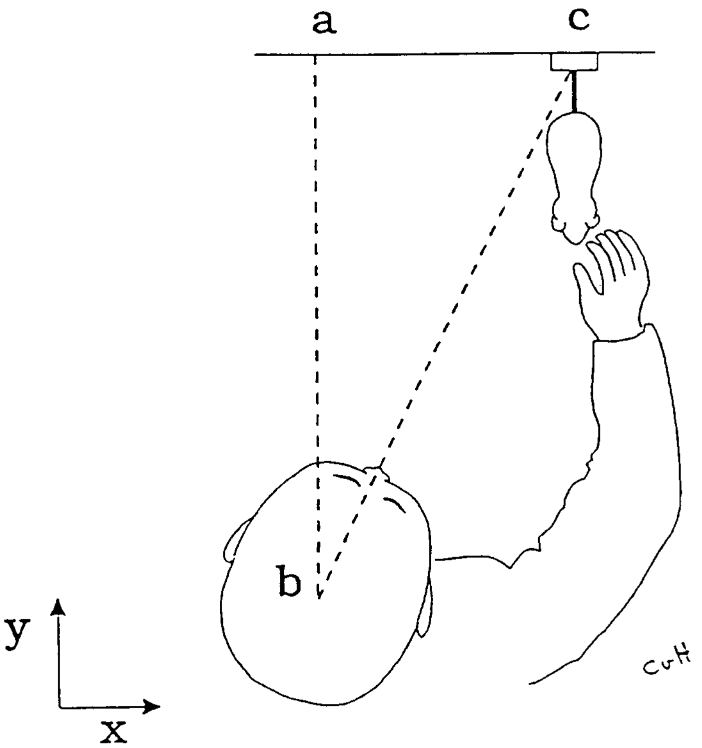

Fig. 3. A top view of a subject reaching for the object showing the axes of the coordinate system used to analyze the results.

and a digital drawing tablet with a resolution of plus or –0.1 mm resulted in an assessment of the hand and head screen positions which were accurate to within a tolerance of around 1 mm.

Head movement data were included in the analysis if the infant was judged to be looking at the display during the first half of the trial. Hand movements were included in the reaching analysis if the infant was judged to be looking at the display and if the hand moved laterally at least 2 cm (approximately one half of a hand width) at any time during the recorded interval. The latter requirement was chosen in order to eliminate from the analyses cases in which an infant's hand underwent so little lateral motion that no reliable assessment of aiming could be made, while including all motions for which an assessment of aiming was possible.

2.2. Results

2.2.1. Head movements

The 11 infants on which the analysis was based looked at the object (as judged from their gaze direction) on 87% of the trials. Two subjects attended to the target

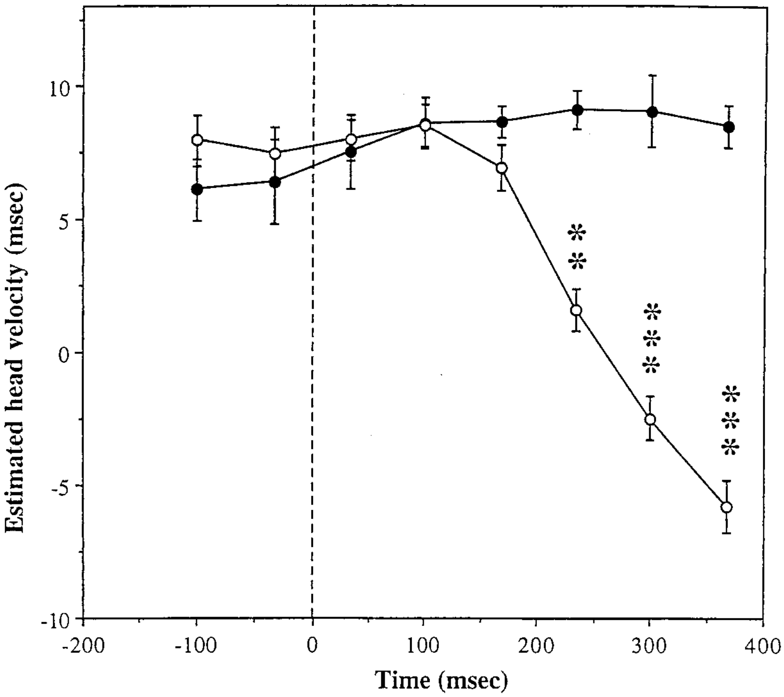

Fig. 4. Mean lateral head velocity at each time interval for the linear (filled circles) and non-linear (unfilled circles) motions used in Experiment 1. The calculated velocity for each interval is represented at the middle of the interval. Motions originating from the left and the right have been collapsed. The error bars represent SEMs. Significant differences in head velocity between the linear and non-linear motions are shown, $^{**}P < 0.01$, $^{***}P < 0.001$.

and tracked it on all 24 trials, four subjects did so on 23 trials, two on 20 trials, one on 18 trials and one on 10 trials. There was no difference in looking rates for different trial types. Fig. 4 depicts the mean lateral velocity of the head at each of the eight codable points in time for each of the four motion paths[1]. For the trials on which the object stopped and turned, the head position continued to accord with a linear extrapolation of object motion for at least 200 ms after the object motion was interrupted. Beginning at the interval 200–267 ms past the point of intersection, head velocity differed significantly between the linear and non-linear conditions (see Fig. 4). No differences in head velocity patterns were obtained between the first and second halves of the experiment for either the linear or the perturbed trials, all t's < 1.44, $P > 0.18$, providing no evidence for learning effects.

2.2.2. Reaching

Table 1 presents the number of trials on which each infant moved the hand

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[1] At each point in time, the lateral velocity of the head is estimated by subtracting its position at that time from its position at the next time step and multiplying by the sampling rate. Head velocity therefore cannot be estimated at the last coded time step.

Table 1
Number of trials meeting the criterion for reaching (see text) for each subject, hand and motion path in Experiment 1

Subject	Linear trials				Non-linear trials				Total trials[a]
	From left		From right		From left		From right		
	L.H.	R.H.	L.H.	R.H.	L.H.	R.H.	L.H.	R.H	
1	5	0	6	0	1	0	3	2	16 (1)
2	5	0	5	4	5	1	4	6	22 (8)
3	3	5	2	5	5	6	0	5	22 (9)
4	5	2	5	5	4	4	2	2	18 (11)
5	4	4	2	3	2	6	4	4	18 (11)
6	0	1	0	4	1	2	0	2	9 (1)
7	0	7	0	1	1	6	0	2	16 (1)
8	3	5	3	6	2	3	4	4	18 (12)
9	3	1	1	5	4	1	3	6	18 (6)
10	1	0	0	0	0	0	0	2	3 (0)
11	4	3	3	5	4	5	3	2	18 (11)
Total	33	28	27	38	29	34	23	37	178 (71)

[a] Number of trials in which reaching is performed with both hands are shown within brackets.

laterally at least 2 cm, for each of the four object motions. Such movements were obtained on 42% of the trials for the left hand and on 52% of the trials for the right hand. In total, reaching movements meeting the 2-cm criterion occurred on 78% of the trials on which the infants looked at the object[2]. Both hands moved on 27% of the trials (see Table 1), but each hand was treated separately in the analyses.

Fig. 5 depicts four sample reaches illustrating the variety of hand movements which could result in successful reaching in this task: The reach could be initiated from anywhere within a broad range of space, and it could be aimed at any location along the motion path of the object within the arm length of the infant. Moreover, infants aimed their reaches toward locations across the entire length of the object, ranging from the head of the stuffed bear to the base of the magnet support. Since this variability in the depth dimension (vertical axis in Fig. 5) is not informative about the predictive nature of infants' reaching, measurements and analyses reported here focus on the lateral positions and velocities of the hands (horizontal axis in Fig. 5).

In the present task, the moving target is only reachable within a limited area during a limited time. This area (hereafter, the 'catching area') is situated on the side contralateral to the origin of the linear motions, and on the side ipsilateral to the origin of the non-linear motions. The tendency to direct reaching movements to one of these areas can be evaluated by analyzing the relationship between the velocity and position of each hand during the reach.

If the infant's hand is initially to the left of the object's catching area, the hand

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[2] Only lateral displacement was considered in the reaching criterion, but most infants moved their hands upward and toward the object as well. Reaching motions therefore typically were much more extensive than the 2-cm minimum.

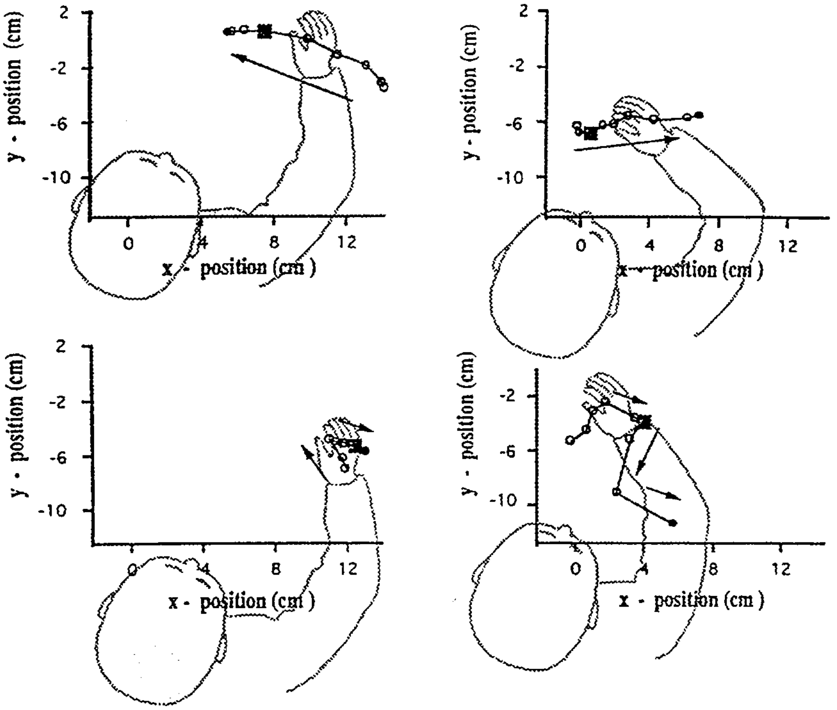

Fig. 5. Four sample right-hand reaches made by four different infants as the target object moved from left to right on the linear path. The movement of the hand in the projection plane (*x*–*y* plane) is shown by open circles. Hand movement progressed in the direction indicated by arrows, making contact with the object at the location indicated by the filled square.

must move rightward in order to approach the object. If the infant's hand is initially to the right of the catching area, the hand must move leftward to approach the object. If the infant's hand is initially far from the catching area, then the hand must move rapidly in order to get to the object in time. If the hand is initially in the path of the object, then the correct reaching action is to hold the hand at this position and wait for the object to move to it. In other words, the function relating lateral hand position to lateral hand velocity at a specific time should be approximately linear, have negative slope, and intersect the position axis within the catching area.

To assess whether infants' reaches showed appropriate aiming to any position, the position and velocity of the hand at each of the eight codable points in time during a reach were subjected to a regression analysis[3]. If the regression line had a negative slope and intersected the position axis at any point within 30 cm to the left or right of midline (the catching area), the reach was considered to be aimed to the object.

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[3] The lateral position of the hand is given by the position data recorded at each time step; the lateral velocity of the hand is estimated by subtracting its position at the same time step from its position at the next time step and multiplying by the sampling rate. Hand velocity could not be estimated at the last time step given this procedure (see footnote 1).

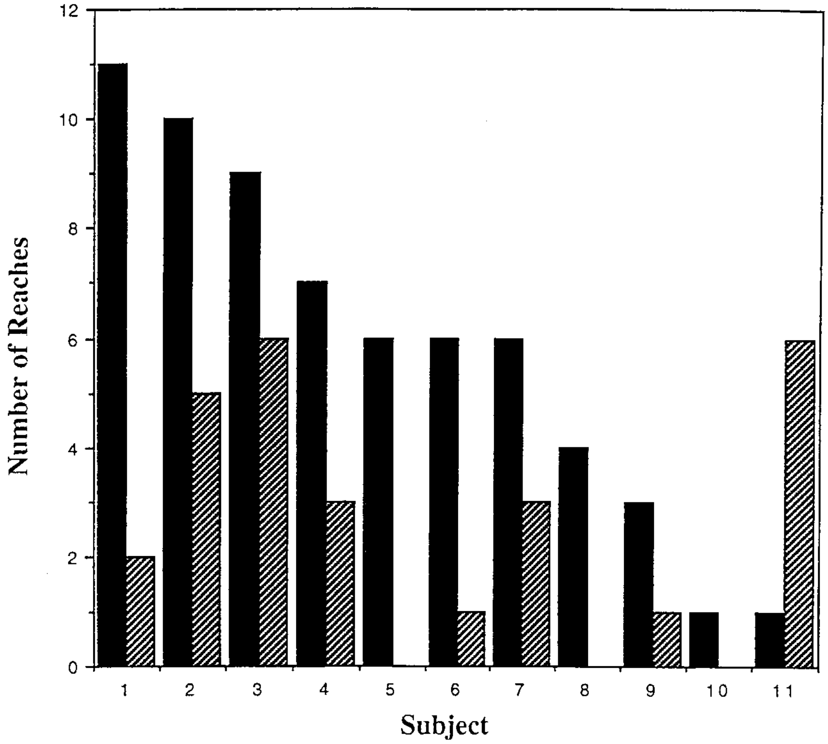

Fig. 6. Number of reaches aimed to the contralateral side of catching space indicating linear extrapolation (black bars) and to the ipsilateral side of catching space indicating non-linear extrapolation (grey bars) in Experiment 1.

These reaches were categorized according to whether they were aimed to the side of reaching space contralateral to the object's initial position (i.e. to the side on which a linearly moving object would enter reaching space) or to the ipsilateral side. Fig. 6 presents the total number of reaches aimed to each of the two sides of the catching area. It can be seen that infants tended to aim their reaches toward the contralateral side of reaching space, in accord with the principle of inertia. Ten of the 11 subjects in the experiment aimed more reaches to the contralateral side ($t(10) = 3.19$, $P < 0.01$).

We next investigated the timing of convergent aiming by analyzing the convergence patterns of different reaches at each measured point in time during the reach. Fig. 7 plots the lateral position and the lateral velocity of each hand for each of the two linear object paths, at the interval 200–267 ms after the object arrived at the intersection point. Least squared error regression lines and 95% confidence intervals are shown for each plot. The two plots in which the hand was contralateral to the starting point of the object motion indicate a negative correlation between the position and velocity of the hand (Fig. 7b,c). In contrast, no correlation is present for the two distributions in which the hand was ipsilateral to the origin of the object motion:

across the full range of position data, the ipsilateral hand tended to move toward the contralateral side of the display (Fig. 7a,d).

The same pattern is evident for the trials in which the object moved along the nonlinear paths (Fig. 8). The hand contralateral to the origin of object motion converged on a position to which the object would have moved had it continued along a linear

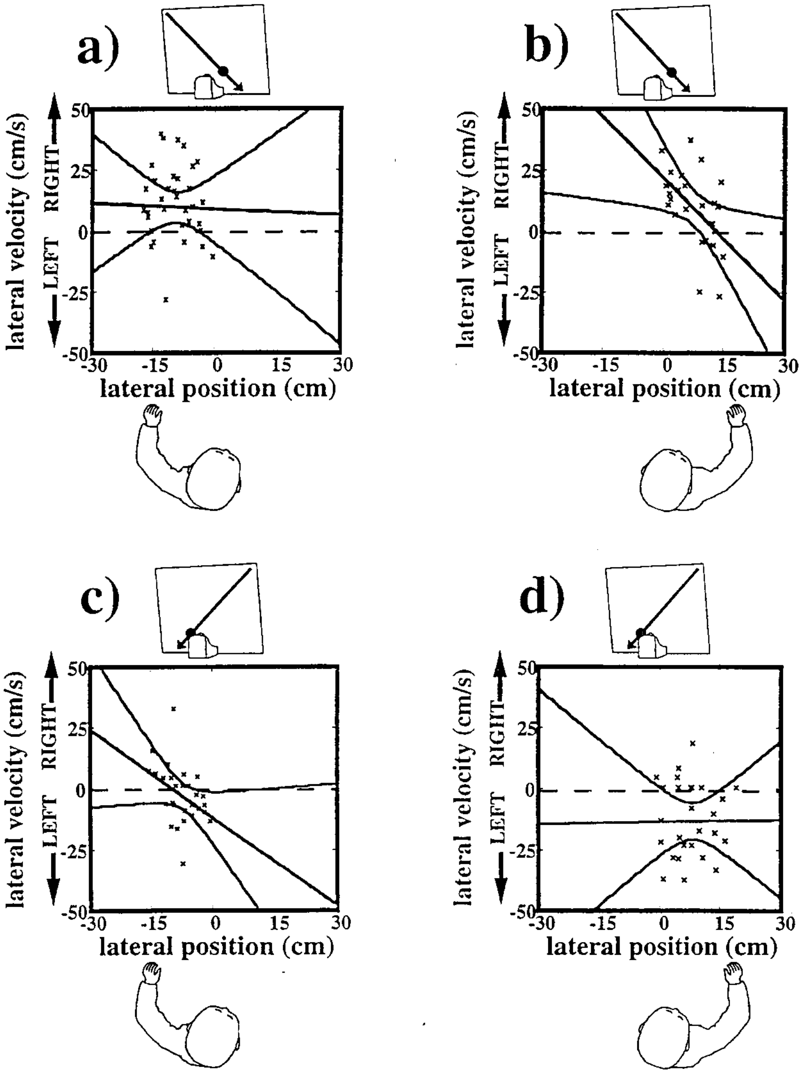

Fig. 7. Scatter plots of the lateral position and velocity of each hand at the 200–267 ms interval after the intersection of the motion paths for each of the linear motion conditions of Experiment 1. Negative numbers indicate positions and velocities directed to the left. The regression line and 95% confidence bands are shown for each distribution. The condition analyzed is indicated by the figure at the top of each graph and the hand used is indicated by the drawing at the bottom of each graph.

path (Fig. 8b,c), whereas the ipsilateral hand moved toward the contralateral side of the display with no convergence on a spatial location (Fig. 8a,d). The contralateral hand's convergence to a linearly extrapolated position is evident, even though the object had turned toward the ipsilateral catching area.

Table 2 summarizes these regression analyses for both hands, in all experimental conditions, at the eight points in time for which hand velocity could be

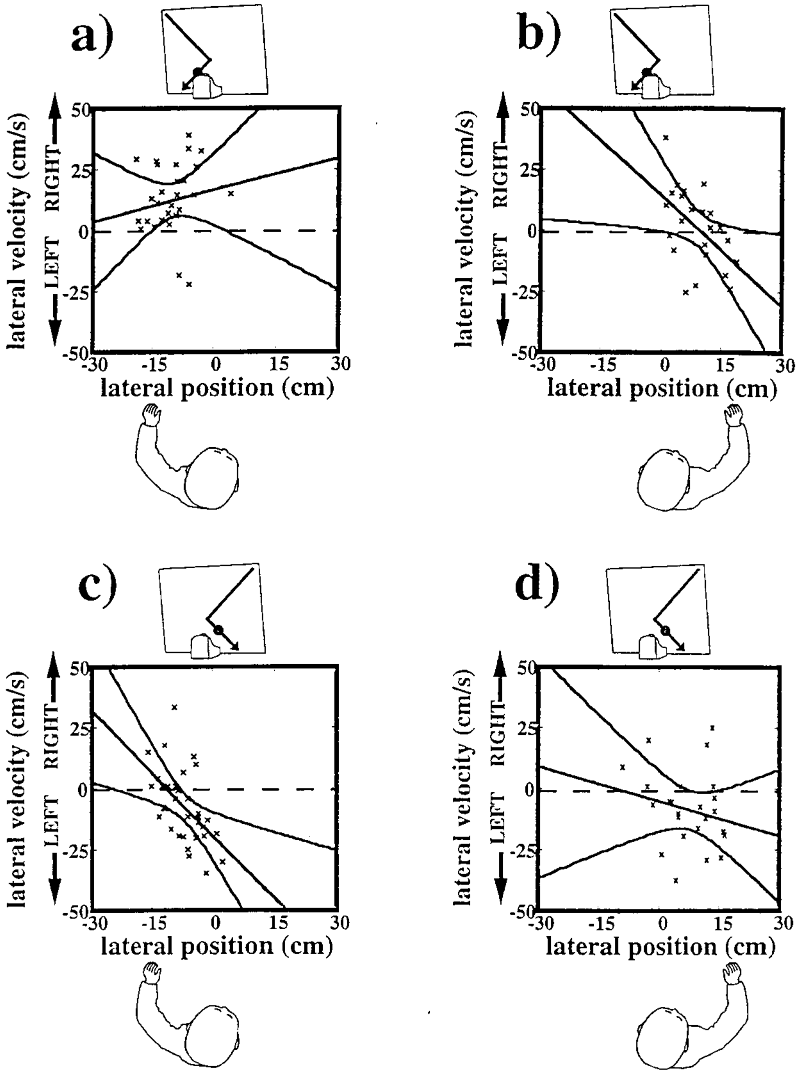

Fig. 8. Scatter plots of the lateral position and velocity of each hand at the 200–267 ms interval after the intersection of the motion paths for each of the non-linear perturbed motion conditions of Experiment 1. Definitions as in Fig. 7.

Table 2
The *x*-intercepts of the regression line relating hand position and velocity for each hand, time interval, and path of motion in Experiment 1[a]

Contralateral hand

Time	Left hand		Right hand	
	Linear trials	Non-linear trials	Linear trials	Non-linear trials
–120	–6.84**	–9.07*	17.98	–
–60	–0.82	–10.43	22.42	–
0	–7.40^{+}	–[b]	12.99**	27.60
60	–8.96**	–16.38	22.00	12.41
120	–10.40**	–12.30***	13.97**	9.61*
180	–9.75**	–11.77***	15.53**	12.24*
240	–9.79***	–13.53*	15.15*	12.51
300	–13.27*	–12.26	16.94	–

Ipsilateral hand

Time	Left hand		Right hand	
	Linear trials	Non-linear trials	Linear trials	Non-linear trials
–120	–	–	–	–
–60	–	–	–33.78	–
0	–	–	–98.33	–
60	–	–	–	–
120	–	–	–	–
180	–	–	–	–10.84
240	–	1.30	–	–0.24
300	–	–10.55**	–	10.24*

$^{+}P < 0.10$; $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

[a] Negative numbers indicate positions to the left of the intersection point.

[b] If a positive correlation between hand position and velocity was present, indicating no convergent reaching, no number is reported (–).

estimated. The data were first subjected to a general linear model analysis[4]: velocity = constant + position + subject + (position × subject).

Because no effects of either subject or of position × subject interaction were apparent, these terms were subsequently removed from the model and the analysis was repeated. Both with and without the subject terms included, many significant correlations between position and velocity were present. Out of concern that these effects might be the result of a few highly influential data points rather than the result of a general tendency of infant reaching, we repeated these analyses after removing any data which exerted an abnormally high influence on the correlation coefficients (Studentized Residual > 2) (see Darlington, 1990). Far from attenuating the result, the removal of high leverage outliers resulted in a more consistent effect. Based on the coefficients of this analysis, the zero-velocity intercepts were calcu-

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[4] Subjects who made only one reach in any given condition were, of necessity, not included in the analysis of that particular condition.

lated. These convergence points are listed in Table 2. The significance level of the position × velocity correlation is indicated by symbols next to the intercept position. For cases in which reaching did not converge on a spatial location (where there was a zero or positive correlation between position and velocity), no intercept is listed.

Several trends should be noted for the cases in which the hand is contralateral to the start of the object motion: first, convergent reaching is present for nearly all (28 out of 32) of the time × condition combinations. Second, the reaching converges in all instances to a position on the side to which the object would have moved if it had continued along a path of linear motion. Third, in all cases the reaches converge on a point within the catching area on that side, i.e. less than 30 cm to the side of the intersection. Finally, the convergence on points within reach along the linear path takes place whether the object continues on the linear path or not.

In contrast to these findings, the ipsilateral hand only rarely exhibited convergence on a spatial location (seven out of 32 cases). The two statistically significant cases both occurred at the last recorded time interval of the non-linear path of motion and showed appropriate convergence on the non-linear path of motion. In the five other cases, the position × velocity correlation accounted for very little variance in the data (maximum $r = 0.13$, $P > 0.49$).

Finally, we assessed whether infants' reaching changed over the course of the experiment by repeating the regression analyses separately on the data from the two blocks of trials and comparing performance on the first and second trial block. Even when data were collapsed across left and right hands within the contralateral and ipsilateral conditions, no differences were obtained across the two trial blocks. Indeed, there was a stronger tendency to converge on a linearly extrapolated position during the second half of the experiment, despite the fact that this convergence led to unsuccessful reaches on half of the trials.

2.3. *Discussion*

When infants were presented with an object that moved either on a continuous linear trajectory or an interrupted non-linear trajectory, both their head turning and their reaching suggested that they extrapolated the object motion on the linear path. Infants' head movements smoothly followed the object on linear trials. On non-linear trials, moreover, the head continued to move at the same speed as for the linear trials, for 200 ms after the object turned. This continued movement suggests that infants extrapolated motion on a linear path at least 200 ms ahead of the object.

In the case of reaching, the principal evidence for a linear extrapolation of object motion came from the analysis of the relation between the position and velocity of each hand during the trials when the infants attended to the object and the hand moved. Two aspects of this analysis suggested that reaching was guided by a prediction of continued linear motion. First, the contralateral hand tended to converge on a location within the catching area on the side to which the object would move if it continued on a linear path. Second, the ipsilateral hand moved consistently toward the contralateral side of space, where a linearly moving object would come within reach. This hand did not converge on a specific location on the contralateral side of the catching area (which might have been too far from the hand's current position to permit a successful reach), suggesting that the convergence shown by the contralateral hand is not a statistical artifact or an evitable pattern in arm movements. In sum, the contralateral hand appears to be aimed toward a specific point within the catching area at which a linearly moving object would appear, and the ipsilateral hand appears to undergo more non-specific motion toward that same side of the catching area.

It might be argued that mechanical forces acting on the head, hand, and body of the infant, rather than extrapolations of object motion, account for the patterns of head turning and reaching that we observed. Perhaps the head and hand moved in the inertially specified direction because they themselves are physical bodies subject to inertia and so cannot immediately change direction. Three aspects of the movement patterns argue against this interpretation. First, tracking by the head and the ipsilateral hand continued with no reduction in velocity for 200 ms after the object stopped its linear motion on the interrupted non-linear trials. If the head and hand were passively carried along by inertia, they should have begun to decelerate when the object stopped moving. Second, although the true velocity of the linearly moving object was constant, its retinal velocity varied nine-fold over the course of its motion (from 10 to 90°/s). Smooth head tracking of the object therefore required continuous changes in head movements, not movement at a constant speed. Third, infants' reaching movements with the contralateral hand did not show a general translatory motion in the direction of the object's motion, but convergence on the region of the catching area that the object would enter if it continued along a linear motion trajectory. On the interrupted non-linear trials, convergence on points appropriate to a linearly moving object continued until at least 267 ms after the object stopped its linear motion. This convergence reveals the physical instantiation of predictive reaches which were planned on the basis of perceptual information gathered more than 267 ms earlier.

At the last time point that was analyzed (333 ms) on the interrupted non-linear trials, the ipsilateral hand showed appropriate convergence on the ipsilateral side of the catching area, and the contralateral hand ceased to show convergence on the contralateral side. These patterns suggest that information that the object had changed direction path began to influence reaching at this time, inducing a new reach with the opposite hand rather than correcting the reach in progress. We may estimate that about 333 ms were required for this new reach to be initiated. Because the reach began as the object was leaving the catching area, however, none of these reaches was successful.

Experiment 1 provided no evidence that infants' predictive actions were influenced by learning. It is striking that infants continued to reach in accord with a linear prediction throughout the study, despite the fact that the object changed its motion four times on every linear trial (as it returned to its starting position), it stopped and changed direction repeatedly during the warm-up trials, and it underwent an abrupt turn on half of its approaches into the infant's reaching space. Infants' continued tendency to reach predictively on a linear path, even in the face of conflicting behavior by the object, indicates the robustness of this property of the reaching system.

Nevertheless, certain features of Experiment 1 may have prevented infants from learning about the non-linear path of motion. First, the linear and non-linear motions in Experiment 1 were presented in a randomized order, rendering the object's motion unpredictable at the midpoint of the display. It is possible that infants would learn to redirect their reaches to accord with a non-linear path of motion if the non-linear motion were predictable. Second, whereas the object moved smoothly on the linear trials, accompanied by a constant noise, the object stopped moving for 100 ms on the non-linear perturbed trials, accompanied by changes in the noise of the apparatus. It is possible that the latter changes were distracting to infants, leading them to learn preferentially about the less distracting, linear motions. The next experiment presented infants with predictable linear and non-linear motions that differed in direction but were equated for smoothness and noise.

3. Experiment 2

The infants in Experiment 2 were presented two linear and two non-linear paths of motion, as in Experiment 1. Each of the four paths was presented in a block of six to nine trials, in order to maximize any short-term learning effects that might be present in the infants' reaching and head tracking. Both kinds of motion were stopped for 100 ms at the intersection point so as to equate for the noises that accompanied the linear and the abruptly turned motions and to evaluate the effect of stopping on reaching and head turning. Except for these changes and for minor alternations of the motion paths, procedure, and analyses noted below, the method was the same as Experiment 1.

3.1. Method

3.1.1. Subjects

Twenty-two infants, aged 24–26 weeks, participated in the experiment. Eight subjects were eliminated from the sample because of fussiness (7) or inattention (1). Eight girls and six boys remained in the final sample. Because three of these subjects did not track the object continuously on any of the trials in one or more blocks, the analysis of head tracking was based on 11 subjects (six female, five male). Because a different set of three subjects never reached for the object, the analysis of reaching was based on 11 subjects as well (six female, five male).

3.1.2. Display and apparatus

The apparatus and the moving objects were the same as in Experiment 1, but the motion paths were altered to raise the intersection point 10 cm farther from the catching area. The intersection point was raised by having the object move horizontally for 12 cm before starting on its diagonal path. (The horizontal motion also served to focus the attention of the infant on the target object.) Each diagonal motion path was 115 cm long and measured 83 cm in the vertical dimension and 80 cm in the horizontal dimension. The four paths intersected 47 cm from the lowest point of the diagonals. The bottom of the seat of the infant chair was 53 cm below the point of intersection of the paths. At the paths' point of intersection, all four motions were interrupted for approximately 100 ms, accompanied by a change in the noise made by the apparatus, so as to equate the timing and the sound of the linear and the non-linear motions.

3.1.3. Design

Subjects were presented with four blocks of trials of each path of motion. Blocks of linear and non-linear interrupted motions were presented in an ABBA order, with linear trials occurring first for seven of the 14 subjects.

3.1.4. Procedure

The procedure was the same as in Experiment 1 except as follows. To maximize opportunities for learning in each condition, all trials of each type were presented within a single block. In addition, if the experimenter judged that the infant did not see the object move along most of its path of motion on every trial of a block, up to three additional trials were presented before moving on to the next block. Each infant therefore received 6–9 trials of each of the four types of motion. All trials passing the criteria for looking and reaching, as judged from the video record by the blind observer, were included in the analysis.

3.1.5. Data analysis

The data collection was based on the video recordings from the same two cameras, mixed onto a single screen. The method of coding, however, differed from Experiment 1 and followed an arrangement described by Page et al. (1989). A video monitor and computer screen were positioned at a 90° angle bisected by a half-silvered mirror. The computer screen image was black except for the image of a mouse-driven arrow that passed through the mirror. The video image was reflected off the mirror such that, from the coder's point of view, the video image and the arrow were superimposed. The arrow was moved by the coder so as to locate the screen positions of the infants' eyes, nose, and hands. Software produced in our laboratory provided instructions for what frame to code and recorded the data for later analysis.

The data from each infant were scored in two stages, as in Experiment 1, at seven different moments in time: −100, 0, 100, 200, 300, 400, and 500 ms, relative to the object's arrival at the intersection point[5]. The coder measured hand position using a 22 × 29 cm video screen and a high resolution computer monitor (21 × 28 cm, 640 × 480 pixels).

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[5] Different times were used in this experiment, because coding took place on a PAL format video system, which recorded 25 frames/s instead of the 30 frames/s NTSC standard.

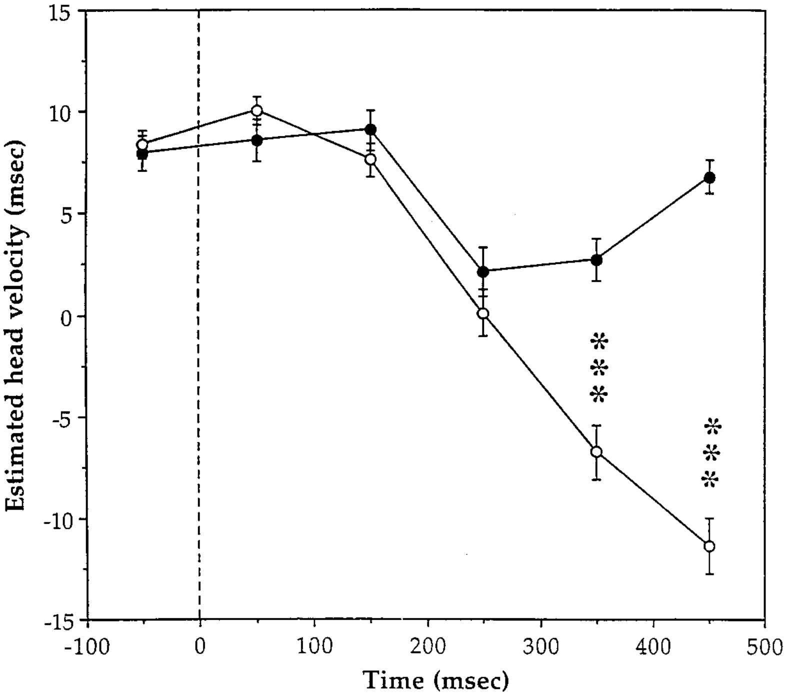

Fig. 9. Mean head velocity at each time interval for the linear (filled circles) and the non-linear (unfilled circles) motions used in Experiment 2. The calculated velocity for each interval is represented at the middle of that interval. Motions originating from the left and right have been collapsed. The error bars represent SEMs. Significant differences in head velocity between the linear and non-linear motions are shown, $^{***}P < 0.001$.

3.2. Results

3.2.1. Head movements

The eleven infants who contributed to this analysis looked at the object, as judged from their gaze direction, on 19 trials or more. One subject attended to the target and tracked it on 30 trials, two subjects did so on 28 trials, one on 26 trials, two on 25 trials, two on 24 trials, one on 23 trials, one on 21 trials, and one on 19 trials. There was no difference in looking rates for different trial types. Fig. 9 depicts the mean lateral head velocity at each time interval during each path of motion, calculated as for Experiment 1. In all conditions, the head moved in accordance with a constant velocity of the target up to 200 ms after the target had stopped. During the next time interval, the head decelerated and nearly stopped. Finally, the head started to move either in the opposite direction (in abruptly turned trials) or in the same direction as before (in the linear trials). Starting at the interval 300–400 ms past the time of the object stopping at the intersection, head velocity differed significantly between the interrupted linear and non-linear conditions (all t's > 5.5, $P < 0.001$).

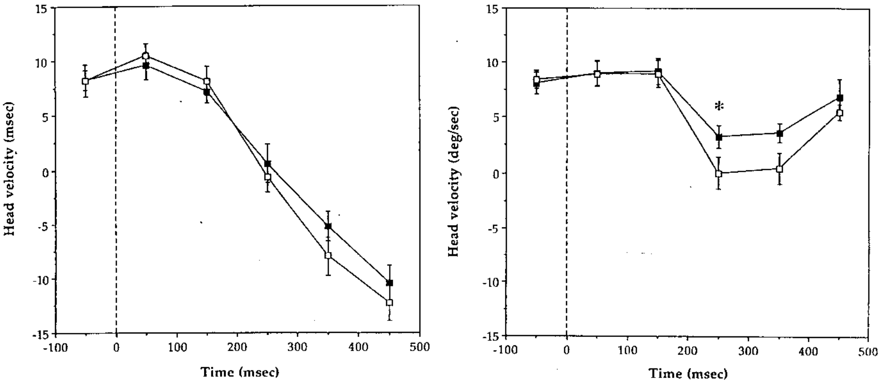

Fig. 10. Mean head velocities at each time interval for the linear (right graph) and the non-linear (left graph) motions used in Experiment 2 plotted separately for the first (filled squares) and second halves (unfilled squares) of the experiment. Definitions as in Fig. 9. Significant differences in head velocity between the first and second half of the experiment are shown, $^*P < 0.05$.

Head velocities during the first three trials of each trial block were very similar to those observed for the later trials. An analysis of variance of position within blocks (first-last half), and with time and condition (linear-non-linear motions) as the other factors showed that position within blocks had no effect ($F < 1.0$). In addition, head tracking patterns changed little from the first to the second half of the experiment: only in the linear condition, and at the 200–300 ms time interval, was there a

Table 3

Number of trials on which infants reached for the moving object, for each subject, hand, motion path, and origin of motion of Experiment 2[a]

Subject trials[b]	Linear paths				Non-linear paths				Total
	From left		From right		From left		From right		
	L.H.	R.H.	L.H.	R.H.	L.H.	R.H.	L.H.	R.H.	
1	0	6	0	3	0	3	2	5	17 (2)
2	4	4	5	0	3	4	4	4	18 (10)
3	6	5	0	4	6	5	2	4	22 (10)
4	1	1	3	4	1	0	5	3	15 (3)
5	7	7	7	7	4	7	7	8	29 (25)
6	4	4	4	4	5	2	2	2	18 (9)
7	7	7	2	2	6	7	5	4	22 (18)
8	4	6	1	2	6	6	3	6	20 (14)
12	0	2	0	1	0	0	0	0	3 (0)
13	0	0	2	0	1	0	0	0	3 (0)
14	0	0	0	0	0	0	3	1	3 (1)
Totals	33	42	24	27	32	34	33	37	170 (92)

[a] Subjects 9, 10 and 11 did not reach and therefore are not shown.

[b] Number of trials for each subject in which reaching is performed with both hands are shown within brackets.

significant change in head velocity ($t = 2.426$, $P < 0.05$; see Fig. 10). Although the object stopped at the center of the display on every trial, the head never anticipated this stopping, but always continued for at least 200 ms before stopping. This pattern, observed for all motion paths, meant that the object was moving full speed again when the head stopped.

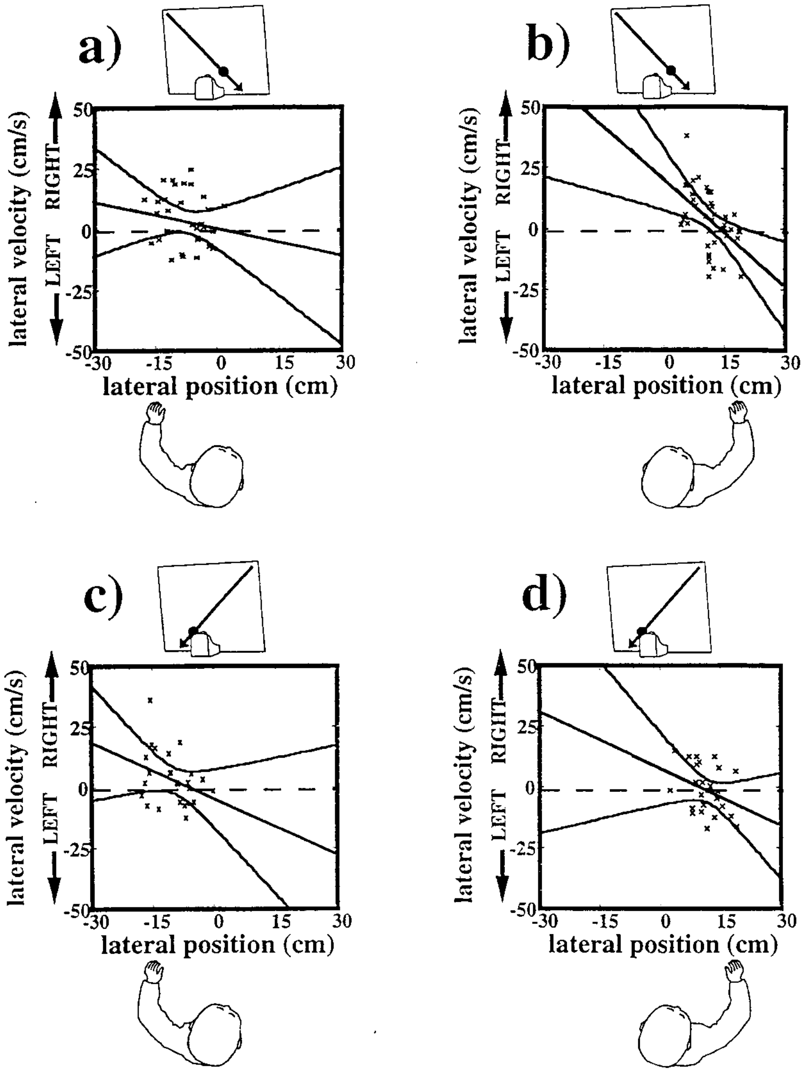

Fig. 11. Scatter plots of the lateral position and velocity of each hand at the 200–300 ms after the intersection of the motion paths for each of the linear motion conditions of Experiment 2. Negative numbers indicate positions to the left and velocities directed to the left. The regression line and 95% confidence bands are shown for each distribution. The condition analyzed is indicated by the figure at the top of each graph and the hand used is indicated by the drawing at the bottom of each graph.

3.2.2. Reaching

Hand movements of at least 2 cm were obtained on 36% of the trials for the left hand and on 40% of the trials for the right hand. Movements of one or both hands occurred on 74% of the trials on which the infants looked at the object. On 26% of the trials, both hands moved 2 cm or more (see Table 3).

With only six codable time points in this study, the convergence analysis could not be performed on individual reaches. As in Experiment 1, we assessed convergence by computing the regression of hand velocity against hand position for each hand, motion condition, and time step in the experiment. To illustrate our findings, Fig. 11 presents the lateral position and lateral velocity of each hand for each of the two linear object paths at 200–300 ms interval after the object arrived at the intersection point. Table 4 presents the findings of the regression analysis of position against velocity for each hand, each point in time, and each path of motion in the experiment. As in Experiment 1, the contralateral hand tended to converge on a position on the linearly extrapolated path of object motion, both when the actual path of motion was linear and when it was not. Although the pattern of convergence on spatial locations was the same as in Experiment 1, the strength of the convergence effect was reduced (compare Tables 2, and 4).

Table 4
The *x*-intercepts of the regression line relating hand position and velocity for each hand, time interval, and path of motion in Experiment 2[a]

Contralateral hand				
Time	Left hand		Right hand	
	Linear path	Non-linear path	Linear path	Non-linear path
–200	–20.23	–[b]	12.22*	20.53*
–100	–63.87	–17.04	9.84*	16.30*
0	–	–13.81*	18.22**	21.96*
100	–	–14.35	14.60**	14.45***
200	–6.05	–5.51*	14.05**	14.46*
300	–5.52*	–	14.41*	31.58
Ipsilateral hand				
Time	Left hand		Right hand	
	Linear path	Non-linear path	Linear path	Non-linear path
–200	–6.61	–11.22*	10.23	16.09
–100	10.23	18.53	–	12.45^{+}
0	–	912.48	–	–5.75
100	16.65	–	–	–1.74
200	–2.30	–	9.93	17.75
300	70.27	–	8.57^{+}	62.55

$^{+}P < 0.10$; $*P < 0.05$; $**P < 0.01$; $***P < 0.001$.

[a] Negative numbers indicate positions to the left of the intersection point.

[b] If a positive correlation between hand position and velocity was present, indicating no convergent reaching, no number is reported (–).

Table 5
The *x*-intercepts of the regression line relating hand position and velocity for trials 1 to 3 and trials 4 and beyond in Experiment 2[a]

Contralateral hand

Time	Trials 1 to 3		Trials 4 and beyond	
	Linear path	Non-linear path	Linear path	Non-linear path
–200	17.95^{+}	30.13	10.33	61.07
–100	21.45^{+}	–[b]	14.82	16.14**
0	23.38^{+}	–	23.80	18.63**
100	15.14**	15.80*	15.50	10.73***
200	13.96^{+}	15.61	10.26^{+}	6.71^{+}
300	13.19	–	12.58^{+}	–

Ipsilateral hand

Time	Trials 1 to 3		Trials 4 and beyond	
	Linear path	Non-linear path	Linear path	Non-linear path
–200	6.64	9.30^{+}	7.99^{+}	22.32
–100	2.28	8.86**	–4.91	–
0	–	7.36^{+}	–	–
100	1.56	7.24	117.57	–
200	6.88	–	2.87	–
300	–0.11	–	–5.82	18.52**

Reaches for objects originating from the left and right have been collapsed. Separate values are shown for each hand, time interval, and path of motion.

$^{+}P < 0.10$; $*P < 0.05$; $**P < 0.01$; $***P < 0.001$.

[a] Negative numbers indicate positions on the side ipsilateral to the starting position.

[b] If a positive correlation between hand position and velocity was present, indicating no convergent reaching, no number is reported (–).

Effects of learning on predictive reaching were assessed in two ways. First, all the regression analyses were performed separately on data from trials 1 to 3 and trials 4 and beyond within each block (see Table 5). There was no tendency to converge less on the contralateral side and more on the ipsilateral side on later trials in a block of non-linear motions. Second, regression analyses were performed separately on the data from the first two and the last two blocks of trials. Again, no learning effects were observed.

3.3. *Discussion*

The findings of Experiment 2 replicate and extend those of Experiment 1. First, the head turning analysis revealed that infants continued to track the linear motion of the object, with no deceleration, for 200 ms after the object stopped moving. This finding suggests that head tracking of a linearly moving object is guided by a linear extrapolation of the object's motion, at least 200 ms into the future. Second, the reaching analysis provided evidence that infants reached predictively to the side of the display where the object would enter reaching space if it continued in linear motion, up to 300 ms after the object stopped and turned on non-linear trials. As in Experiment 1, evidence for a predictive linear extrapolation came both from the finding that the ipsilateral hand moved uniformly toward the contralateral side of space, with no convergence, and from the finding that the contralateral hand converged on a location within the catching area, on the side where a linearly moving object would appear.

Curiously, the infants in this experiment showed no signs of learning to anticipate motions in violation of inertia, either within a single block of trials or over the whole experiment. Although the object motion was interrupted at the center of the display on every trial of the study, infants did not learn to anticipate this interruption in their head tracking: On the later trials as on the earlier ones, head tracking continued at constant velocity for 200 ms after the object stopped. Moreover, although the object changed direction after this interruption on two blocks of six consecutive trials, infants' reaching continued to show convergent aiming toward a location that would be occupied by an object in linear motion.

The findings of Experiment 2 suggest one difference between the patterns of head tracking and reaching. The head tracking system appeared to be responsive to the immediately preceding motion of the target, such that even the short stopping of the target was reflected in the head movement. Reaching, in contrast, was not affected by the transient stopping of the target and continued to converge on the reaching area appropriate for an object in linear motion. Despite this difference, both action systems were responsive to inertia and were resistant to learning in the present situation. Although one might expect that infants would quickly learn to disregard the short stopping of the target in the linear conditions, the stopping of the head actually became more pronounced on later trials. And although one might expect that infants would learn not to aim for the contralateral side of catching space during a block of trials in which the object always turned and remained on the ipsilateral side, no such learning was evident.

4. General discussion

The present findings provide evidence that 6-month-old infants act prospectively on moving objects by extrapolating object motion on linear paths. The clearest evidence for these extrapolations came from observations of the convergent reaching behavior of the contralateral hand on trials. In the present studies, infants aimed for the area 10–20 cm contralateral to the starting position of the object motion. The reaching movements of the contralateral hand converged consistently on this region even before the object had passed the midpoint or had stopped there and reversed its motion (see Tables 2, and 4). These findings indicate that the reaches predicted future positions of the target and were not just on-line extrapolations bridging the sensorimotor delay. Aiming was not accomplished by moving the contralateral hand in the same direction as the object, but rather by moving the hand so as to approach the object and intercept it.

Further evidence for linear extrapolations came from infants' head tracking. In these experiments, tracking the velocity of the object could not be accomplished in any simple way by extrapolating the object's sensory or motor consequences: although the distal velocity of the object was constant, its angular velocity changed substantially, from 10°/s at the start of the motion to 90°/s when it was at its closest distance. Despite these changing angular velocities, infants extrapolated the external velocity rather well on linear trials. The head sped up as the object passed the subject and reached its maximum velocity at the point where the object was closest to the infant, with no indication of a systematic lag. These findings suggest that head tracking was based on the spatial properties of the object motion, not on 'inertial' properties of the infant's sensorimotor systems.

What do these results tell us about the mechanisms subserving infants' predictive abilities? Students of action development might approach this question from multiple perspectives. We believe that the simplest explanation for the predictive head turning and reaching here observed attributes to the infant a set of perceptual, cognitive, and action systems for representing the distal velocity of the object (its speed and direction), for representing the catching space around the infant (the region of the environment in which the object can be intercepted) for extrapolating the object's motion into the catching area, and for guiding the head and hand to this area. Others might propose a more sophisticated extrapolation mechanism that includes higher-order derivatives of the motion (Pavel, 1990) and enables correct predictions of the smooth, non-linear motions that objects undergo when they are subject to various forces. Still others might propose that predictive reaching and headturning involves no separate extrapolation process, and that extrapolations emerge from the dynamics of sensorimotor systems. Although the evidence for convergent reaching and for distally appropriate headturning challenges the latter view, in our opinion, it does not refute it.

Neurophysiological studies of visually guided directed movements in monkeys provide further evidence for a predictive extrapolation mechanism. Georgopoulos et al. (1984) measured the activity of directionally-selective neurons in primary motor cortex while monkeys performed a well-trained directional response to a visual target. They showed that the population vector of the group of neurons pointed in the direction of the target well before the movement began. In adult monkeys as in human infants, the goal of a visually-directed action is specified well in advance of the movement itself.

Further research by von Hofsten (1980) supports a similar conclusion for human infants. Six-month-old infants were observed catching a moving object, and their reaching was analyzed into successive movement units. The earliest unit analyzed already showed consistent aiming for the target, with no lag. This evidence, like the present results, suggests that reaches for moving objects are aimed at the catching area from their onset. The reaches analysed had a duration of more than half a second, which gives an idea of how far ahead of the moving object they were aimed.

In the present studies, planning of predictive reaches evidently is determined by the seen object motion and not by remembered object trajectories. Even after having experienced 12 motions where the motion was perturbed at the midpoint of the screen, so that the object remained on the ipsilateral side throughout its motion, the infants persisted in reaching for the target at the contralateral reaching area. When the object had changed its course, it took a third of a second before any changes were observed in the infants' behavior, indicating that the sensorimotor delay is larger for reaching movements than for head movements.

The present findings raise further questions about the nature of the prediction process. One question concerns the role of vision in guiding predictive actions. Although infants in the present experiments reached for continuously visible objects, it is possible that reaching also can be guided by representations of unseen objects (Clifton et al., 1991; Munakata et al., 1996). Experiments in progress are investigating how head tracking and reaching are affected if the moving object is occluded or obscured by darkness.

A second question concerns the ability to modify reaching for moving objects once they have started. In the present study, the perturbation of the object's motion occurred when reaches were well underway, and about a third of a second before the hand would have intercepted the object had it continued on a straight path. As this time interval is equal to the found lag, one may ask whether it would remain the same if the perturbation had occurred earlier or later in the reach. It is interesting to note that the performed reach was not modified in any obvious way after the perturbation. Rather, a new reach was launched with the other hand, now closest to the object.

A third question concerns the class of motions that infants extrapolate, either spontaneously or with learning. The present experiments show that infants can extrapolate straight, constant-speed motions. Because linear and non-linear motions were presented with equal frequency in both studies, this ability cannot be explained by a learned expectation, developed over the course of an experiment. Earlier studies on predictive reaching suggest that 5-month-old infants also extrapolate circular motions with constant velocity (von Hofsten, 1980; von Hofsten, 1983) and track sinusoidally changing motions without any lag (von Hofsten and Rosander, 1996, 1997. Because these motions were repetitive, however, it is unclear whether infants extrapolate such motions the first time they are presented. Again, further research is needed to answer this question.

A fourth question concerns the ability to learn about and predict non-inertial perturbations of visible motion. Our findings suggest that infants' head tracking and reaching are not greatly influenced by repeated observation of perturbations of object motion. The findings of Experiment 2 are especially telling in this regard, because the target stopped for 100 ms on every trial, and yet infants persisted in stopping the head momentarily at a point 200 ms after the target had stopped, in spite of the fact that the target had then already started moving again. This pattern suggests that infants fail to learn to adjust their head tracking to non-inertial perturbations of object motion. Although infants have been found to develop anticipations about discrete events (Haith, 1993; von Hofsten and Rosander, 1997), they do not appear to do this in the present studies.

Are infants truly unable to learn new rules for predicting object motion, or did the present task in some way prevent optimal performance? It is possible that the direct visual guidance available in the current studies prevented the infants from using their earlier experience with the object in order to predict its future motion. If performance was limited by this ‘visual capture’, then occluding the middle part of the object’s trajectory might facilitate learning about non-linear motion. Another possibility is that the absence of any landmark at the object’s turning point prevented infants from learning to predict the non-linear motion. If learning about turning motions depends on landmarks, then introducing a marker or a barrier at the turning point should facilitate infants’ predictive actions. Finally, it is possible that infants would learn to reach for a turning object if given a greater amount of exposure to the object’s motion. Studies investigating these possibilities are in progress.

A fifth question concerns the relation between the system(s) that guide infants’ predictive head turning and reaching and the system guiding infants’ inferences about object motion in preferential looking experiments. Whereas reaching and head turning accord with inertia, infants do not appear to use knowledge of inertia to guide their inferences about the behavior of an object that moves from view. Although the present experiments did not test infants in exactly the same situation as preferential looking studies, the contrasting findings of the two sets of studies suggests that the principles guiding certain object-directed actions may be relatively inaccessible to other cognitive processes in infants, as in older children (Krist et al., 1993) and adults (e.g. Piaget, 1976). It is possible that the functional separation of the task of predicting object motion for purposes of action, and the task of representing hidden objects on which one does not act, relates to the functional separation between the neural systems for representing visible objects that have emerged from studies of neurologically impaired human patients (Goodale and Milner, 1992) and from electrophysiological and behavioral studies in monkeys (Ungerleider and Mishkin, 1982). We plan, in further experiments, to pursue this suggestion.

Finally, the present experiments introduce a new method for studying perception, action, and cognition in infancy. Their procedure appears to elicit high levels of interest and activity from infants, most of whom followed and reached for objects over a considerable number of trials. Given the precision of infants’ predictive reaching, this method should provide a useful tool for studies of visual motion perception, the coordination of perception and action, and early cognitive development.

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