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Predictive Reaching for Occluded Objects by 6-Month-Old Infants

Elizabeth S. Spelke
Department of Brain and Cognitive Sciences
Massachusetts Institute of Technology

Claes von Hofsten
Department of Psychology
Uppsala University

Infants were presented with an object that moved into reaching space on a path that was either continuously visible or interrupted by an occluder. Infants' reaching was reduced sharply when an occluder was present, even though the occluder itself was out of reach and did not serve as a barrier to direct reaching for the object. We account for these findings and for the apparently contrasting findings of experiments using preferential looking methods to assess infants' object representations, by proposing that (a) object representations increase in precision over the infancy period, and (b) the precision of object representations varies in common ways at all ages as a function of object visibility and task demands.

How do babies represent events in which an object moves completely from view? Despite intensive study using a variety of experimental methods, this question has not been answered definitively. On one hand, numerous experiments provide evidence that young infants represent the existence, location, and properties of objects that move behind occluders or are obscured by darkness (for reviews, see

Requests for reprints should be sent to Elizabeth S. Spelke, Department of Psychology, Harvard University, Cambridge, MA 02138. E-mail: spelke@wjh.harvard.edu

Baillargeon, 1993, 1995, 1998; Bertenthal, 1996; Spelke, 1998). Evidence for infants' representations of hidden objects comes from experiments that focus on a precociously developing skill: active, selective looking at new objects and events (Bornstein, 1985; Fantz, 1961). Infants as young as 2 months look systematically longer at events in which a hidden object undergoes a novel or unexpected transformation than at otherwise comparable events in which an occluded object behaves in a familiar and natural manner (e.g., Aguiar & Baillargeon, 1999; Hespos & Rochat, 1997; Wilcox, Nadel, & Rosser, 1996; Wynn, 1992). Because control conditions in these experiments have shown that this looking preference does not stem from idiosyncratic features of the displays or from a preference for the more expected outcome, the experiments provide evidence that infants represented the occluded object and its behavior.

In contrast, studies of infants' active search for occluded objects have suggested that the capacity to represent hidden objects develops slowly over the first 18 months of life. When an interesting object is visible, infants as young as 2 months typically follow it with their eyes, and infants as young as 4 to 5 months may attempt to reach for it. If the object moves behind an occluder, however, infants of these ages usually make no attempt to retrieve the object either by looking or by reaching. Infants younger than about 8 months often appear to lose interest in occluded objects—a pattern that has imposed constraints on the preferential looking experiments referenced previously, in which infants' interest in an occlusion event must be actively maintained by other visible objects in the scene. When an infant who was fascinated by a visible object suddenly loses interest as the object is hidden, his or her altered behavior invites the interpretation that he or she no longer realizes that the object exists (Piaget, 1954).

Why do infants younger than 9 months lose interest in occluded objects and fail to search for them? One class of attempts to address this question appeals to limits on infants' representational capacities. Although preferential looking experiments show that infants represent occluded objects on some level, such representations may be formed at a level that is too superficial to guide goal-directed actions such as reaching. For example, such representations may be formed at a sensory level (e.g., Haith & Benson, 1998; although, see Baillargeon, 1999; Spelke, 1998), or they may reside in visual pathways that are relatively independent of the pathways that guide object directed action (e.g., Bertenthal, 1996; Spelke, Vishton, & von Hofsten, 1994). Such accounts reinforce Piaget's (1954) claim that capacities to represent hidden objects develop gradually over the first 2 years. In contrast, a second class of accounts appeals to limits on infants' action capacities. When an object is occluded, an infant can only recapture it visually or manually by removing or circumventing the occluder (Diamond, 1990). In Piaget's object search experiments, therefore, the occluder that was introduced to serve as a barrier to vision also served as a barrier to direct action. It is possible that infants failed to reach for or attend to occluded objects because they perceived (perhaps correctly) that such objects were unattainable given their limited manual skills. On these accounts, capacities to represent objects are continuous over development in infancy—only capacities to act on objects undergo developmental change.

To decide between these accounts, it is necessary to devise search tasks in which an object loses its visibility without losing or diminishing its attainability through direct actions such as reaching. Two such situations have been investigated in the past—reaching for objects in the dark and acting to retrieve objects by performing a trained operant response—but their findings suggest opposite conclusions. When 6-month-old infants are presented with a visible object that is obscured by darkness, they tend to reach for the object despite the loss of perceptual contact (Clifton, Muir, Ashmead, & Clarkson, 1993; Clifton, Rochat, Litovsky, & Perris, 1991; Hood & Willatts, 1986; Jansson & von Hofsten, 2001; Munakata, 1997). Because a stationary object in darkness can be obtained by a direct reach, whereas a stationary occluded object cannot, the contrasting effects of darkness versus occlusion on infants' search behaviors suggests that infants fail to search for occluded objects because of limits on their actions and not limits on their object representations. In contrast, when 6-month-old infants are trained to obtain a visible object by pulling on a support or by pushing a button, they fail to perform the trained action when the object is occluded (Munakata, McClelland, Johnson, & Siegler, 1997). Because the occluder is not a barrier to action in these training experiments, their findings suggest that infants fail to search for occluded objects because of limits on their object representations and not limits on their actions.

How can these findings be reconciled? On one hand, it is possible that infants' ability to search for nonvisible objects is impaired only by their limited action capacities, and training studies fail to overcome those limits because they pose special problems for infants. For example, unnatural, trained behaviors may be fragile or demanding of memory resources and, therefore, may fail to be guided by infants' representations. On the other hand, it is possible that infants' ability to search for nonvisible objects is impaired by their limited representational capacities, and studies of reaching in the dark fail to challenge those capacities sufficiently. For example, infants who view an object that is obscured by darkness may continue to attend to the object because no other objects are in view. Infants who view an object that is occluded, in contrast, may direct their attention partly to the occluder. Numerous studies of adults have provided evidence that multiple visible objects compete for attention: As more attention is devoted to one object, representations of other objects lose strength and precision (e.g., Rensink, O'Regan, & Clark, 1997; Simons, 1996). If multiple objects compete for infants' attention as well, then infants may retrieve objects obscured by darkness more effectively than occluded objects because they attend to them more strongly and therefore represent them more precisely.

In this research, we addressed this controversy by investigating infants' spontaneous, predictive reaching for a moving object that is occluded during a portion of its trajectory just before it comes within reach. Von Hofsten (1980) was the first to show that young infants reach predictively for moving objects, aiming their reach ahead of an object's current position so as to intercept it farther along on its trajectory. Infants begin to reach for moving objects as early as they reach for stationary objects, and their reaching is of comparable accuracy and effectiveness (von Hofsten & Lindhagen, 1979). Reaching for moving and stationary objects, therefore, appears to depend on common mechanisms with a common developmental course.

Experiments by von Hofsten, Vishton, Spelke, Feng, and Rosander (1998) provided the basis for this study. Six-month-old infants were presented with an object that approached them on one of four trajectories. Two of the trajectories were linear: The object began from a position above and to the left or right of the infant, it moved downward on a diagonal path through the center of the display, and it entered the infant's reaching space on the side opposite to its starting point. The other two trajectories were nonlinear: The object moved to the center as on the linear trials and then turned abruptly and moved into the infant's reaching space on the same side as its starting point. Because the object was out of reach until after it had crossed the central point where the four paths intersected, infants could only reach for the object by aiming appropriately to the left or right side of their reaching space. Because the object moved rapidly, however, infants could only hope to attain it if they began their reach before the object reached the central intersection point.

In this situation, 6-month-old infants reached predictively by extrapolating a linear path of object motion. On linear trials that began on the left, for example, infants began to reach for the object when it was still on the left side of the display—aiming their reach to a position on the right side of reaching space and timing the reach so that their hand intersected the object as it arrived on that side of reaching space. On nonlinear trials that began on the left, infants showed the same pattern of rightward reaching and aiming until about 200 msec after the object had turned left, and therefore they typically missed the object: a pattern that provides further evidence for predictive reaching on a linear path.

The experiments presented here investigate infants' predictive reaching for an object that moved on the same four paths but with an occluder that covered a portion of the object's trajectory just before it came within reach. Because the bottom of the occluder did not intrude into the infant's optimal reaching space, the occluder presented no barrier to a direct reach for the object. Because the occluder covered the trajectory of the object around the central intersection point, however, it blocked the visibility of the object during a critical time for the execution of a predictive reach. Infants could not capture the object unless they began to reach before or during the period of occlusion, and maintained their reaching throughout the occlusion period.

This predictive reaching situation allows us to test infants' reaching for occluded objects under conditions as favorable to reaching as those used in studies of reaching in the dark. It focuses on a naturally occurring, direct search action, rather than on actions that are trained or indirect. Moreover, it presents an occluder that is a barrier to vision during the time that a predictive reach is planned and executed, but that is not a barrier to a direct reaching action. If occluders reduce search for stationary occluded objects because of limits on infants' action capacities, then infants should reach for occluded objects successfully in our experiments, as they did in studies of reaching in the dark. In contrast, if occluders reduce search for occluded objects because they impair infants' representations of those objects, then infants should fail to reach for occluded objects in our experiments.

We focused on 6-month-old infants' predictive reaching for moving objects under three different conditions of visibility. In one condition (no occluder), the object was fully visible throughout its path of motion. In a second condition (small occluder), the object was hidden by a narrow occluder just as it arrived at the center of the display, above the infant's reaching space. In a third condition (large occluder), the object was hidden by an occluder twice as high the narrow occluder. This occluder covered a section of the trajectory both above and below the center of the display. Both the large and the small occluder were positioned with their lower edge at the same place on the screen just above the infant's reaching space. On the critical trials of this experiment, the object moved from one of the top corners of the display, crossed the display (passing behind an occluder in two of the three conditions), and entered the infant's reaching space. We observed infants' rates of reaching for the object to assess whether the occluder impaired either the amount or the accuracy of reaching.

If the occluder impaired accuracy of reaching, it could do so for a number of reasons. First, the occluder might distract infants' attention from the object. To test that possibility, each infant's head orientation toward the object was observed on every reaching trial, and the rates of object-directed head orientation in the different occlusion conditions were compared. Second, the presence of the occluder might lead infants to reposition themselves, and their resulting position might be less conducive to reaching. To test that possibility, each infant's position was measured on every reaching trial, and the positions of infants in the different occlusion conditions were compared. Third, infants might perceive the occluder (incorrectly) as intruding into their reaching space, and they might inhibit their reaching to avoid colliding with it. To test that possibility, each infant also was observed in a series of control trials. On control trials, the occluder (if any) was positioned as on the critical experimental trials, but the object did not pass behind it. Instead, the object moved horizontally from the lower left or right side of the display and passed below the occluder into the infant's reaching space. Although the path of motion was different on the control trials, the object moved into the same region of reaching space as on the experimental trials and, therefore, could be obtained by the same reaching action. If the occluder was perceived incorrectly as intruding into this space, then its presence should reduce reaching on both the control and the experimental trials. If the occluder was not perceived as a barrier to the infant's actions, in contrast, then infants should reach for the objects on the control trials, regardless of the occlusion condition. The critical comparison then would concern reaching on the experimental trials, when the object either was fully visible or passed behind the small or large occluder before entering the infant's reaching space.

METHOD

Participants

Sixty-three infants participated in the experiment. There were 6 girls and 10 boys in the no-occluder condition ($M = 25.6$ weeks, $SE = 0.9$ days), 7 girls and 8 boys in the small-occluder condition ($M = 24.9$ weeks, $SE = 1.2$ days), and 15 girls and 17 boys in the large-occluder condition ($M = 26.3$ weeks, $SE = 1.8$ days). These ages differed reliably, $F(2, 60) = 8.36$, $p < 0.01$.[1] Nineteen additional participants were excluded from the experiment because of fussing or lack of interest in the objects: 3 from the no-occluder condition, 4 from the small-occluder condition, and 12 from the large-occluder condition.[2]

Displays

Infants were tested with the same apparatus and object motions as in Experiment 2 of von Hofsten et al. (1998). The object motions were produced by a 98- × 130-cm rectangular plane plotter (Roland DPX–4600) in which the computer-controlled pen was replaced by a magnet and the plotting area was covered by an aluminum sheet that was painted white, coated with a silicone lubricant, and placed in a supporting structure so that it tilted 15° forward from the vertical (Figure 1). The object was supported by a 12-cm wooden rod that was attached to a second magnet. When

[1]Because reaching tends to increase with age and the infants in the large-occluder condition were older than those in the other conditions, the age differences across the three conditions would tend to attenuate any suppressive effect of occlusion on reaching. As the data show, a robust suppressive effect was observed despite any such attenuation.

[2]Although the study initially was designed to include equal numbers of infants in each condition, the numbers of infants in the large-occluder condition was doubled because the first 16 infants were tested erroneously without the final set of control trials. The number of excluded infants also was higher in the large-occluder condition because infants more frequently became fussy or bored in the presence of the large occluder.

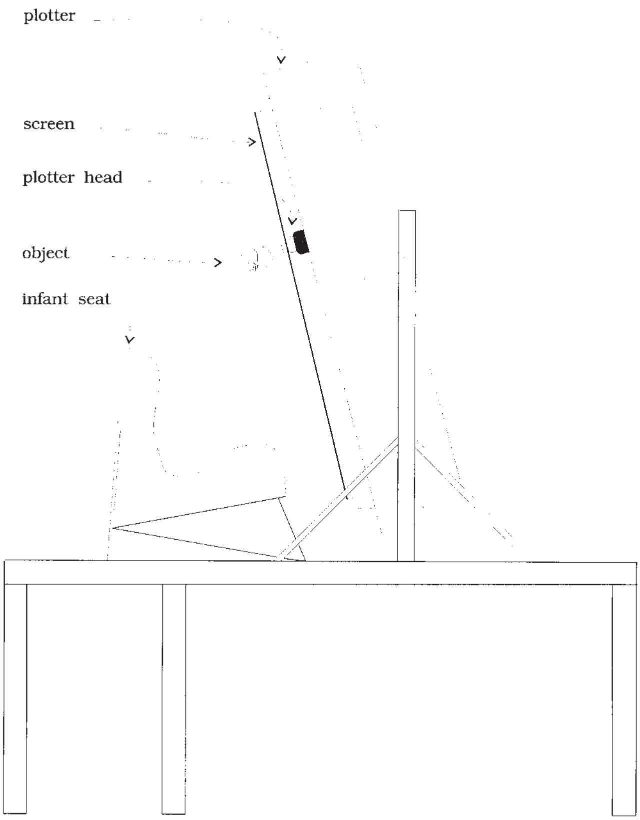

FIGURE 1 Apparatus used in this experiment and previous studies (after von Hofsten et al., 1998).

the magnet on the object 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 intended to direct the motion of the plotter pen, this apparatus enabled us to direct the motion of the object very precisely along the surface of the plotter.

A small stuffed bear, 8 cm in length, served as the target object for most infants on most trials. If an infant failed to reach for this toy, it was replaced by a stuffed blue bird of about the same size. The toy moved horizontally on the upper part of the plotter surface for 13 cm before starting on its diagonal path (see Figure 2). During this part of the motion, the velocity of the object increased in two steps from 10 cm per sec to 20 cm per sec. Then the object turned and moved downward

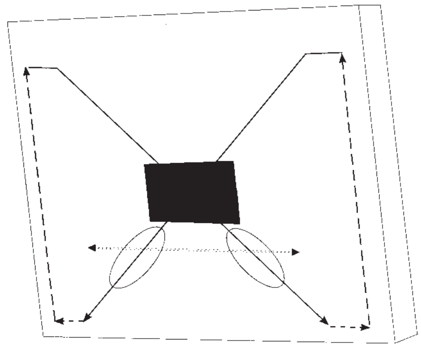

FIGURE 2 Displays used in these experiments. The light and dark gray areas together indicate the position of the large occluder, and the dark gray area indicates the position of the small occluder. Solid lines indicate the paths of motion on the experimental trials; the dotted line indicates the motion path on the control trials. The oval areas indicate where reaching was possible on the experimental trials. The dashed lines indicate the path of the object at the end of the trial.

on a diagonal path that was 115 cm in length: 83 cm in the vertical dimension and 80 cm in the horizontal dimension. The two diagonal paths intersected 47 cm from the lowest point of the diagonals. The object moved along these diagonal paths at a speed of 30 cm per sec, producing an angular velocity that accelerated from approximately 13 cm per sec at the start of the diagonal motion to about 65 cm per sec at the center of the display. The velocities used in this experiment were identical to those used by von Hofsten et al. (1998): They were slow enough to allow infants to follow the object's motion with ease but fast enough to ensure that infants would only capture the object reliably if they began to reach before or during the period of occlusion.

On separate blocks of trials, the object followed one of four paths of motion. It either started from the left or the right, and it either moved linearly along the full length of the diagonal or abruptly turned at the intersection of the two diagonals and continued along the other diagonal. On all four paths, the object stopped for about 100 msec at the center of the display (this delay was caused by the change in motion on the nonlinear trials and was introduced on the linear trials to equate the durations of the different events). The infant chair was centered between the two diagonal paths, standing on a platform such that the bottom of the seat was 53 cm below the paths' intersection point.

On the control trials, the object moved on a horizontal path through the center of the infant's optimal reaching space (Figure 2). On each trial, it began at the center, moved left at 30 cm per sec to a position 13.5 cm to the left, moved right for 27 cm to a position 13.5 cm to the right, and finally returned to the center.

In the two occluder conditions, a rectangular object was attached over the intersection of the motion paths (see Figure 2). The large occluder had two openings on its upper side and two openings on its lower side, each measuring 6 × 13 cm. The small occluder had only one opening on the top (positioned at the intersection between the two paths) and two openings at the lower side, as with the large occluder. Both occluders were covered with a white woolly fabric and were oriented horizontally. The object became occluded by entering an opening on the occluder's upper side, and it reemerged through one of the openings on its lower side. In the large-occluder condition, the box measured 25 × 16 × 15 cm, and the object was occluded for about 0.9 sec (800 msec traveling time plus 100 msec at the intersection); in the small-occluder condition, the box measured 25 × 8 × 15 cm, and the object was occluded for about 0.5 sec (400 msec traveling time plus 100 msec at the intersection). The object entered reaching space just after it reappeared from behind the occluder. Both occluders ended 8 cm below the intersection point. The lower side of the occluders was situated 2 cm above the intersection point used in Experiment 1 of von Hofsten et al. (1998). In that study, no reaches were directed to positions above that point.

Design

Infants were presented with one to six control trials, followed by four blocks of six to nine trials of each path of motion. One half of the infants in the large-occluder condition and all of the infants in the small-occluder and no-occluder conditions also were presented with one to six control trials after the experimental trials. Blocks of linear and nonlinear motions were presented in an ABBA order, with one half of the infants beginning with a block of linear trials. The first two blocks presented motions that started from one side, and the last two blocks represented motions that started from the other side, with the order of starting sides also counterbalanced.

Procedure

Infants were placed in a reclining infant chair and were given several minutes to become accustomed to their surroundings and to play with the toy to be used in the experiment. During this time, the experimenter encouraged infants to reach for the toy as he held it in front of them. Infants then were positioned in front of the plotter screen with the occluder, if any, in position, and they were encouraged to reach for the stationary toy in a location 15 cm directly below the intersection point of the four paths. Then infants were given one to six control trials with the horizontally moving object. The number of control trials administered to infants depended on their mood and readiness to reach for the object: Infants who were in a more sensitive mood were transferred to the experiment proper as soon as possible, whereas those who were more happy and calm but not inclined to reach were given additional trials. The average number of control trials for the infants in the large-occluder, small-occluder, and no-occluder conditions were 3.12 (*SE* = 0.26), 3.13 (*SE* = 0.26), and 2.80 (*SE* = 0.11), respectively.

After the control trials were completed, 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 or the screen until the infant looked at the starting point. The experimenter then stepped back, set the object in motion by pressing a key on the computer, and the object moved downward past the infant. If it was not pulled from the screen by the infant, it continued to move along the edges of the plotter surface to the starting position for 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 lost interest in the toy during the experiment, it was taken off the screen and held in front of the infant until he or she reached for it. Motion trials were resumed when the infant's interest had been rekindled. Trials continued until the experimenter judged that the infant had attended visually to the object on six trials or until a total of nine trials had been presented (whatever came first). At the end of the first two blocks of trials, the chair was turned around, and the infant was given a short break. The average number of trials presented to the infants was 28.0 (*SE* = 0.62) in the large-occluder condition, 29.6 (*SE* = 0.85) in the small-occluder condition, and 29.6 (*SE* = 1.11) in the no-occluder condition. The conditions did not differ with respect to the number of trials presented, $F(2, 60) = 1.36$, $p = .27$.

After all four blocks of trials, one half of the infants in the large-occluder condition and all infants in the other conditions received an additional one to six control trials before ending the experiment. The number of trials varied according to the degree to which the infant was tired and irritated, or calm and attentive. The average number of control trials for the infants tested in the large-occluder, small-occluder, and no-occluder conditions were 3.07 (*SE* = 0.25), 3.13 (*SE* = 0.27), and 3.20 (*SE* = 0.30), respectively. The whole session was completed in about 10 min.

Data coding and analysis. An infant was determined to have visually attended to the object over a trial if he or she tracked the object with continuous head movements before it disappeared behind the occluder and resumed tracking movements after it reappeared. The judgment of head tracking was made by two observers of all infants in the no-occluder and small-occluder conditions and of 12 randomly chosen infants in the large-occluder condition. Reliability, assessed by Cohen's kappa test, was found to be 0.91, 0.88, and 0.84 for the three respective conditions.

Three measures of reaching were recorded: predictive approach, touching, and grasping. First, we determined instances of predictive approach. For this measure, the video was examined at 100 msec and 200 msec after the object had reappeared from behind the occluder, and coders assessed whether either of the infant's hands was positioned within 5 cm of the object on each of the two video views (from above and from the side). The position of the hand was examined both with respect to the real position of the object and the position it would have occupied if it had continued on the opposite trajectory (linear or nonlinear). The 200-msec window was chosen because the experiments of von Hofsten et al. (1998) revealed that infants' reaches were purely predictive during this time window: When a fully visible object changed direction suddenly, infants reacted to the change with a minimum delay of 200 msec. The measure of predictive approach, therefore, reflects only infants' representation of the object before and during the period of occlusion. Consequently, only the predictive approach measure was used in the principal analyses.

To assess the reliability of the coding of predictive approach, two observers coded the reaches of all infants in the no-occluder and small-occluder conditions and of 12 infants in the large-occluder condition. Reliability was 0.91, 0.95, and 0.91 for the conditions of no occluder, small occluder, and large occluder, respectively.

Each trial was examined further to determine whether (a) the infant's hand approached to within 5 cm of the object after the end of the 200-msec window for predictive approaches, (b) the infant succeeded in touching the object, and (c) the infant succeeded in grasping the object and pulling it off the display board. The grasping and touching measures were subdivided according to whether the approach to within 5 cm of the object had occurred within (predictive reaches) or after (late reaches) the window of prediction. Note that for both predictive and late reaches, most of the touches and grasps were completed after the window of pure prediction; thus, the measures of grasping and touching likely reflect a mixture of processes guided by representations of the object during its occlusion and vision of the object after its reappearance. Because the grasping and touching measures were unambiguous and taken primarily for descriptive purposes, these measures were made by a single coder.

The design of the study called for the infant to be seated with his or her face 22 cm from the display surface (i.e., 10 cm from the front of the object). At this distance, however, infants could push against the display surface with their feet and increase their distance from the display. To assess any effects of distance on infants' reaching, the infant's distance from the screen was coded on every trial, and the mean distance per trial block was calculated. Distance was measured from the tip of the infant's nose to the tip of the object when it stood at its straight-ahead position.

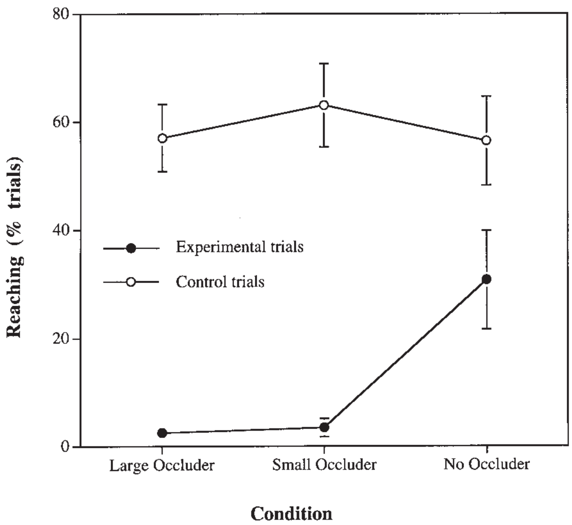

FIGURE 3 Percentage of trials, with standard errors, on which the infants predictively approached the object in the large-occluder, small-occluder, and no-occluder conditions on the control trials (open circles) and the experimental trials (filled circles).

RESULTS

Control Trials

Figure 3 presents infants' mean rates and standard errors of predictive approach to the moving object on the control trials of the three occlusion conditions. For the trials presented before the experiment proper, infants reached for the object on the average on 1.53 (*SE* = 0.36) of the control trials in the large-occluder condition corresponding to 50% of the trials, 1.88 (*SE* = 0.31) of the control trials in the small-occluder condition corresponding to 60% of the trials, and 2.00 (*SE* = 0.43) of the control trials in the no-occluder condition corresponding to 63% of the trials. The differences between conditions was tested with a one-way analysis of variance (ANOVA) and found not significant, $F < 1$. For the trials presented after the experiment proper, infants reached for the object on the average on 1.87 (*SE* = 0.43) of the control trials in the large-occluder condition (61%), 2.07 (*SE* = 0.36) of the control trials in the small-occluder condition (66%), and 1.87 (*SE* = 0.44) of the control trials in the no-occluder condition (58%). These differences between conditions also were not significant, $F < 1$. Most of the infants reached for the object on at least one control trial; only 6 (of 32), 2 (of 15), and 4 (of 16) infants never reached for the object in the large-occluder, small-occluder, and no-occluder conditions, respectively.

Experimental Trials

Looking. Table 1 presents the distribution of trials on which infants were scored as attentive to the object, in each of the three occlusion conditions. Infants attended to the object on an average of 17 trials (*SE* = 1.17) for no occluder (57%), 19 trials (*SE* = 1.23) for the small occluder (64%), and 21.8 trials (*SE* = 0.73) for the large occluder (78%). Differences between conditions, tested with a one-way ANOVA, based on the numbers of attentive trials, were found to be significant, $F(2, 60) = 6.64$, $p < .01$.

Predictive approach. Figure 3 presents infants' rates of predictive reaching in the different experimental conditions when the object moved diagonally on a linear or nonlinear path. In the no-occluder condition, infants met the criterion for predictive approach on an average of 2.75 (*SE* = 0.96) linear trials (34%) and 3.00 (*SE* = 0.92) nonlinear trials (39%). In contrast, infants in the small-occluder condition reached for the object on an average of 0.33 (*SE* = 0.23) linear trials (3.6%) and 0.47 (*SE* = 0.25) nonlinear trials (4.8%). In the large-occluder condition, reaches dropped to an average of 0.25 (*SE* = 0.09) linear trials (2.3%) and 0.31 (*SE* = 0.14) nonlinear trials (2.8%). A 3 (condition) × 2 (motion: linear vs. nonlinear) ANOVA based on the number of reaches per infant and condition revealed a significant main effect of condition, $F(2, 60) = 11.25$, $p < .001$, and no other effects, other *F*s < 1. For most infants, introduction of the occluder abolished predictive approach altogether. In the no-occluder condition, only 5 of the 16 infants failed to reach for the object. In contrast, 11 of the 15 infants in the small-occluder condition and 23 of the 32 infants in the large-occluder condition never reached for the object.

Grasping and touching. Table 2 gives the mean reaching rates and standard errors for the subsidiary measures of grasping and touching—both for predictive reaches and for late reaches. Infants never grasped and removed the object in the large- or small-occluder conditions, whereas they succeeded in doing so on a small number of trials in the no-occluder condition; all of these reaches were well timed.

TABLE 1
The Number of Infants Who Were Scored as Attentive On a Given Number of Trials for Each of the Three Occlusion Conditions

	Number of Trials			
Condition	*< 17*	*17–19*	*20–22*	*> 22*
Large occluder	4	5	7	16
Small occluder	5	2	4	4
No occluder	8	4	4	2

TABLE 2
Mean Number of Trials with Grasping or Touching of the Object During Well-Timed Reaches and Late Reaches for Each of the Three Occlusion Conditions

	Predictive Reaches						*Late Reaches*					
	Approach		*Touching*		*Grasping*		*Approach*		*Touching*		*Grasping*	
Grasping Condition	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Large occluder	0.56	0.19	0.03	0.03	0	0	1.00	0.33	0.12	0.09	0	0
Small occluder	0.80	0.43	0.07	0.07	0	0	0.26	0.12	0	0	0	0
No occluder	5.75	1.81	2.81	1.24	0.38	0.33	2.69	0.51	0.50	0.27	0	0

High rates of touching were observed in just one of the scored categories: predictive reaches for no occluder. Infants touched the object on about half of the trials showing predictive approach in the no-occluder condition but on very few trials in any other condition. Four chi-square tests were performed to determine whether the probability that an approach resulted in a successful touch or grasp varied in relation to the conditions of occlusion and the timing of the reaches. Well-timed reaches were more successful than late reaches in the no-occluder condition, $\chi^2(1, N = 133) = 17.03$, $p < .001$, but not in the two occluder conditions, $\chi^2(1, N = 65) = 0.36$, $p < .001$. Well-timed reaches in the no-occluder condition also were more successful than well-timed reaches in the two occluder conditions, $\chi^2(1, N = 119) = 22.79$, $p < .001$, but the success of late reaches did not vary across the occlusion conditions, $\chi^2(1, N = 79) = 0.86$, $p < .001$.

Distance Effects

Table 3 presents the distributions of distances between the infants and the object over blocks of trials for each of the three occlusion conditions. Infants in the no-occluder condition were considerably closer to the display, on average, than those in the two occluder conditions. A 3 (condition) × 2 (motion: linear vs. nonlinear) ANOVA revealed a significant effect of condition, $F(2, 60) = 63.38$, $p < .001$, and no other effects, other *F*s < 1.

Because reaching may be affected by the infant's distance from the object (Yonas & Granrud, 1985), further analyses investigated whether this was the case in this study. First, the 32 infants in the large-occluder condition were split into two groups according to their distance from the display, and their levels of predictive approach were compared. The 15 infants whose distance was less than the median (16.8 cm to the tip of the object) executed a total of eight reaches (reaching on an average of 0.53 trials), whereas the 17 infants whose distance equaled or exceeded the median executed a total of seven reaches (reaching on an average of 0.42 trials). A 2 (group: high distance vs. low distance) × 2 (motion: linear vs. nonlinear) ANOVA revealed no main effect of group or motion, both *F*s < 1. There was, however, a Group × Motion interaction, $F(1, 30) = 6.03$, $p < .02$: Infants who were closer to the object reached more on linear trials, whereas those who were farther away reached more on nonlinear trials. We have no explanation for this unexpected interaction.

Second, we compared predictive approach levels for no occluder to the levels shown by a subset of infants in the large-occluder condition in which the distance, on at least 1 block of 6 reaching trials, did not exceed the maximum distance observed in the no-occluder condition (11.4 cm). Eight infants in the large-occluder condition contributed a total of 13 blocks of trials to this analysis. Their average distance from the tip of the object on the 13 blocks, 10.1 cm ($SE = 0.24$), closely approximated the average distance of the infants in the no-occluder condition (10.2 cm, $SE = 0.13$). The infants in the large-occluder condition exhibited a total of 2 reaches in the 13 trial blocks ($M = 0.15$ reaches per trial block, $SE = 0.11$). In contrast, those in the no-occluder condition exhibited 92 reaches in 64 trial blocks ($M = 1.44$ reaches per trial block, $SE = 0.52$). These reaching levels differed significantly, $t(22) = 1.80$, $p < .05$. Thus, the infants who viewed occluded object motion showed lower levels of reaching than those who viewed nonoccluded motion, even when the distance of the object was equated.

DISCUSSION

Infants' predictive reaching for the object was markedly disrupted when the object underwent a brief period of occlusion before it came within reach. In the presence of an occluder, most infants approached the object predictively on the control trials in which its motion was continuously visible below the occluder, indicating that the occluder was not perceived as a barrier to reaching. In contrast, when the object moved behind the occluder, most infants failed to reach for it. The low levels of ob-

TABLE 3
Distributions of Distances Between the Infant and the Object over Blocks of Trials for Each of the Three Occlusion Conditions

	Distance (cm)				
Condition	*9–12*	*12–15*	*15–18*	*18–21*	*21–24*
Large occluder	25	24	38	39	2
Small occluder	0	1	5	37	17
No occluder	64	0	0	0	0

ject-directed grasping, touching, and predictive approach in the two occlusion conditions contrasted with the much higher levels of reaching observed with all these measures when the object moved on the same paths without any occluder. These contrasts provide evidence that reaching is perturbed when the visibility of an object is interrupted by occlusion.

These findings replicate those of Piaget (1954) and Munakata et al. (1997), using a design that addresses a number of alternative explanations for infants' search failures. Unlike Piaget's experiments, the studies reported here allowed infants to obtain an object by reaching for it directly: Infants did not need to remove or circumvent the occluder. Unlike Munakata et al.'s experiments, these studies focused on a naturally occurring behavior that required no training. Indeed, this study presented infants with a task that, in principle, should have been easy for them: To catch the object after it emerged from behind the occluder, it sufficed for infants to position their hand correctly in the object's path while it moved visibly at the start of its trajectory and to maintain that position while the object was hidden. Nevertheless, infants failed to pursue this simple strategy. Despite large and important differences of method, therefore, three sets of studies have yielded quite similar results: suppression of object-directed reaching when the object is occluded.

Why did infants fail to reach for the object in which the path was temporarily occluded? One possible explanation, discussed in the context of Piaget's (1954) and Munakata et al.'s (1997) research, is that an occluded object may appear visually unattainable to infants, and so infants may cease to look at it. Infants' failure to search for the object may follow from their shift of visual attention away from it. This explanation, however, receives no support from this study. The analysis of attentive trials revealed that infants showed the highest levels of head tracking for the moving object with the large occluder and the lowest levels of head tracking with no occluder. This unexpected finding is opposite in direction to that which would be expected if the presence of an occluder reduced infants' visual attention to the object. Moreover, von Hofsten, Feng, and Spelke (2000), who reported detailed analyses of the head-tracking patterns of the infants in the study reported here, found that infants continued to track the object when it moved behind the occluder. Over successive trials with linear motion, infants even began to anticipate the reappearance of the object by turning their head to the far side of the occluder. Even when attention is high, therefore, occlusion perturbs infants' reaching.

A second potential explanation for the suppressive effect of occlusion on reaching is that the occluder may induce infants to change their position (perhaps to minimize the period of occlusion), and their new position may be less conducive to reaching. An analysis of infants' distance from the display is consistent with this possibility because infants tended to move farther from the object in the occlusion conditions than in the no-occluder condition. However, further analyses provided no evidence that differences in distance influenced infants' levels of reaching: A split-median analysis of the large-occluder condition (the only condition with enough infants and enough variability in distance for this analysis) revealed that infants who were more distant from the object were as likely to reach for the object as those who were closer. Most important, an analysis comparing reaching rates for no occluder to reaching rates in the subset of infants in the occluder conditions, who were equally close to the display, revealed the same reliable effect of occlusion as did the main analysis: Infants who sat close to the object tended to reach for it if its path of motion was fully visible but not if its path of motion was partly occluded.

This experiment, therefore, suggests that search failures in Piaget's (1954) tasks stem from limits to infants' object representations and not just from limits to their action capacities. What is the nature of the limits on infants' object representations that produces the search failures reported here and elsewhere?

Piaget (1954) proposed that infants are unable to represent objects that are hidden. That proposal, however, is contradicted by experiments using preferential looking methods, studies of reaching in the dark, and studies of visual tracking of objects that are temporarily occluded (von Hofsten et al., 2000). Bertenthal (1996) and Spelke et al. (1994) proposed that infants represent hidden objects within two distinct pathways—the ventral and dorsal pathways—and their failure to reach for occluded objects reflects a failure to coordinate information in the two pathways. That proposal, however, is contradicted by studies of both reaching in the dark and tracking of an object that moves behind an occluder, because the successful responses to occluded objects measured in these studies also would depend on coordination of the two pathways. Nevertheless, a variant of this proposal is possible: Infants may be capable of coordinating information about the perceived and represented properties of an hidden object, but such coordination may take time. When an object moves rapidly, therefore, infants may fail to coordinate their perception and representation of the object quickly enough to reach for it. This possibility could be tested by varying the timing demands of a predictive reaching task.

We suggest a third possible account of infants' reaching failures, following Munakata and Stedron (in press) and Scholl (2001). In this view, young infants represent both visible and hidden objects, and their object representations depend on the same mechanisms as those used to represent and attentively track objects in adults (see Scholl, 2001, for discussion of these mechanisms). More specifically, the object representations of infants and adults have three properties. First, these representations are more precise, at all ages, when objects are visible than when they are hidden. Second, representations of different objects are competitive: The more objects one attends to, the less precise will be one's representation of each object. Third, precise representations are required for reaching: To reach for an object, one must know where it is, how big it is, what shape it is, and how it is moving. In contrast, less-precise representations suffice to determine that a hidden object exists behind an occluder in a scene that one observes but does not manipulate.

We propose that object representations change over human development in just one respect: They become increasingly precise. Just as infants' sensory and perceptual capacities become more acute with age (e.g., Banks & Shannon, 1993; Kellman & Arterberry, 1998), so does their capacity to represent objects. Both visible and occluded objects therefore are represented with increasing precision as infants grow.

These properties suffice to account for all of the findings discussed previously. Object representations are more precise in the dark than in the presence of a visible occluder, because the occluder competes with the hidden object for attention. The differing precision of object representations under conditions of darkness versus occlusion, therefore, can account for infants' differing abilities to reach in the two situations. When a young infant participates in a preferential looking experiment involving an occluded object, moreover, he or she can draw on her imprecise representation of the object to determine that it exists behind the occluder, and he or she may detect gross properties of the object such as its approximate location (e.g., Baillargeon & Graber, 1988) and the orientation of its principal axis (Hespos & Rochat, 1997). Nevertheless, a young infant likely will fail to represent the exact shape, size, or location of an occluded object because his or her representation is less precise than that of an older child. When a young infant is presented with an occluded object in a reaching experiment, this same imprecise representation is not sufficient to guide object-directed reaching. The differing precision required by many preferential looking experiments versus many reaching experiments, therefore, can account for their different outcomes.

Our hypothesis is supported by several further findings. First, object-directed reaching is less accurate in the dark than in a lighted environment in which the object is visible (Clifton et al., 1991; Hood & Willatts, 1986); this effect follows from the thesis that representations of visible objects are more precise than representations of nonvisible ones. Second, young infants in preferential looking experiments succeed at recognizing anomalous events by detecting whether an object is present behind a screen, but they fail to recognize many anomalies that depend on specific properties of a hidden object such as its size or shape (see Baillargeon, 1993). For example, 4½-month-old infants showed a novelty reaction when a screen that had covered an object rotated entirely through the space the object occupied, but they showed no novelty reaction when the screen rotated through 80% of that space. By 6½ months, infants were sensitive to the 80% violation but still showed no sensitivity to a 50% violation (Baillargeon, 1991). Detection of the latter anomalies requires that infants represent not just the presence of the occluded object, but its size; their insensitivity to small violations of solidity can be explained by the assumption that the precision of infants' representations of the sizes of occluded objects increases gradually over the 1st year.

Third, infants' ability to use object representations to guide reaching increases when the objects are partly visible. Hespos and Baillargeon (1999) presented 6-month-old infants with a tall toy frog to play with, and then they removed the frog from view and presented two occluders with frog legs wrapped around their sides so that the frog's feet protruded in front of the occluder. One occluder was tall enough to conceal the entire frog behind it, and the other was much too short. Infants reached reliably more for the display with the tall occluder, providing evidence that they represented at least the gross height and location of the occluded parts of the frog. When a reach could be directed to a visible part of the object, reaching no longer required a precise representation of the occluded parts of the object. Under these conditions, reaching patterns provided evidence for object representations that agreed closely with the evidence from studies using preferential looking methods.

Our account of infants' search failures makes a number of predictions. Two predictions concern the performance of adults in predictive reaching tasks. First, adults should show more accurate predictive aiming for a fully visible moving object than for a moving object that is temporarily obscured by darkness, as do infants. Second, adults should show more accurate predictive aiming for an object when its visibility is interrupted by darkness than when it is interrupted by occlusion. Recent experiments have confirmed both of these predictions (Hespos & Spelke, unpublished data, cited in Spelke & Hespos, 2001).

Two further predictions concern the performance of infants. First, if infants' object representations vary continuously in precision as a function of visibility and attention, then the effects of occlusion and darkness should interact in predictable ways with the duration of the period of interrupted visibility. As this duration increases, predictive actions should decline more sharply for occluded objects than for objects obscured by darkness. Second, if infants are presented with a temporarily occluded object in a predictive reaching experiment, such as this one, their reaching may be enhanced if the room is plunged into darkness at the time the object is occluded. In the darkness, the occluding object's representation will weaken, and thus, it will compete less strongly with the representation of the occluded object. The first of these predictions has been tested and confirmed (Jansson & von Hofsten, 2001). The second prediction has received a preliminary test with positive results (Munakata, Spelke, & von Hofsten, unpublished data, cited in Spelke & Hespos, 2001). Currently, we are testing it further.

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