

Using Object Knowledge in Visual Tracking and Reaching

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Nine-month-old infants were presented with an engaging and challenging task of visually tracking and reaching for a rolling ball that disappeared and reappeared from behind an occluder. On some trials, the infant observed the experimenter place a barrier on the ball's track; the barrier remained partially visible above the occluder throughout the remainder of the trial. When the task involved only predictive tracking, infants' anticipatory gaze shifts were faster when no barrier was present. When the task involved both tracking and reaching, there were more reaches when no barrier was present. If the infant reached, the timing and extension of the reach and the accompanying gaze shift did not differ with regard to the barrier. Because catching the ball was quite difficult for these infants, task demands interfered with the integration of visual information and visuospatial reasoning about the barrier with the reaching action.

The origins and early development of infants' physical knowledge about the world is a source of intense debate. Contrary to the traditional view espoused by Piaget

(1937/1954) and others that infants younger than 7 to 9 months old do not appreciate the continued existence of objects, an impressive number of recent studies suggest that infants show sensitivity to the continuity, solidity, and coherence of objects from the first few months after birth (e.g., Baillargeon, Spelke, & Wasserman, 1985; Spelke, Breinlinger, Macomber, & Jacobson, 1992). These later studies used preferential looking to test for object knowledge in contrast to the manual tasks that involve reaching and searching for objects used by Piaget.

Why should performance differ so dramatically as a function of the assessment task? Willatts (1997) proposed that infants fail in action tasks because they cannot coordinate the necessary specific actions with the spatial information in a visual display. In applying this idea to means–end tasks, he hypothesized that infants can reason about events (e.g., a hidden object under a cover) before they have acquired the specific action operators of lifting the cover and setting it aside to retrieve the objects.

Willatts's (1997) hypothesis is especially intriguing in the context of a recent proposal that the visual system is split into two functionally dissociable pathways (Bertenthal, 1996; Milner & Goodale, 1995). One pathway is concerned with the recognition and representation of the visual world (ventral pathway), whereas the other pathway is concerned with the visual control of different motor responses, such as visual tracking, reaching, and locomotion (dorsal pathway). In general, the ventral pathway is responsible for processing the enduring characteristics of objects that are stored in memory so that they can be recognized again when seen from the same or different vantage points. By contrast, the dorsal pathway focuses on the visual control of actions, such as visually guided reaching and grasping. In this pathway, visual information is coupled directly to different motor responses that are hierarchically organized as input–output modules. This view of visual processing contrasts with the traditional psychological view that all inputs converge first into a unified representation before guiding both thought and action. According to this proposal, visual representations and sensorimotor transformations are guided initially by distinct processes and follow different developmental trajectories (Bertenthal, 1996).

This study tested some of the developmental implications of this proposal by exploring infants' ability to use their knowledge of physical objects in a task that involved predictive visual tracking and reaching. This task, which was modeled after Spelke et al. (1992), featured a ball that rolled across a stage, behind an occluder, and out the other side. Infants reached for the ball as it reappeared from occlusion. On test trials, a wall was placed behind the occluder in the path of the ball to stop its motion. The top of the wall was visible above the occluder. Our experiments differed from earlier studies in that we assessed the output of two action systems, visual tracking and manual reaching, and determined the sensitivity of those action systems to the presence of the partially visible barrier before, during, and after the initial reaching movement was made. These measurements allowed

us to go beyond the simple question of whether infants possess object knowledge and to assess the possibility that object knowledge is tied to particular actions and uses.

We expected that infants would predictively track the moving ball into and out of occlusion. This hypothesis is consistent with other studies demonstrating predictive visual tracking and reaching (e.g., Robin, Berthier, & Clifton, 1996; van der Meer, van der Weel, & Lee, 1994; von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998). These earlier results showing successful predictive tracking by infants do not, by themselves, prove that infants possess sophisticated object knowledge or explicit representations of objects. The inertia of the limbs and the time lags involved in the conduction of neural signals requires some anticipation or prediction if action is to be smooth and continuous (Bertenthal, 1996; von Hofsten, 1993). Information to specify upcoming events is available in the spatial-temporal patterning of perceptual inputs, and there is striking evidence that the perceptual systems are organized to anticipate future movements (Bertenthal, Bradbury, & Banton, 1993). For example, retinal slip signals allow the oculomotor system to smoothly track moving objects (Lisberger, Morris, & Tychsen, 1987; Robinson, Gordon, & Gordon, 1986). Clearly, such lower level signals derived directly from retinal information do not constitute explicit physical knowledge of objects. However, if the path of the moving object was occasionally perturbed behind a barrier, successful integration of this knowledge with appropriate action would suggest a cognitive process directing the anticipatory tracking and reaching.

On test trials with the partially visible barrier, we predicted that if infants can maintain a memory for the wall-placement event and use that memory in action planning, then anticipatory visual tracking will be disrupted. Disruption of tracking might be seen as delays in shifting the gaze to the normal reappearance point of the ball or as complete disruption of looking to the right of the occluder. Because the visual tracking systems are involved in controlling reaching, predictive visual tracking might also depend on whether a reach is generated or whether a reach is even possible on that particular trial. The effect of the barrier on reaching might be expressed in several ways. Infants might reach less or not at all on barrier trials. If they did reach, then subtle kinematic changes in the approach movement could reveal hesitation, reversals, or endpoint inaccuracies not present in reaches on trials without the barrier.

Four experiments were conducted. The first experiment tested predictive reaching in a group of 9-month-old infants. This age was selected based on previous research by van der Meer et al. (1994), who reported that 11-month-old infants are quite good at predictive reaching and tracking of a moving object reappearing from behind an occluder. Predictive tracking was present by 6 months, but predictive reaching emerged between 7 and 8 months. In van der Meer et al. (1994), movement of the toy was unobstructed. In Experiment 1, we compared the coordination between visual tracking and reaching in the presence and absence of a bar-

rier placed behind the occluder. One question that we sought to answer was whether the additional knowledge required by the barrier might disrupt the coordination between gaze shift and reaching van der Meer et al. (1994) observed. The earlier developing visual tracking response might be better organized to reflect knowledge of the barrier, whereas the later developing reaching response might still require further development before it is modulated by stored knowledge about objects. On the other hand, if the two systems have become truly coordinated by 9 months old, whatever one shows so will the other.

A second issue is whether predictive tracking behaves the same in reaching and nonreaching tasks. In a reaching task, tracking is part of a nested hierarchy of behaviors (eye movements, eye-head coordination, postural stability of the trunk, and eye-hand coordination) that must work synergistically to capture the object. In the nonreaching task, tracking involves only the coordination of the head and eyes, and thus, the processing load for controlling this response is conceivably less. If so, then predictive tracking might show greater sensitivity to additional task factors, such as the presence or absence of a wall. Experiment 2 was designed to test predictive tracking in a nonreaching task at 8.5 months, as well as in a younger 6.5-month-old group. Experiments 3 and 4 were designed to test further the specific information that 8.5-month-old infants coordinate with their predictive tracking.

EXPERIMENT 1

Method

Participants. Nineteen 9.5-month-old infants, ranging in age from 271 to 301 days ($M = 291$ days), participated in this study. Participants were identified using Massachusetts state birth records and contacted with an explanatory letter followed by a telephone call. All infants were full term and in good health on the day of testing. An additional 4 infants were tested but not included in the analyses due to fussiness or failure to complete the session ($n = 1$) and equipment failure ($n = 3$).

Apparatus. Infants sat on their mother's lap during the experiment and in front of a white table top (see Figure 1). During a trial, a blue racquet ball (6 cm diameter) decorated with orange and red spots was rolled across the table top from the infant's left to right. The ball rolled along a 101-cm track that ran the length of the stage at a right angle to the infant's sagittal plane. The ball was within reach of the infant at the right side of the track. The start of the track had a small wooden ramp (10 cm length; in plain view) that allowed the experimenter to roll the ball at a consistent initial speed. The average speed of the ball during a trial was 29 cm/sec. If the ball was untouched by the infant, the ball would roll off the end of the table top into a pocket.

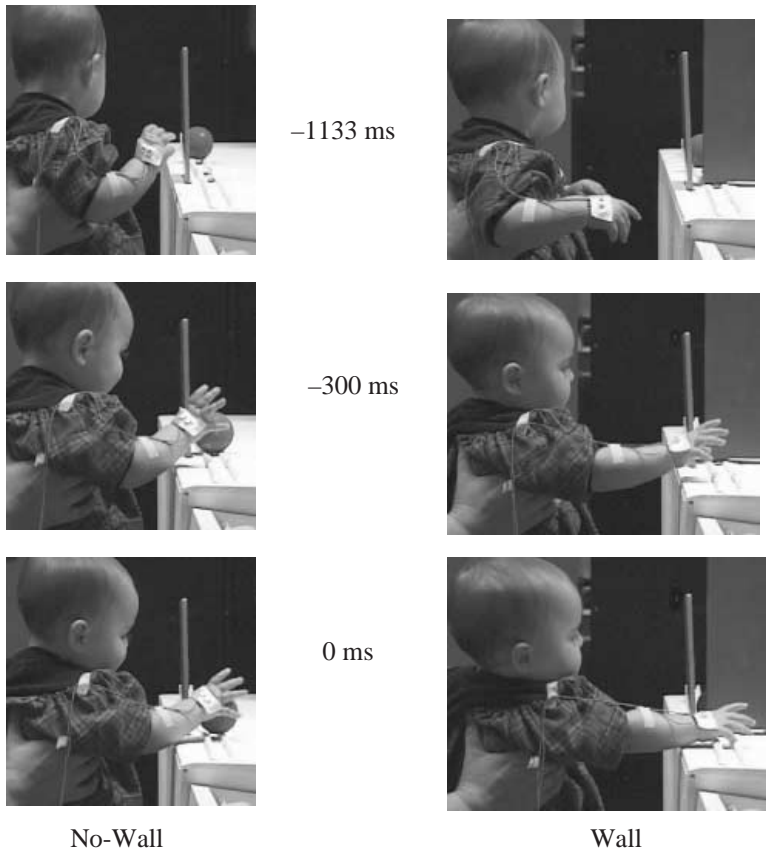


FIGURE 1 Examples of reaches for the ball on a no-wall trial (left) and a wall trial (right). The reaches are from Infant 2 from a pair of temporally adjacent trials. The 0 msec time is the time of contact on the no-wall trial and the time of the first halt of the hand on the wall trial. The video frame from $-1,133$ msec is the start of forward hand movement on the no-wall trial, and the frame from -300 msec is from shortly after the occlusion of the ball on the no-wall trial.

On the right side of the ramp a small screen could be positioned to occlude a portion of the infant's view of the track. The screen was gray in color and was 13.5 cm wide and 19 cm tall, and its left edge was 54 cm from the start of the track. The beginning and ending portions of the track were clearly visible to the infant when the occluder was in place. A green wooden wall could be placed on the track behind the screen to stop the movement of the ball. The wall was 13 cm wide \times 27 cm tall \times 2.5 cm thick. When it was placed at right angles to the track and the occluding screen raised into position, the top of the wall extended 8 cm above the screen.

Two cameras were used to videotape participants during the testing sessions. A Panasonic PV810 video camera recorded a frontal view of the infant's face, and a Sony DCR-VX1000 digital video camera recorded a side view of the infant's reaching behavior. Video was time coded and recorded on standard video recorders.

Finally, infants' reaches were monitored using an Optotrak motion analysis system (Northern Digital). This system consists of three infrared-sensitive CCD camera arrays and computes the coordinates of infrared-emitting diode markers (IREDS) in 3-D space. In this study, a total of four IREDS were used, with the Optotrak system estimating their positions at a rate of 100 Hz. Two IREDS were taped onto the back of each infant's right hand, one proximal to the joint of the index finger and one on the ulnar surface just proximal to the joint of the little finger. Optotrak data were filtered using the algorithm of Busby and Trujillo (1985), as discussed by Clifton, Rochat, Robin, and Berthier (1994).

Two additional IREDS were taped to the track to monitor the location of the ball. When the ball rolled down the track, it passed over both IREDS and caused them to briefly disappear from the Optotrak camera's view. The IREDS were positioned in such a way that when the occluder was in place, the disappearance of the first IRED signaled that the ball had disappeared behind the occluder and was no longer visible to the infant. The disappearance of the second IRED, on the other hand, indicated that the ball had reemerged from behind the occluder and was once again visible.

Procedure. Each infant was seated on a parent's lap during the entire testing session. Parents were instructed to hold their infants securely at the hips to allow for free arm movement. Once the IREDS had been taped to the infant's hand, the infant was positioned at a comfortable reaching distance from the apparatus and slightly to the right of where the occluding screen would be placed. This positioning was designed to encourage right-hand reaching to the right of where the occluder would be placed. Each trial began with the experimenter releasing the ball from the top of the ramp and allowing it to roll down the length of the track.

Testing consisted of three phases: familiarization, training, and testing. During familiarization, infants received two different types of trials. On one trial type, the ball was rolled down the track and the infant was encouraged to reach for the moving ball. On the other trial type, the wall was placed on the track, obstructing the path of the ball, and the ball was rolled down the track. The infant was also encouraged to reach for the ball on this type of trial and could obtain the ball after it came to rest against the wall. These two types of trials were given alternately for a total of four trials.

Infants then received training trials. These trials consisted of placing the occluding screen on the track and releasing the ball on the ramp. The ball then rolled down the track, behind the occluding screen, reappeared to the right of the screen,

and went into the pocket. The infant could reach for the moving ball at any time, but the screen was positioned to prevent the infant from obtaining the ball except for the brief period after it emerged from behind the screen and before dropping into the pocket. Five training trials were given to all infants.

The test phase consisted of two trial types. Trials of one type are referred to as no-wall trials and consisted of trials identical to the training trials. The other trial type consisted of placing the wall on the track to block the path of the ball, placing the occluding screen in front of the wall, and rolling the ball down the track. These latter trials are referred to as wall trials. Five trials of each type were given in the order of wall, no-wall, wall, wall, no-wall, wall, no-wall, no-wall, wall, no-wall for one half of the participants, and with the same order but trial types reversed for the second half of the participants.

On both wall and no-wall test trials, the infant was allowed to reach for and obtain the ball. If the infant did not obtain the ball on no-wall trials, the ball was removed from the pocket and the next trial was initiated. On wall trials, the infant could search to the left of the screen and reach around to obtain the ball. If the infant did not obtain the ball on wall trials, the occluding screen was removed, revealing the ball resting against the wall. The ball was then removed and the next trial initiated. If the infant obtained the ball on either type of trial, the infant was allowed to play briefly with the ball before the ball was taken away by the experimenter and the next trial initiated.

Data scoring. Gaze shift was defined as the time delay between the ball's reappearance to the right of the screen and the infant's redirection of gaze to the right of the screen. It was scored from the videotape record of the trial. A scorer examined the close-up of the infant's face and noted the first video frame where the infant shifted his or her gaze to the right. The gaze-shift latencies presented in this article are relative to the reappearance of the ball to the right of the occluder. Because the ball did not actually reappear to the right of the occluder on trials with an obstructing wall, we computed the average time of reappearance from data on unobstructed trials for each participant. To be consistent in our computation of gaze-shift times, we used this average time of reappearance for both obstructed and unobstructed trials.

Reaching behavior was also scored from the videotape. Reaches were defined as a forward motion of the arm toward the ball that was not part of a turning motion or torso rotation. Contacts were defined as the contact of any part of the hand with the ball. The times of reach onset and contact were noted from the video date timer. Because the primary interest of this study was to examine the infant's response to occlusion, we excluded from further analysis the 10 trials where infant's reached and contacted the ball before occlusion.

Reliability was computed by instructing a second observer to score the times of reach onset for 6 of the infants and for time of ball occlusion for 8 of the infants.

The observers agreed to within four video frames on 90.5% of the trials for reach onset and for 100% of the trials for ball occlusion.

Results

Looking. Nineteen infants completed all three phases of the experimental protocol. All infants received five training trials, but 4 infants had a trial that was not scorable for technical reasons. Because of these missing data, we only analyzed the looking behavior on the last four scorable trials of the training phase for all 19 infants.

Mean gaze shifts decreased over the last four training trials ($M = 0.20, 0.18, -0.03, -0.17$, respectively), and an analysis of variance (ANOVA) revealed a significant linear trend, $F(1, 18) = 6.85, p < .02$. A negative score indicates that infants shifted their gaze to the right of the occluder before the expected reappearance of the ball.

We next analyzed the gaze shifts for the test phase of the experiment. Thirteen of the 19 infants had usable data for at least three no-wall and three wall trials. The overall mean gaze shift for the wall trials was -0.28 sec and -0.22 sec for no-wall trials. An ANOVA revealed that neither trial type (wall vs. no-wall), $F(1, 12) = 0.90, p < .36$; repeated trials, $F(2, 24) = 0.84, p < .43$; nor Trial Type \times Repeated Trials, $F(2, 24) = 2.73, p < .11$, varied significantly (Greenhouse–Geisser adjusted probabilities are given here and in the following). Infants shifted their gaze to the right of the occluder at approximately the same time regardless of whether the wall was present or not.

To determine if gaze shift was determined by reaching per se, we examined whether gaze shift timing varied as a function of trial type for trials where reaching did not occur. Three infants never reached, and three other infants who did reach had more than two trials of each type where they did not reach. The mean gaze shifts for these infants on nonreaching wall and no-wall trials was -0.18 sec and -0.04 sec, respectively. ANOVA of these data did not show a significant effect of trial type, $F(1, 5) = 2.87, p < .15$; moreover, the pattern of results was opposite to that expected if infants were sensitive to the occluded wall.

Reaching. Three of the 19 infants did not reach during testing and were excluded from further analysis. Overall, the remaining 16 infants received a total of 81 training and 162 testing trials. During training, infants reached 101 times (note that infants could reach more than once per trial) and were successful in contacting the object on 24 occasions. During testing, infants reached 153 times and were successful in contacting the object to the right of the occluder 32 times on no-wall trials. Table 1 presents a summary of the reaches for the testing phase of the experiment.

TABLE 1
 Number of Trials, Wall and No-Wall Trials, Number of Reaches, Number of Reaches to the Left and Right of the Occluder, and the Number of Contacts to the Right of the Occluder for Each Infant During the Testing Phases

<i>Infant</i>	<i>Trials</i>	<i>Wall Trials</i>	<i>No-Wall</i>		<i>Left</i>	<i>Right</i>	<i>Contacts to Right</i>
			<i>Trials</i>	<i>Reaches</i>			
1	10	5	5	14	4	10	3
2	10	5	5	9	0	9	5
3	10	5	5	5	0	5	0
4	7	3	4	9	5	4	3
5	10	5	5	14	4	10	4
6	10	5	5	11	6	5	0
7	11	5	6	16	4	12	1
8	10	5	5	10	4	6	5
9	10	5	5	6	2	4	1
10	10	5	5	3	0	3	0
11	11	5	6	11	4	7	0
12	11	6	5	4	1	3	0
13	12	6	6	22	11	11	6
14	9	4	5	7	0	7	4
15	10	5	5	5	0	5	0
16	11	5	6	7	1	6	0
Total	162	79	83	153	46	107	32

Infants tended initially to reach for the ball when they first saw it rolling to the left of the occluder, but they seemed to learn that this was a relatively unsuccessful strategy. Reaches to the left of the occluder declined from 40 of 81 training trials to 46 of 162 test trials. After missing the ball on the left, infants frequently made a second reach to the right of the occluder around the time the ball reappeared (or when it would have reappeared on wall trials). This pattern of reaching was seen on 32 of the training trials, 15 of the no-wall test trials, and 8 of the wall test trials.

Overall, there were more reaches on no-wall ($n = 95$) than on wall ($n = 58$) trials, although each infant reached at least once on each trial type. The difference in the reaches on the two trial types was due to reduced reaching to the right on wall trials. Infants were equally likely to reach to the left on no-wall and wall trials (23 reaches on each trial type), and these reaches were made with the ball in sight. More important, infants were more than twice as likely to reach to the right on no-wall trials (72 reaches) than on wall trials (35 reaches).

This finding of a greater frequency of reaches on the no-wall trials than on wall trials is consistent with the hypothesis that infants were sensitive to the occluded wall. Yet, a second possible reason for the more frequent reaching to the right of the occluder on no-wall trials is that infants reached in response to seeing the ball reappear, rather than anticipating its reappearance. To test this possibility, we di-

vided reaches into those that began before the ball emerged from behind the screen and those that began after its reappearance. The critical comparison is for the number of reaches on wall and no-wall trials that were made at short latency (see the following for defining criterion), and thus could not have been made in response to reappearance of the ball to the right of the occluder.

The distributions of the reach onset timings for the two trial types are shown in Figure 2. We computed the reach onset latency relative to the reappearance time of the ball for 103 of the 107 reaches to the right of the occluder (we could not score the onset of the reach from the videotapes for four reaches). Reaches initiated before the reappearance of the ball were scored as negative values. Assuming a conservative reach reaction time of 150 msec after seeing the ball (Berthier & Robin, 1998), reaches that occurred before 150 msec after the reappearance of the ball on no-wall trials must have been initiated in anticipation of the ball's reappearance. Reaches initiated after this time on no-wall trials might have been in response to the ball's reappearance. Reaches initiated after this time on wall trials were initiated even though the ball had not reappeared. We termed reaches initiated before the 150-msec cutoff *short latency reaches*. We were able to compute reach onset times for first reaches on 71 no-wall trials and 32 wall trials.

Short latency reaches are shown in Figure 2 by the open bars, and long latency reaches are shown by the hatched bars. The open bars represent reaches initiated in anticipation of the ball's reappearance on both trial types. The long latency reaches on no-wall trials were initiated after the ball reappeared, and thus were not unambiguously anticipatory.

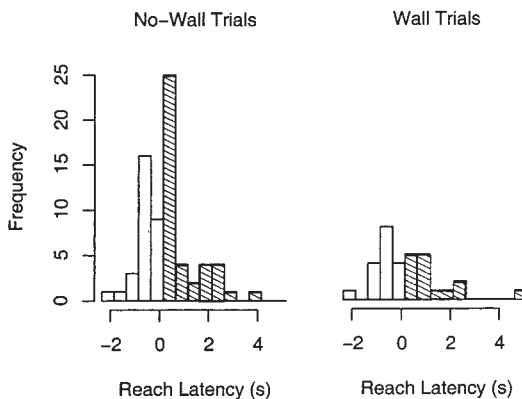


FIGURE 2 The distribution of reach onsets for no-wall (left) and wall (right) test trials. Time zero is the expected time of reappearance of the ball to the right of the occluder. The open bars represent short latency reaches, and the hatched bars represent long latency reaches.

If the increased reaching on no-wall trials relative to wall trials was only due to infants reaching for the reappearing ball, we expected that when we excluded long latency reaches, the number of reaches on the two trial types would be comparable. We found, however, that infants were roughly twice as likely to show short latency reaching on no-wall trials ($n = 30$) than on wall trials ($n = 17$). All short latency reaching was from 8 of the infants, and a test of these infants' data revealed that they were more likely to initiate a reach for the ball on no-wall than wall trials, $p < .05$, Wilcoxon Matched-Pairs Test.

Kinematics of reaching on no-wall and wall trials. Although infants were less likely to reach on wall trials, they nevertheless reached frequently (35/79 = 44%). However, it is possible that infants on wall trials were uncertain about future contact with the ball even though they had initiated a reach. This uncertainty might have led to hesitant reaching characterized by slower average speeds and longer durations when compared to reaches on no-wall trials. Reaches on wall trials might also have stopped short of the target and never reached the track. We found, however, numerous instances where short latency reaches appeared remarkably similar on wall and no-wall trials. Figure 1 shows typical examples of right-directed reaches on no-wall (left), and wall test trials (right). The timing of the video frames is aligned with the hand contacting the ball on the no-wall trial and with the first significant pause of the hand on the wall trial. On the no-wall trial, the hand starts to move forward well before occlusion of the ball with contact following the ball's reappearance to the right of the occluder. The reach on the wall trial terminates in a similar region at the right of the occluder and shows similar timing to the reach on the no-wall trial.

To systematically compare the kinematics of reaching on the two trial types, we analyzed the forward extent of the hand's motion: If the hand progressed all the way to the track, this would suggest a strong expectation of intercepting the ball at that point. To define comparable endpoints to reaches on the two trial types, we selected the time of crossing the frontal plane defined by the occluding screen. Reaches that progressed to this point were likely to result in full extension of the hand to the region of the track. The time of crossing the defined plane was determined from the lateral videotaped view (e.g., Figure 1).

We first examined the likelihood that the infant's hand would break the defined plane. Contrary to the hypothesis that reaches would be more hesitant or less extensive on wall trials when the ball did not reappear, we found that when infants reached on wall trials, their hands almost invariably extended past the plane of the occluder. On 35 reaches on wall trials, the hand broke the occluder plane 34 times. When no-wall trials were analyzed, we found that infants were actually less likely to break the occluder plane, with 52 of 72 reaches breaking the occluder plane. This finding suggests that infants saw the ball reemerge on no-wall trials and realized that their reach was initiated too late to be successful, then aborted their reach.

No such reappearance of the ball occurred on wall trials, so that reaches continued once initiated. These data give no hint that infants were hesitant or uncertain when reaching on wall trials.

To compare the speed and duration of reaches on wall and no-wall trials, we examined the occluder crossing times for the two trial types. As discussed earlier, because the ball reappeared on no-wall but not wall trials, any differences between the two trial types late in reaching could be in response to the visual reappearance of the ball on no-wall trials. To eliminate this influence, we limited our comparisons of the timing and speed of reaching on the two trial types to the short latency reaches, reaches that were initiated before the reappearance of the ball. Also, because only the right hand was instrumented for Optotrak recording, we limit our analysis to right-handed reaches.

The time of crossing the plane of the occluder relative to the reappearance of the ball was .02 sec ($n = 17$) on no-wall trials and $-.09$ sec ($n = 13$) on wall trials, $p < .79$, Mann-Whitney. The distribution of crossing times for short latency reaches is shown in Figure 3, and the mean crossing time is approximately the time the ball reappeared (or would have reappeared) to the right. Examination of speed and duration of these short latency reaches required unoccluded Optotrak data for the entire trajectory, which were available for 7 infants on 14 no-wall and 12 wall trials. The average time from reach initiation to crossing the defining plane was .57 sec on no-wall trials and .59 sec on wall trials, $p < .96$, Mann-Whitney; and the average speed of reaching before crossing the defining plane was 246 mm/sec on no-wall trials and 290 mm/sec on wall trials, $p < .26$, Mann-Whitney. In sum, there was no evidence that reaching was more hesitant on wall trials once a reach had been initiated. Infants reached just as quickly with timing geared to the ball's expected reappearance on wall and no-wall trials.

Characteristics of successful reaching on no-wall trials. We compared the infants' behavior on no-wall trials that had reaches ending in contact with those that did not end in contact. The gaze shift of infants could be computed on 60 of the test trials with reaches to the right, and it was comparable on contact and no-contact

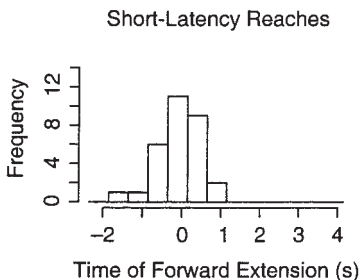


FIGURE 3 The time the forward extension of the hand broke the frontal plane defined by the occluder for the short latency reaches.

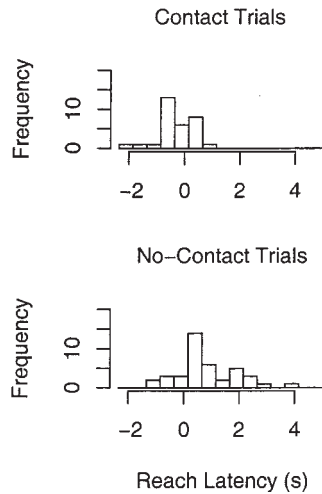


FIGURE 4 Latency of reaching on trials with contacts (left) and without contacts (right) on no-wall trials. The latency of the reach is given with respect to the reappearance of the ball to the right of the occluder.

trials. Infants' gaze shifts relative to reappearance of the ball averaged -0.20 sec on 31 trials without contacts and -0.21 sec on 29 trials with contacts, $p < .57$, Mann-Whitney.

The time of the reach initiation did differ substantially on contact and no-contact reaches with mean reach latencies of -0.32 sec on 31 contact reaches and 1.10 sec on 40 no-contact reaches, $p < .001$, Mann-Whitney. The distribution of reach latencies for the contact and no-contact trials is given in Figure 4. These latencies indicate that reaches initiated around the time of the ball's disappearance had the greatest chance of success. Obviously, many infants at this age find it difficult to initiate a reach about the time when the ball disappears from sight.

Because of the finding that reaches that result in contact are initiated sooner, and because only 8 of our infants showed short latency reaches (see earlier), we investigated whether the infants who showed short latency reaching accounted for the majority of contacts with the ball. This hypothesis was confirmed by the finding that contacts were more likely to be made by short latency than long latency reachers during training (18 of 24 contacts, $p < .03$, binomial test) and testing (24 of 32 contacts, $p < .01$, binomial test). The short latency reaching infants were also more likely to reach during testing (66 vs. 41 reaches, $p < .02$, binomial test) but equally likely to reach during training (32 vs. 29 reaches, $p < .79$, binomial test).

Given the 30-day range in age of our infants, we considered the possibility that the short latency infants were older and more experienced than the other infants. However, the average ages of the two groups of infants is similar, with mean ages of 289 days and 292 days for the short latency and long latency reachers, respectively.

Infant search behavior. On wall trials during testing, the ball rolled behind the occluder and did not reappear to the right of the occluder. The ball could be easily seen and even retrieved by leaning to the left and reaching around the occluder. Even though it was possible to obtain the ball on wall trials, infants only succeeded in contacting the ball behind the occluder once in 79 wall trials.

To further examine this lack of success, we scored the infant's search behavior on wall trials. Search behavior was defined as either looking for or reaching for the ball after it disappeared behind the occluder. If reaching and looking occurred simultaneously, we scored it as a single behavior. We scored five categories of behavior: searches to the left of the occluder, searches directed at the occluder, searches directed to the right of the occluder, searches to the pocket where the ball finally rested on no-wall trials, and social referencing defined as gaze directed at either the experimenter or the infant's parent.

Table 2 summarizes the sequence of behaviors shown by the infants. Almost always (93% of trials), initial search behavior was directed toward the right of the occluder. The infants peered around the occluder and reached into the empty space beside the wall, without success. This initial behavior was followed by a mixture of searching to the left ($n = 33$), social referencing ($n = 17$), and searching directed at the occluder itself ($n = 13$). This second behavior led to the infants observing the ball behind the occluder five times and to touching the ball once. On 41 trials, the infants stopped searching after the second behavior. On the 29 remaining trials, infants showed a variety of behaviors during their third search, but none of these behaviors led to either touches or successful views of the occluded ball. On only 17 trials was a fourth search behavior observed.

Discussion

The behavior of the 9.5-month-old infants in the no-wall condition was consistent with the behavior of the infants in the study reported by van der Meer et al. (1994). Infants learned to anticipate the reappearance of the ball from behind the occluder,

TABLE 2
Search Behavior of the Infants on Wall Trials

<i>Behavior</i>	<i>First</i>	<i>Second</i>	<i>Third</i>
Search to left	0	33	2
Search to center	3	13	5
Search to right	72	4	8
Search to pocket	1	3	3
Social reference	1	17	11
Total	77	70	29

shifting their gaze to the right at approximately the time the ball disappeared. Infants were likely to initiate reaches anytime during a trial, but successful reaching was characterized by the reach starting around the time of the ball's disappearance. Most infants were not consistently successful in contacting the ball, but 8 infants who adopted a pattern of initiating reaches with short latency were successful more often. In general, reaching was coordinated with looking in that both gaze shifts and hand movements anticipated the reappearance of the ball.

On wall trials, where the ball was stopped by the barrier behind the occluder, infants still showed equally rapid gaze shifts to the right of the occluder as on no-wall trials and substantial reaching to the right of the occluder. The likelihood of initiating a reach was significantly less on wall trials than on no-wall trials. Once initiated, reach kinematics were identical on wall and no-wall trials, with reaches usually extending all the way to the track even though no ball was present. Analysis of time of crossing the plane of the occluder, speed of reaching, and duration of reaching did not indicate any differences between reaches on wall and no-wall trials.

In summary, gaze shift timing to the right of the occluder was identical on wall and no-wall trials; this was true whether all trials were considered, or a subset where no reaching had occurred. The kinematics of reaches that were initiated on the two types of trials did not differ. The single difference in behavior between wall and no-wall trials was that the likelihood of initiating a reach was lower on wall trials, but recall that the reason for this difference was ambiguous for the majority of infants.

The failure of infants on wall trials to show the same disruption of visual tracking that they showed when tested in preferential looking paradigms was unexpected. One possibility for this difference rests on the increased complexity of tracking over preferential looking. In tracking, vision functions simultaneously to track objects, control posture, and coordinate itself with head movements to maintain gaze stability (Bertenthal & von Hofsten, 1998). In visual preference paradigms there is no dynamic coupling between perception and action, one merely looks longer at something interesting. A second possibility is that tracking is coupled with reaching, which in our situation involved catching a moving object. The attentional demands of executing the reach may have interfered with the additional processing demands of the gaze control systems on wall trials (Passingham, 1996). Experiment 2 was designed to test that possibility. In contrast to Experiment 1, predictive tracking was tested in a situation that did not also require predictive reaching. If object knowledge does not affect predictive tracking, then performance in this next experiment should be similar on wall and no-wall trials. If, however, infants' tracking in Experiment 1 did not show evidence of object knowledge because of the complexity of the reaching task and its attentional demands, then eliminating the possibility of reaching should allow infants to adjust their predictive tracking using object knowledge.

EXPERIMENT 2

Method

Participants. Infants 6.5 and 8.5 months old were used as participants in this study. The 6.5-month-old infants averaged 196 days of age (range, 193–206; 28 weeks), and there were 11 girls and 3 boys. The 8.5-month-old infants averaged 253 days of age (range, 246–260; 36.1 weeks), and there were 7 girls and 7 boys.

Prospective participants were identified by birth announcements published in the Charlottesville, Virginia, area, and their parents were contacted by telephone. Four additional infants were tested, but their data were not analyzed because of fussiness or because the infant failed to meet the anticipation criterion during training (see later).

Apparatus. The apparatus was similar to the apparatus used in Experiment 1, and infants sat on their mother's lap during the experiment. The infants were centered approximately 90 cm in front of a white puppet stage. Two black-and-white Panasonic video cameras (WV-BD400) were used to monitor the infant and the events on the stage. One camera was mounted above the stage and gave an overhead view of the trial events, whereas the other camera was mounted below the stage and provided a full-frame view of the infant's eyes. These two views were combined with a time code into a single image using a video splitter (Pelco VSS200DT) and output to a video tape recorder.

The apparatus was the same as Experiment 1, with the addition of a second green wall 13 cm wide \times 17 cm high \times 2.5 cm thick placed at the right side of the track; that served to stop the ball at the end of the trial.

Procedure. The study consisted of three phases: familiarization, training, and testing. For all three phases, the experimenter placed the ball on the ramp, released it, and allowed it to roll across the stage to the infant's right. Both groups of infants received the same familiarization and training trials. The familiarization phase lasted for two trials. On the first trial, the ball was placed on the ramp and allowed to roll down the track until it stopped at the wall on the far right. On the second trial, the tall wall was first placed across the track. The ball was then placed on the ramp and rolled down the track to the infant's right, stopping at the tall wall. The occluding screen was not used for the two familiarization trials.

The training phase consisted of trials where the occluding screen was raised and the ball rolled down the ramp and behind the screen, reappearing to the right of the screen. Training trials were given until the infant made three consecutive anticipatory looks to the right of the screen before the ball reappeared. An anticipatory look was defined as a look to the right of the occluder before the ball reappeared.

The testing phase consisted of a total of 10 trials. Two different trial types were given in alternating order and were counterbalanced with regard to the first event presented. One of the trial types was identical to the training trials. These continued training trials are termed no-wall trials.

The other type of trial, wall trials, consisted of trials where the wall was placed on the track followed by the raising of the screen. The ball was then placed on the ramp and released. The ball rolled down the track behind the occluding screen and stopped next to the wall out of sight of the infant.

All trials were scored by two independent observers who agreed within 50 msec 86% of the time on gaze shift delays.

Results

Training trials. Infants in both age groups received at least three training trials. Training trials for both groups were identical and were composed of trials where the screen occluded a portion of the track but no wall was used. On average, 6.5-month-old infants required more training trials ($M = 4.1$) than 8.5-month-old infants ($M = 3.4$) to reach the anticipation criterion, $t(26) = 2.26, p < .04$.

Infants in both age groups came to shift their gaze to the right of the occluder over the repeated training trials. The average gaze shift delays were 0.12 sec, 0.06 sec, and -0.03 sec for the 6.5-month-old's last three training trials; and 0.01 sec, -0.05 sec, and -0.14 sec for the 8.5-month-old's last three training trials. An ANOVA revealed that older infants shifted their gaze more quickly to the right than did younger infants, $F(1, 25) = 7.03, p < .01$. A significant linear trend with repeated trials was found, $F(1, 25) = 11.34, p < .01$. No significant Group \times Trials interaction was observed, $F(2, 50) = 0.0, p < .99$. (One infant was eliminated from this analysis because of missing data.)

Test trials. Table 3 presents the mean gaze shift delays for the two groups of infants on the wall and no-wall test trials. Both groups of infants continued to anticipate the reappearance of the ball on no-wall trials, but both groups showed delayed looks to the right on wall trials. ANOVA of the gaze shift delays on the test trials

TABLE 3
Mean Gaze Shift Delays for Experiment 2

Age	Wall	No-Wall	M
6.5 months	0.18	-0.02	0.10
8.5 months	0.26	-0.07	0.10
M	0.22	-0.04	

with age, trial type, and repeated trials as factors confirmed these impressions. Infants looked with significantly shorter latencies to the right on no-wall than on wall trials, $F(1, 26) = 15.63, p < .0005$. None of the effects of age, repeated trials, nor any interaction effects approached statistical significance. The overall gaze shift was 0.22 sec for wall trials and -0.04 sec for no-wall trials.

Discussion

The results of this experiment appear to contrast sharply with those of Experiment 1. Whereas infants' visual tracking in Experiment 1 showed no evidence of differentiating between the wall and no-wall conditions, infants' visual tracking in this experiment was disrupted significantly when a wall was placed on the path of the rolling ball. This finding is thus consistent with the earlier findings reported by Spelke et al. (1992) in which a visual preference paradigm was used to reveal infants' knowledge of the continuity and solidity of objects. This rules out the possibility that tracking was not sensitive to the presence of the wall in Experiment 1 because it is part of a complex perception-action system.

More important, these results convincingly show that the added demands of reaching in Experiment 1 interfered with the expression of object knowledge provided by the visual system. The same information in two different situations was used very differently by infants. This failure of different actions to respond to the same information in the same way is a common theme in the infant literature (Bertenthal & Clifton, 1998). For example, Adolph (1997) reported that infants who discriminate safe from dangerous slopes when crawling fail to initially discriminate this same information when they begin walking. Apparently, the visual tracking of objects as an end unto itself is a different action than the visual tracking in the service of attempting to catch a moving object. These differences are clearly manifested in the way that infants responded to the occluded object information.

A factor that could account for the disrupted visual tracking on wall trials in Experiment 2 is the visible disruption of the wall extending above the occluder. This was more likely to happen in Experiment 2 than Experiment 1 because the infant's closer position to the apparatus in Experiment 1 caused the visible portion of the wall to be above the line of sight. In Experiment 2, the infant's greater distance from the apparatus resulted in a larger field of view, with the protruding wall as part of the scene. This possibility is argued against by the very rapid, almost saccadic shift of visual attention from the left to the right over the occluder and the phenomena of visual suppression during saccadic eye movements, but this possibility is still not completely eliminated by our data.

To test whether visual disruption occurs because of the protruding wall, we designed an experiment where the visual appearance of the wall behind the occluder was very similar to that before, but the ball was not obstructed by the wall. The

wall was placed just behind the track so that the ball continued to roll unimpeded. Because the infant's eyes were approximately at the level of the top of the occluder, the height of the wall above the occluder was roughly the same, just slightly lower than when the wall was on the track. If the delayed gaze shifts seen in Experiment 2 were due to the wall's visual disturbance of tracking, we expected to observe delayed tracking when the wall was not on the track. On the other hand, if delayed gaze shifts were the result of the infant's understanding of the barrier wall, we did not expect delayed tracking when the wall was behind the track.

EXPERIMENT 3

Method

Participants. Twenty infants served as participants in this experiment. Infants were recruited as in Experiment 2 and were 8.5 months old (258 days; 36.9 weeks) on average (range = 251–260 days). There were 7 girls and 13 boys participating in this experiment.

Apparatus and procedure. The apparatus was identical to that of Experiment 2. The overall procedure was identical to that of Experiment 2 with infants receiving two familiarization trials, a sequence of training trials until the anticipation criterion was met, and an alternating sequence of two test trial types during a test phase. Two groups of infants were tested. Infants of *group behind* received familiarization, training, and test trials identical to that of Experiment 2 with the modification that for the wall test trials, the wall was placed behind the path of the ball so as to not obstruct the ball's movement.

In this experiment, a lack of gaze shift delay for wall trials might be due to the infant's knowledge that the partially occluded wall would not block the path of the ball, but also might be due to the infant's lack of attention to the wall itself because the ball always appeared to the right of the occluder independent of the presence or absence of the wall. For this reason we also ran a second group of infants where the position of the wall was paramount to the reappearance of the ball. *Group on-behind* received training trials identical to the training trials of Experiment 2. The test trials for group on-behind consisted of two types of wall trials. One type consisted of the wall trials of Experiment 2 where the wall was placed on the track stopping the movement of the ball behind the occluder, and a second type where the wall was placed behind the ball's track, not altering the movement of the ball. This second type of trial was identical to the wall trials of group behind.

Group on-behind also received slightly altered familiarization trials. Two familiarization trials were given without the occluding screen as for the other groups, but on one trial, the wall was placed on the track stopping the movement of

the ball, and on the other trial, the wall was placed behind the track and did not affect movement of the ball.

Two observers scored all the data and agreed within 50 msec on 89% of trials in gaze shift delay.

Results

Groups behind and on-behind each required an average of 3.5 trials to reach the anticipation criterion. An ANOVA of the delays in gaze shift for the last three training trials showed a significant linear trend, $F(1, 18) = 8.18, p < .01$, but did not result in significant group, $F(1, 18) = 3.97, p < .07$, or Group \times Repeated Trial differences, $F(2, 36) = 0.26, p < .78$. The average gaze shift delays for the last three training trials were 0.01 sec, -0.03 sec, and -0.12 sec.

Table 4 shows the gaze shift delays for the two groups of infants to the two types of test trials. Group behind showed similar anticipatory gaze shifts on the two types of test trials. An ANOVA of group behind's data showed no effect of trial type, $F(1, 9) = 0.61, p < .45$, nor a significant linear trend with repeated trials, $F(1, 9) = 1.57, p < .24$, but did show a significant Repeated Trial \times Trial Type effect, $F(3, 27) = 3.53, p < .05$. Analysis of the interaction effect with t tests showed a significant difference between the two types of trials on the first, $t(9) = 2.32, p < .05$, but not the second, third, or fourth test trials. The significant difference on the first test trial type was the result of an earlier gaze shift for the no-wall ($M = -0.22$) than the wall-back ($M = -0.03$) trial.

Group on-behind showed anticipatory gaze shifts during wall-back but not wall-forward test trials. An ANOVA showed a significant gaze shift difference on the two types of test trials, $F(1, 9) = 5.49, p < .05$, but did not show a significant linear trend with repeated trials or a significant Trial \times Trial Type effects.

In sum, infant gaze shift in both groups reflected the action of the ball accurately; only when the wall actually blocked the path (wall-forward trials for group on-behind) did infants fail to shift their gaze in anticipation of the ball's reappearance.

TABLE 4
Gaze Shift Delays for Experiment 3

Group	Gaze Shift Delay
Behind	
Wall-back	-0.15
No wall	-0.18
On-behind	
Wall-back	-0.06
Wall-forward	0.07

Discussion

This experiment was designed to clarify why infants showed disrupted tracking in the wall condition of Experiment 2. The results from both conditions are relevant. For the wall-behind group, where the top portion of the wall was visible on wall trials in a way that was highly similar to the wall condition of Experiment 2, infants did not show a consistent disruption of anticipation. An analysis of this group's Trial Type \times Repeated Trials interaction suggested that a temporary disruption of anticipation did occur on the first wall-behind test trial, but that this disruption did not persist as one would expect if infants were responding to the visible protrusion of the wall. Similarly, for the wall on-behind group, infants did not show a significant disruption of tracking in the condition where the wall was behind the path of the ball, but they did show a disruption in the condition where the wall blocked the path of the ball. This difference is also significant because the wall protruded above the occluding screen in both conditions. It is thus concluded that the differences in gaze shift delays on the two types of test trials in Experiments 2 and 3 were not due to interruption of tracking by the partial appearance of the wall. Apparently, infants were sensitive to the location and solidity of the unseen portion of the wall, and this sensitivity disrupted their tracking of the rolling ball.

The results from the wall on-behind group are significant for another reason as well. Relative to the performance of the 8.5-month-old infants in Experiment 2, where test trials were composed of wall and no-wall trials, this group showed a significantly smaller difference in anticipatory gaze shifts where test trials were composed of wall on-behind trials. The difference between the two trial types in Experiment 2 was 0.33 sec, but the difference between the two trial types in the wall on-behind group was only 0.13 sec, primarily because infants in the wall-behind condition were more likely to show some disruption of tracking than were infants in the no-wall condition. This difference approached significance, $F(1, 22) = 2.70, p < .11$. One reason for the difference is that it was not necessary for infants to perceive and represent the specific location of the wall relative to the path of the ball in Experiment 2, whereas the precise location of the wall was more important in this experiment. Apparently, 8.5-month-old infants are able to not only represent the continuity of objects, but also to anticipate whether or not the future spatial location of one object relative to another will intersect. Nevertheless, this latter level of object knowledge is more differentiated and thus requires greater processing of the relevant information. Perhaps it is the greater processing demands that explain why infants show less clear-cut differences in their responses to the two conditions in Experiment 3 versus Experiment 2.

As true in the previous experiments, the findings from this experiment support the position that object knowledge is not represented in an all-or-none fashion. Rather, this knowledge emerges piecemeal and interacts with the specific response and task used for its assessment. In view of this qualification for assessing object

knowledge, we thought it would be informative to manipulate the level of object representation necessary for assessing object knowledge in this task. Recall that a portion of the wall remains visible in all wall conditions. This information was included to reduce the memory load for the infant, but it was still necessary to represent the continuity and solidity of the ball and wall. In the next experiment, we test to determine whether increasing the memory load for infants by occluding the entire wall will change the likelihood that infants will disrupt their tracking in the wall condition.

EXPERIMENT 4

Method

Ten infants at 8.5 months old were recruited as in the previous experiments. Eight girls and 2 boys participated, and they averaged 255 days of age (36.4 weeks; range = 250–260). The apparatus and procedure were identical to Experiment 2, except that a shorter wall (17 cm high) was used that was not visible when placed behind the occluding screen.

Two observers scored all the data and agreed within 50 msec on 91% of the trials on gaze shift delay.

Results

Infants required an average of 3.4 trials to reach the anticipation criterion. An ANOVA of the last three training trials did not reveal a significant linear trial effect. The average gaze shift delays for the last three training trials were -0.06 sec, -0.12 sec, and -0.04 sec.

An ANOVA of the test phase data did not result in any significant effects. The average gaze shift delays were -0.12 sec and -0.16 sec, for the wall and no-wall test trials, respectively.

Discussion

The results from this last experiment were very straightforward. Infants' showed no evidence of their object knowledge interfering with their predictive tracking when the wall was completely occluded. Apparently, infants' representation of a completely hidden object does not provide sufficient activation of their knowledge of objects and barriers to interfere with their predictive tracking. When some portion of the occluded wall remains visible, this level of activation is conceivably en-

hanced, and a disruption of tracking ensues. It is interesting to note that Baillargeon (1986) reported that infants shown a moving object, that completely disappears and then reappears from behind a screen, look significantly longer when the box hidden behind the occluder is located in the path of the object than when located behind that path. Baillargeon interpreted this differential response as evidence for knowledge of the continuity and solidity of objects. Structurally, this event is very similar to the one used in this study, but the response measure, preferential looking, is different. Thus, it appears that the assessment of infants' knowledge depends not only on the stimulus information, but also on the responses utilized and the context of the task.

GENERAL DISCUSSION

The goal of this set of studies was to determine if infants took into account a partially observable barrier to motion in their visual tracking and reaching. Preferential looking studies have concluded that infants represent unseen objects and use those representations to reason about the location of unobserved moving objects (e.g., Baillargeon, 1986; Spelke et al., 1992). Using a different looking measure involving anticipatory gaze shift, Experiments 2 and 3 showed that infants also take into account a partially visible barrier to motion when infants are simply asked to visually track a moving object that disappears for a brief period of time. The differences in gaze shift to the barrier's presence are seen in both 6.5- and 8.5-month-old infants of similar age as Baillargeon's (1986) infants. Experiment 4 showed that infants do not take into account a completely hidden barrier in their visual tracking, a difference from preferential looking studies that did find evidence of representing fully hidden objects.

In Experiment 1, where infants were able to reach for as well as track the rolling ball, the effects of the partially visible barrier wall were much more complex. When infants reached, they reached identically on wall and no-wall trials. Analysis of the kinematics and timing of initial reaches on wall and no-wall trials revealed no differences in speed, duration, and extent. Further, when given the opportunity to find the ball after the initial reach in open-ended search, infants were almost completely unable to find the ball on trials when it had stopped behind the occluder.

In Experiment 1, reaching and looking were coordinated. Anticipatory gaze shifts and successful reaches began at about the time the ball disappeared behind the occluder. Gaze shifted to the right of the occluder well before the ball reappeared, with reaches typically contacting the rolling ball within 100 to 200 msec after reappearance. On trials when the wall blocked the ball, infants continued to show both anticipatory gaze shifts and reaches to the empty track. Furthermore, even on trials when no reaching was observed, infants still showed anticipatory gaze shifts regardless of the presence of the wall. This suggests that just being in a

situation where reaching is possible recruits tracking differently from the passive observer situation in Experiments 2 and 3.

Although most measures indicated a total disregard for the effects of the barrier, one measure suggests otherwise. Nine-month-old infants reached less frequently when a barrier was on the track. Examination of individual infants' performance revealed that a subset of 8 infants was responsible for this effect. As was true for the entire group, when infants in this subset reached, their reaches were kinematically similar on the two trial types. Our interpretation of this effect on frequency of reaching is that infants' knowledge of the wall's blockage of the ball led them to decide not to reach. This decision likely resulted from some preliminary knowledge about the solidity and location of the wall, which is mediated by the ventral visual stream. These decisions to inhibit reaching were not consistently made either across or within infants. When an infant made a decision to reach, the reach was executed as if the barrier wall did not exist. Furthermore, knowledge of the location of the hidden ball appeared to be missing or incomplete on reaching trials because subsequent search behavior was consistently wrong. In contrast to the processing of object properties, the reach itself was mediated by the dorsal visual stream. On most trials, the execution of the reach was sufficiently difficult that it recruited most of the processing resources and may have blocked further processing by the ventral stream. In other words, task demands affected the coordination of these two perceptual pathways.

A similar increase in task demands may explain why there was no disruption of visual tracking in Experiment 4. In the case of the partially visible wall in Experiments 2 and 3, it is conceivable that the ventral pathway was only minimally involved because some information about the wall was available from stimulus information alone. Thus, it was not necessary for as much information from both ventral and dorsal pathways to converge at some higher level of processing for infants to show an appreciation of physical constraints. By contrast, the completely occluded wall used in Experiment 4 demanded activation of the ventral pathway to represent the hidden object. Apparently, this representation was not sufficiently developed to converge on the control of visual tracking mediated by the dorsal pathway. We hypothesize that the disruption of visual tracking in the completely occluded condition was more difficult specifically because it involves the integration of both visual pathways, which necessarily demands additional stages of processing.

Passingham (1996) obtained similar results with adult participants executing simple manual tasks. In learning new visuomotor tasks, functional imaging shows involvement of prefrontal and anterior cingulate cortex, but once the task is well learned, activity of these regions returns to baseline. Passingham argued that these regions of the brain mediate *attention-to-action*, a focusing of attention when participants must concentrate on controlling action. Passingham showed that tasks requiring attention-to-action interfere with other working memory tasks, such as

verb generation. When considering our data, catching a moving ball is certainly a demanding visuomotor task (infants were only successful on 38% of the trials) and would require considerable attention-to-action. If Passingham's results can be extended to infants, executing a reach for a moving object would interfere with visuospatial reasoning tasks such as determining whether the ball would reappear to the right of the occluder. It is not surprising, therefore, that once the infants' reaches were initiated, any visuospatial reasoning about the effects of the barrier wall on the path of the ball were not observed in our data. This hypothesis also explains the lack of success in open-ended search because the attention-to-action required during execution of the reach blocked visuospatial representations and reasoning so that once the initial reach was completed, the infant could not find where the ball was.

A second factor that may have contributed to the lack of infants' ability to respond differentially to the two types of test trials is that infants had to keep track of a changing stimulus situation and inhibit a response that had been rewarded on previous trials. Diamond (1990) stressed that infants in this age range have difficulty inhibiting responses such as a direct reach for a toy behind a transparent barrier. Thelen and Smith (1994) interpreted the A-not-B error in terms of a strong propensity to reach to a previously reinforced position. In our situation, that would be a reach to the right of the occluder, which was reinforced during training trials. Another data set indicating that infants have trouble inhibiting responses comes from the classic covered toy task. Infants continued to reach and lift the cover even when they saw the experimenter place the cover with no toy underneath (Appel & Gratch, 1984; McCall & Clifton, 1999). This suggests that infants have problems switching between reward and no-reward situations when such trials are intermixed. If trials were blocked, infants refrained from searching on no-toy trials (Appel & Gratch, 1984).

One problem with explaining our infants' reaching behavior in terms of lack of inhibition is that their subsequent search behavior did not support the conclusion that they had knowledge of the ball's location. One might hypothesize that the reach to the right was impulsive and uninhibited, even though infants had knowledge of the ball's whereabouts behind the occluder. Recall, however, that infants did not successfully retrieve the ball from behind the occluder even though they continued to search when the ball failed to reappear to the right of the screen on wall trials. Infants looked to the left and right of the occluding screen, they looked at the screen, they looked in the pocket at the end of the track, and they looked at the experimenter or parent. They rarely looked behind the screen to the left, even though the ball was within grasp or sight with the proper body movement; this was not due to an inability of the infants to execute an indirect reach around or behind the occluder. Diamond (1990) reported that 9-month-old infants readily executed reaches around a barrier to obtain an object, and in this study, 13 out of 16 infants reached behind the screen 32 times. Nevertheless, these indirect reaches were un-

successful in obtaining the ball, because with one exception, they occurred to the right of the occluder where the ball could not be. The failure of infants in open-ended search suggests that the infants' knowledge of the hidden trajectory of the ball was quite limited. These results suggest that infants have either forgotten about the barrier wall or failed to encode its presence in the first place.

Studies that use the preferential looking response yield valuable data on infants' knowledge of objects, but this response is not anchored to any specific source of information. The advantage of our paradigm is that it is possible to more definitely identify the information that infants are processing. Specifically, infants' expectations about a future event can be assessed. Both predictive tracking and reaching are guided by the inertia of the moving ball such that, even when the ball disappears briefly behind the occluding screen, these actions continue in anticipation of the reappearance of the ball. If, and only if, infants on wall trials (a) correctly represent the path of the ball relative to the occluded barrier and (b) represent the physical constraints imposed by the solidity of the objects, will they appreciate that the ball will not reappear to the right of the screen. It is specifically the disruption of predictive tracking or reaching that indexes this appreciation.

We found that when reaching was not involved as in Experiments 2 and 3, predictive tracking was disrupted, in agreement with studies of preferential looking. If reaching was involved, the effects of the wall were more complicated. Infants reached less often when the wall was there, but if a reach was launched, it was carried out with the same timing and kinematics regardless of the wall's presence. Significantly, predictive tracking remained locked to this situation and did not reflect any knowledge of the occluded wall. This conjunction of results suggests that execution of the difficult catching motion interfered with the coordination of object knowledge and each of the component actions involved in reaching. Thus, it appears that the probability of integrating physical knowledge of objects and visuospatial reasoning with the action plan may be dependent on the difficulty and novelty of the upcoming action. We hypothesize that less demanding motor tasks, or this same task used with more skilled older children, would not show the same disjunction between tracking and reaching found in this study.

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