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Phenomenal Permanence and the Development of Predictive Tracking in Infancy

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The perceived spatiotemporal continuity of objects depends on the way they appear and disappear as they move in the spatial layout. This study investigated whether infants' predictive tracking of a briefly occluded object is sensitive to the manner by which the object disappears and reappears. Five-, 7-, and 9-month-old infants were shown a ball rolling across a visual scene and briefly disappearing via kinetic occlusion, instantaneous disappearance, implosion, or virtual occlusion. Three different measures converged to show that predictive tracking increased with age and that infants were most likely to anticipate the reappearance of the ball following kinetic occlusion. These results suggest that infants' knowledge of the permanence and nonpermanence of objects is embodied in their predictive tracking.

The perception of a stable visual world is highly dependent on the capacity to predict how it changes from moment to moment. Although complex events, such as state changes or the conservation of momentum, require visual experience and explicit knowledge, many simple visual events, such as the spatiotemporal continuity of briefly occluded objects, are perceived without explicit knowledge or conscious inference, suggesting that they are consistent with a set of core principles that are deeply entrenched in our cognitive architecture (cf. Shepard, 1984; Spelke, 2000).

Consider, for example, the task of visually tracking an automobile moving along a crowded street. Depending on your vantage point, this automobile may be initially completely visible, but gradually disappears behind a larger truck. A moment later, the automobile reappears but the location of this reappearance is neither surprising nor discrepant. The key to this predictability is that you are able to extrapolate from the path of motion to predict future locations of this moving vehicle. Implicit in this extrapolation is that the automobile continues to exist and follow the same path of motion even when no longer visible. This sort of predictive behavior thus suggests that observers are sensitive to the inertia and the continuity of moving objects (e.g., Ramachandran & Anstis, 1983; Scholl & Pylyshyn, 1999; Spelke, Breinlinger, Macomber, & Jacobson, 1992).

Does sensitivity to these properties emerge from years of experience and gradually become encapsulated within the cognitive architecture of the adult observer or are these properties anticipated by the organization of the infant's brain? A first step toward addressing this question is to examine carefully the capacities and limitations of infants for predicting visual events. In this paper, we present a preliminary investigation toward achieving this goal by focusing on one specific question: When and how do infants begin to predict the spatiotemporal continuity of moving objects?

Development of Predictive Tracking

This question has had a long and venerable history dating back to Piaget's theory of the object concept. Piaget (1937/1954) claimed that infants begin to show anticipations of briefly occluded visual events by Stage 3 (approximately 4–8 months of age), but attributed these anticipations to motor persistence. More recent studies using violation of expectancy paradigms challenge this interpretation with evidence showing that infants are indeed sensitive to violations of spatiotemporal continuity by this stage of development. In one of the first of these

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studies, Moore, Borton, and Darby (1978) found that tracking of a moving object was disrupted in 5-month-old infants when it went behind an occluder and reappeared too early or changed identity. By contrast, tracking was not disrupted when the object failed to appear through a gap in the occluder until 9 months of age. Contrary to these results, studies testing sensitivity to numerical identity as a function of whether or not a translating object appears across a gap suggest that infants can detect this spatiotemporal violation by 5 months of age (Spelke, Kestenbaum, Simons, & Wein, 1995; Xu & Carey, 1996). Currently, the reason for these discrepant results is unclear, but for present purposes, the main limitation of the preceding studies is that they are based on infants' *detection of discrepancies or interpretations* of spatiotemporal events as opposed to infants' *predictions* of spatiotemporal events. In the former case, the response to the spatiotemporal event is based on both the disappearance as well as the reappearance of the transiently occluded moving object, whereas prediction necessitates that a response is executed solely on the basis of the spatiotemporal information preceding its reappearance.

One paradigm that is better suited for addressing the question of prediction is to investigate infants' predictive tracking of briefly occluded events. In this paradigm, prediction is assessed by measuring whether infants anticipate the reappearance of a moving object following a brief occlusion. Tracking is scored as predictive if, after following the moving target before occlusion, infants shift their gaze to the far side of the occluding surface before it reappears. Predictive tracking emerges between 3 and 5 months of age depending on the width of the occluder, the duration of occlusion, and the velocity of the target (Johnson, Amso, & Slemmer, 2003; Jonsson & von Hofsten, 2003; Rosander & von Hofsten, 2004; van der Meer, van der Weel, & Lee, 1994).

How do infants predict these visual events? As previously discussed, Piaget (1937/1954) suggested that anticipatory tracking is an epiphenomenon of motor persistence. Recent evidence reveals, however, that motor persistence cannot account for such predictive tracking, as infants rarely track smoothly and continuously once the target disappears. Instead, they tend to stop and fixate on the occluding edge for a brief period of time, and then make one or two saccades to the other side of the occluder (Rosander & von Hofsten, 2004). In addition, motor persistence is unable to account for predictive tracking along circular trajectories (Gredebäck & von Hofsten, 2004; Gredebäck, von Hofsten, & Boudreau, 2002), as the location of the reappearance will not be coincident with a straight-line trajectory formed by the tangent angle of the disappearing target (cf. Bower, 1971).

Another possibility is that prediction develops from a simple type of contingency learning. By observing a target repeatedly disappear and then reappear in a new location, infants might learn a spatiotemporal contingency. This possibility is supported by findings that 2- to 3-month-old infants learn to predict sequential alternations of targets appearing in two locations (Canfield & Haith, 1991; Haith, 1994). It is not clear, however, whether contingency learning is sufficient for explaining infants' predictive tracking of a moving target, because the likelihood of predictive tracking by 4-month-old infants increases following 2 min of visual experience with an unoccluded object (Johnson, Amso et al., 2003). During this familiarization period, the moving object was always visible so there was no opportunity for learning the contingency that a target disappearing in one location would reappear some time later in another location. Instead, it appears that the familiarization stimulus increased infants' sensitivity to the trajectory of the target so that they were able to extrapolate from the preceding spatiotemporal information to predict the reappearance of the target. This extrapolation is consistent with the predictive mechanisms available in the adult motion detection system for perceiving a moving target. In essence, a linearly moving image stimulates a set of motion detectors that feedforward in anticipation of the future location of the image (Bertenthal, Banton, & Bradbury, 1992; Ramachandran & Anstis, 1983). As such, some representation of the future location of the target is stimulated before the reappearance of the moving target.

More direct evidence supporting the contribution of trajectory information in predicting the reappearance of a moving target was first reported by von Hofsten, Feng, and Spelke (2000). Six-month-old infants quickly learned to predictively track an object that emerged from behind an occluder along a linear trajectory, but showed difficulty learning to track along a nonlinear trajectory. A related study by Gredebäck and von Hofsten (2004) tested the development of predictive tracking of circular trajectories by infants between 6 and 12 months of age. Unlike a linearly translating target, a circularly moving target requires extrapolation of the previously visible trajectory in order to predict both the timing and position of the reappearing target. In this condition, the location of the reappearance will not be coincident with a straight-line trajectory formed by the tangent angle of the disappearing target. The findings showed that infants can extrapolate from the past history of a moving target to predict its reappearance. Additional evidence supporting this conclusion was provided by Gredebäck et al. (2002), who showed that 9-month-old infants systematically adjusted the latency of their gaze shifts to a circularly moving target as a function of the target speed and the location of the occluder relative to the target trajectory. Taken together, these findings suggest that predictive tracking is a function not only of infants responding to the inertia of the moving target, but to other spatiotemporal properties as well. One of the most important spatiotemporal properties of objects concerns the way they appear and disappear behind nearer objects, although the relevance of this information for predictive tracking by infants has yet to be investigated.

Object Continuity and Occlusion Information

For adults, the continuing existence of objects is specified by the lawful manner in which objects disappear and reappear behind occluding surfaces (Gibson, 1979; Michotte, 1950; Michotte, Thinès, & Crabbé, 1964/1991). An object leaving the visual field may be perceived as going *out of sight* or as going *out of existence*, depending on the manner in which it disappears (Gibson, Kaplan, Reynolds, & Wheeler, 1969; Kaplan, 1969). More specifically, the continuity of an object is specified by the progressive deletion and accretion of texture at the occluding edges of a surface, whereas the discontinuity of an object is specified by its abrupt disappearance or reappearance.

Following up on these findings, Scholl and Pylyshyn (1999) tested whether adult observers are sensitive to the manner by which an object disappears in a multiple object tracking task. In this task, observers were instructed to track four of eight objects that moved independently and unpredictably on a computer screen. Tracking performance was not impaired when the objects were briefly occluded during their movement on the screen, regardless of whether the occluding surfaces were visible or invisible. By contrast, performance was significantly impaired when the moving objects abruptly disappeared and then reappeared at a new location consistent with the object moving at a constant velocity or imploded and subsequently exploded at a new location that was also consistent with the object's velocity. If adult observers were simply using trajectory information for predictive tracking of the objects, then the way that the object disappeared would not have been significant. The finding that tracking was impaired when occlusion information was missing suggests that this information contributes to predictive tracking of moving targets.

Statement of Problem

Currently, it is not clear whether infants are sensitive to occlusion information for predictive tracking. A few previous studies reveal that infants are sensitive to kinetic occlusion information for specifying the segregation of surfaces by 3 months of age and for specification of the implicit form of a surface by 5–8 months of age (Bertenthal, Proffitt, Spetner, & Thomas, 1985; Craton & Yonas, 1988; Granrud et al., 1984; Kaufmann-Hayoz, Kaufmann, & Stucki, 1986). Additional studies have tested infants' sensitivity to object continuity following a transient occlusion (e.g., Aguiar & Baillargeon, 1999; Spelke et al., 1992), but the relevance of these studies for the current investigation is limited because moving objects always disappeared lawfully in a manner consistent with the continued existence of the object.

Finally, a recent study measuring electroencephalogram (EEG) activity from the scalp of 6-month-old infants found increased gamma-band oscillatory activity over right temporal sites when an object was deleted gradually at an occluding edge, but not when it disintegrated gradually as an occluding edge moved across the object (Kaufman, Csibra, & Johnson, 2005). These results were interpreted to suggest that infants are sensitive to the continued existence of objects that disappear via kinetic occlusion, but not via disintegration. This interpretation follows from a previous paper in which these same authors argued that gamma oscillations reflect the representation of occluded objects (Kaufman, Csibra, & Johnson, 2003).

Although the preceding findings are clearly relevant to the current investigation, they do not address the central question motivating this study, which pertains to how spatiotemporal information is used to control predictive tracking. If infants rely only on trajectory information and occluder width (i.e., spatiotemporal properties previously investigated) for predictively tracking moving targets, then the presence or absence of occlusion information at the locus of disappearance would be inconsequential. If, however, infants are sensitive to occlusion information for specifying the continuity of a moving target, then the presence of this information should improve the likelihood of predictive tracking.

Infants' sensitivity to occlusion information for predictive tracking was tested in the current study by adapting the paradigm previously used by Scholl and Pylyshyn (1999) to study adults' tracking of moving targets. A brightly colored ball rolled horizontally across a projection screen and was occluded for approximately 1 or 2 s by an opaque rectangular surface in the ball's path. Disappearance and reappearance of the ball conformed to one of four stimulus transformations: (1) kinetic occlusion and disocclusion, (2) instantaneous disappearance and reappearance, (3) implosion and explosion, and (4) virtual occlusion and disocclusion.

A majority of infants show some evidence of predictive tracking by 4–6 months of age (Johnson, Amso et al., 2003; Rosander & von Hofsten, 2004), so it seemed reasonable to begin testing at 5 months of age. Infants at 7 and 9 months of age were also tested because it was unclear whether sensitivity to occlusion information would be present from the onset of predictive tracking or whether this sensitivity would develop more gradually. If infants were sensitive to kinetic occlusion information, then we expected that predictive tracking would be significantly greater in the occlusion condition than in the instantaneous disappearance and implosion conditions. It was less clear whether virtual occlusion would enhance or impair performance, because, on the one hand, the presence of a visible contour serves as a cue for the reappearance of a moving target (Bennett & Barnes, 2006), but, on the other, it competes for attention with the moving target and thus degrades the strength of the target's representation (Rosander & von Hofsten, 2004; Simons, 1996). Scholl and Pylyshyn (1999) and Kaufman et al. (2005) found performance in this condition to be similar to fully specified occlusion, arguing that the continuity of the target is sufficiently specified by the accretion and deletion of texture. Contrary to these findings, two recent habituation studies (Bremner et al., 2005; Johnson, Bremner et al., 2003) tested 2- to 6-month-old infants' perception of a briefly occluded oscillating object moving along a continuous trajectory and reported that infants perceived a virtual occlusion event as significantly different from the event in which occlusion was fully specified.

In addition to testing the effects of the four stimulus conditions on predictive tracking, we also tested the effects of delaying the reappearance of the ball on predictive tracking. This manipulation was introduced to test the possibility that previous studies underestimated the likelihood that infants *anticipated* the reappearance of a briefly occluded target because of (1) "sticky fixations" following the disappearance of the ball at the edge of the occluding surface, and/or (2) reaction times to program and execute a saccade to the far side of the occluder were not consistently fast enough to precede the reappearance of the target. (In most previous studies, predictive saccades were observed on 30–50% of the trials, whereas reactive saccades were observed on the majority of trials.) In order to evaluate this possibility, we delayed the reappearance of the ball by doubling the period of its invisibility from 0.9 to 1.8 s. If infants' predictive tracking increased in the delayed condition, this result would be consistent with the hypothesis that infants are able to *anticipate* the reappearance of a briefly occluded target more often than suggested by the results from a typical *predictive tracking* experiment.

One problem with this interpretation is that infants might show greater predictive tracking in the delayed condition simply because there would be more time for infants to execute a saccade before the reappearance of the ball. As a consequence of the additional time, infants would be more likely to produce a saccade and by chance alone some percentage of these saccades would be directed to the correct location and thus scored as predictive. If, however, the improvement in predictive tracking in the delay condition was primarily a function of chance responding, then we would not expect the likelihood of predictive tracking during the delayed portion of the occlusion period to differ as a function of condition. Thus, a second goal of this study was to test whether delaying the reappearance of the ball would indiscriminately increase the likelihood of predictive tracking, or instead increase predictive tracking as a function of whether or not the stimulus information was consistent with the persistence of the briefly occluded ball.

Method

Participants

A total of 36 healthy full-term infants participated in this study. Twelve infants of each of the following three ages were tested: 5 months ($M = 21.14$ weeks, $SD = 10.2$ days; 6 males, 6 females), 7 months ($M = 29.57$ weeks, $SD = 9.46$ days; 6 males, 6 females), and 9 months ($M = 38.57$ weeks, $SD = 8.36$ days; 7 males, 5 females). Three additional infants were tested but not included in the final sample because of fussiness. Infants were recruited from a participant database maintained by the Center for Infant Studies at the University of Chicago. Approximately half of the sample was Caucasian (53%), and the remainder were African American (22%), Hispanic (21%), or unclassified (4%).

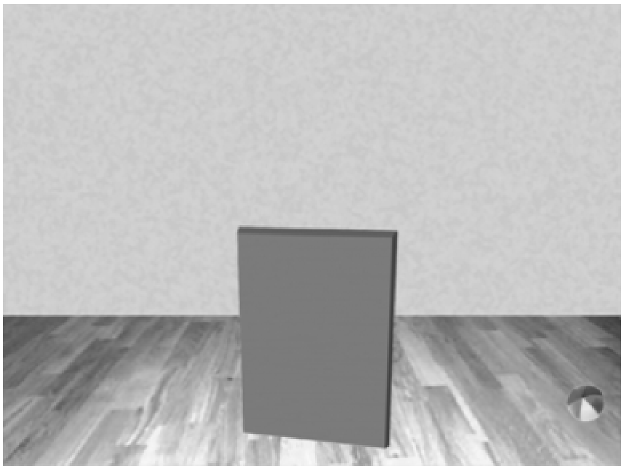

Figure 1. Visual scene depicted in the stimulus events. At the beginning of each event, a multicolored ball bounced up and down with an accompanying bouncing sound, and then rolled from right to left across the flat wooden floor until it disappeared behind the left edge of the stimulus display.

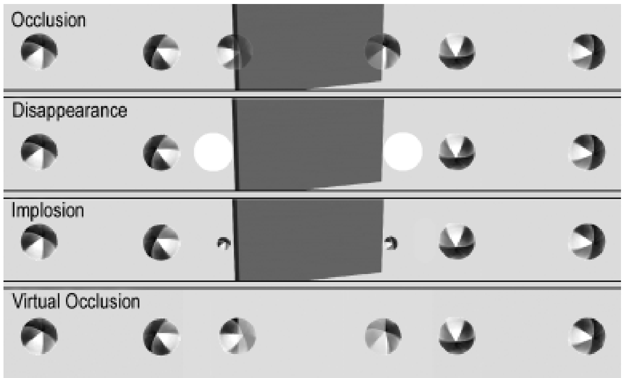

Figure 2. The four horizontal panels depict the location and appearance of the rolling ball at different times during the stimulus event. (1) Occlusion: The ball gradually disappears behind the right side of the occluding surface (located in the center of the display), and then after 0.9 or 1.8 s reappears from behind the left side of the occluding surface. Note that the shaded portion of the ball is meant to depict its nonvisible portion behind the occluding surface. (2) Instantaneous Disappearance: The ball abruptly disappears when it reaches the location of the white circle and abruptly reappears 0.9 or 1.8 s later at the location of the second white circle on the other side of the occluding surface. (3) Implosion: The rolling ball rapidly decreases in size as it approaches the occluding surface and rapidly increases in size as it reappears 0.9 or 1.8 s later on the other side of the occluding surface. Note that the ball completely disappears or begins to reappear at the same exact time that the ball abruptly disappears or reappears in the Instantaneous Disappearance event. (4) Visual Occlusion: This event is identical to the Occlusion event, except that the occluding surface is invisible.

Stimuli

Four computer-animated stimulus displays were created with Macromedia Director and assembled with scripts so that they could be interactively controlled when played with a web browser. Each display depicted a multicolored ball (dia-5.7 cm, 2.9°) that appeared to roll from right to left across a flat wooden floor until it disappeared behind the left edge of the stimulus display (see Figure 1). The horizontal dimension of the display was 96.5 cm (42.7°) and the vertical dimension was 70 cm (34.1°). Located horizontally in the middle of the display was a brown rectangular surface (horizontal dimension = 23 cm, 11.5°; vertical dimension = 33 cm, 16.4°) that appeared supported by the floor and aligned so that its horizontal extent was slightly slanted away from the observer. The ball appeared at a depth that was further back than the rectangular surface so that it became occluded as it rolled across the screen from right to left. The ball rolled at a velocity of 19.2 cm/s (9.6°/s).

The four stimulus displays differed in terms of how the ball disappeared as it moved behind the occluding surface (see Figure 2). In the *kinetic occlusion* condition, the rolling ball was gradually deleted along a straight vertical contour as it passed behind the rectangular occluder, and was gradually accreted as it passed from behind the screen. This transition from fully visible to invisible or vice versa lasted approximately 300 ms. In the *disappearance* condition, the rolling ball reached the occluding screen and then disappeared all at once; it reappeared all at once on the other side of the screen at a time corresponding to when the forward edge of the ball in the occlusion condition would first become visible. In the *implosion* condition, the disappearance and reappearance of the ball involved optical transformations that were similar to the occlusion condition, but accretion and deletion did not occur along a straight contour. Instead, disappearance corresponded to an implosion whereby the texture was deleted symmetrically around the center of the ball, and reappearance corresponded to an explosion whereby the texture was accreted symmetrically around the center of the ball. During implosion and explosion, the ball was programmed to rapidly shrink into oblivion or rapidly expand from nothing as its front or backside, respectively, contacted the near or far edge of the occluding surface. The time for this transition was identical to the time for the transition in the occlusion condition (300 ms). Adult observers perceived the ball in these displays as rapidly disappearing (i.e., implosion) or appearing (i.e., explosion). In the *virtual occlusion* condition, the ball was transformed in a manner identical to the

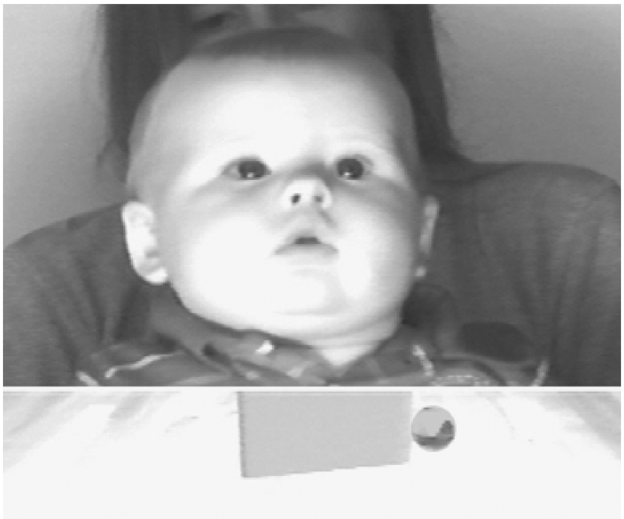

Figure 3. Still frame from the split video screen recording showing the baby's gaze behavior on the top two thirds of the screen and the stimulus event on the bottom third of the screen. The calibration light reflected on the baby's cornea was used by coders in judging the location of the baby's gaze.

occlusion condition, except that the occluding surface was not visible.

Apparatus

Infants sat on their caretaker's laps and faced a large rear-view projection screen (200 × 100 cm) suspended 40 cm above the floor by a metal frame. The experimenter and equipment were located behind the screen, which prevented infants from seeing anything except the stimulus displays. These displays were generated by a Dell computer (1.2 GHz CPU; 1.5 GB RAM) and output to a high-resolution projector (Proxima Ultralight DX2, InFocus Corporation, Wilsonville, OR, USA) and video screen splitter. A video camera (Panasonic WV-B0400, Panasonic Corporation, Secaucus, NJ, USA) located below the projection screen recorded the infant's face and visual behavior. The output from the video camera was also sent to the video splitter where it was gen-locked to the stimulus display and recorded on videotape. As can be seen in Figure 3, the image of the infant's face was stored on the upper two thirds of the video, while the center of the stimulus display was aligned with the infant's face and stored on the bottom third of the video. This video was used for scoring infants' gaze behavior.

Procedure and Design

On each trial, infants were first shown a vertically bouncing ball with an associated bouncing sound to direct their attention to the right side of the screen. Once infants were oriented, the ball rolled across the screen in a manner consistent with one of the four stimulus conditions. Trials were organized into blocks of eight trials, consisting of the four stimulus conditions crossed with the duration of ball disappearance. The ball disappeared for either 0.9 s, consistent with its visible velocity (*no delay* condition) or for 1.8 s, which was twice as long as expected given the ball's velocity before occlusion (*delay* condition). Trials were randomized within blocks. Infants were presented with two to four blocks, depending on their ability to sustain attention to the stimulus displays. Before the first block of trials, infants were shown two trials of an unoccluded ball rolling across the screen to familiarize them with the event.

Scoring and Dependent Measures

Before scoring infants' visual behavior, all coders spent extensive time observing the visual behavior of adults tracking the moving ball. During this initial training they received feedback from the adults as to when they were tracking the ball and when they were fixating the near or far edge of the occluder. A fixed calibration light located below the center of the stimulus display was reflected off the observer's cornea and was used to assist in the judgment of the direction of gaze.

Infants' gaze behavior was scored offline with a computerized frame-by-frame observational coding system (33 ms resolution). All coders were trained with this system, and did not begin coding new data until the correlation between their coding and the coding established for a standard data set was .95. Frame-by-frame analysis enabled coders to identify precisely when infants started and stopped tracking the ball because the pupil would show a displacement between any two frames during which movement occurred. It was thus possible to determine when infants executed a saccade following the disappearance of the ball and to judge the direction of the saccade. Although there was no precise measure of where the saccade landed, it was reasonable to assume that it landed on the reappearing ball if tracking commenced immediately. If the saccade was predictive, the location was specified only by the previous calibration with the adults' eye movements. In this case, there is some possibility that the infant undershot or overshot the location at which the ball would reappear, but this measurement error would not affect whether the timing of the saccade was predictive or reactive, which was the question addressed by these analyses.

Three dependent measures were calculated: (1) *Gaze shift*: the time delay between the first frame of the ball's reappearance and the infant's redirection of gaze to that same location on the far side of the occluding surface. Positive values indicate that the redirection of gaze preceded the reappearance of the ball, whereas negative values indicate that the redirection of gaze lagged behind the reappearance of the ball. (In the virtual occlusion condition, the near and far edges of the occluder were specified by the gradual deletion and accretion of the ball's texture. It was thus possible to score gaze shift in this condition in the same way that it was scored in the other three conditions.)

(2) *Percent predictive tracking*: the percentage of trials yielding usable data on which gaze shift is positive or is negative by less than -200 ms. Note that 200 ms corresponds to the time necessary to plan and execute a saccade (Engel, Anderson, & Soechting, 1999; Rosander & von Hofsten, 2004). (3) *Fixation duration*: the duration of fixation at the occluder edge following the disappearance of the ball.

For gaze shift and fixation duration, a mean value for each participant was computed for each age by stimulus condition. Means were based on the number of replicates available for each of these conditions. If there were no observations for a participant at a particular stimulus by delay condition, mean imputation was used to interpolate missing values (Little & Rubin, 2002), and one degree of freedom was removed for each interpolated value (Dodge, 1985). There were 2 out of 288 missing observations for the gaze shift and percent predictive tracking measures, and 4 out of 288 for the fixation measure.

Results

Effects of Age and Condition

The first analysis examined the effects of age and stimulus type on two of the three dependent variables using a multivariate analysis of variance (MANOVA). Because gaze shift and percent predictive tracking were highly correlated, $r = .80$, only gaze shift and fixation duration were included as dependent measures in the MANOVA. The independent variables were *age* (5, 7, 9 months), *condition* (occlusion, disappearance, implosion, virtual occlusion), and *delay* (delay, no delay). The results revealed a main effect of age, Wilks's $\lambda = .72$, $F(4, 64) = 2.80$, $p < .05$, and of condition, Wilks's $\lambda = .86$, $F(6, 196) = 2.59$, $p < .02$, but the interaction between these two variables was not significant, Wilks's $\lambda = .91$, $F(12, 196) = 0.78$, *ns*. There was also a main effect of delay, Wilks's $\lambda = .54$, $F(2, 32) = 13.80$, $p < .0001$. In order to unpack these results, mixed design analyses of variance were conducted on each dependent variable separately.

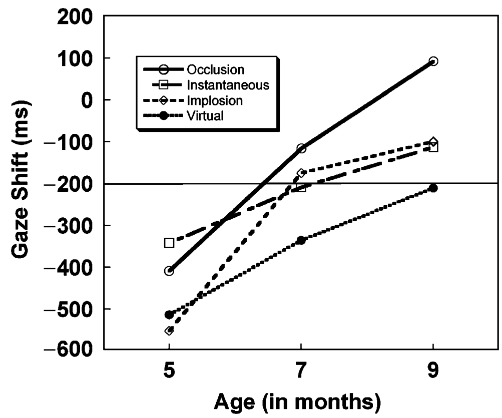

Figure 4. Mean gaze shift as a function of age and stimulus condition (occlusion, instantaneous disappearance, implosion, virtual occlusion). Note that gaze shifts greater than -200 ms were scored as predictive.

Gaze Shift

Gaze shift times increased as a function of age, $F(2, 31) = 3.59$, $p < .04$, and differed marginally as a function of condition, $F(3, 97) = 2.55$, $p = .06$ (see Figure 4), but these two variables did not interact, $F(6, 97) = 0.64$, *ns*. Planned comparisons revealed that gaze shift times were significantly faster in the occlusion condition relative to the other three conditions, $t(35) = 2.49$, $p < .01$, as well as relative to just the disappearance and implosion conditions, $t(35) = 1.75$, $p < .05$. (These as well as all subsequent planned comparisons were based on predicting that performance in the occlusion condition would be better than performance in each of the other three conditions; thus one-tailed *t* tests were used.) There was also a significant effect of delay, $F(1, 31) = 8.62$, $p < .01$; the overall lag in gaze shift times was faster in the delay condition than in the no-delay condition. This difference averaged between 100 and 200 ms, and is attributable to more time available to redirect gaze before the ball reappeared in the delay condition. Delay did not interact with either age, $F(2, 31) = 0.63$, *ns*, or condition, $F(3, 97) = 1.15$, *ns*, but the age by condition by delay interaction was significant, $F(6, 97) = 2.22$, $p < .05$. This difference was primarily attributable to 9-month-old infants in the occlusion condition showing faster gaze shifts in the no delay than in the delay condition, and infants in all the other age by stimulus-type conditions

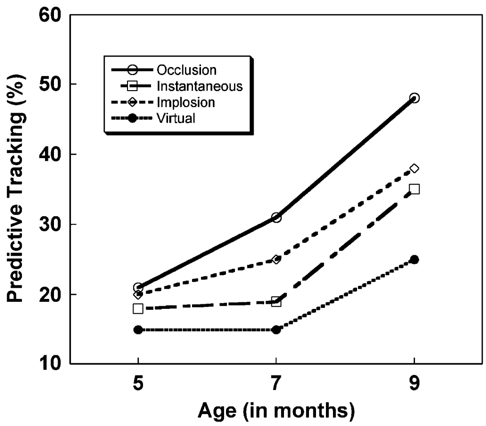

Figure 5. Mean percent predictive tracking as a function of age and stimulus condition (occlusion, instantaneous disappearance, implosion, virtual occlusion).

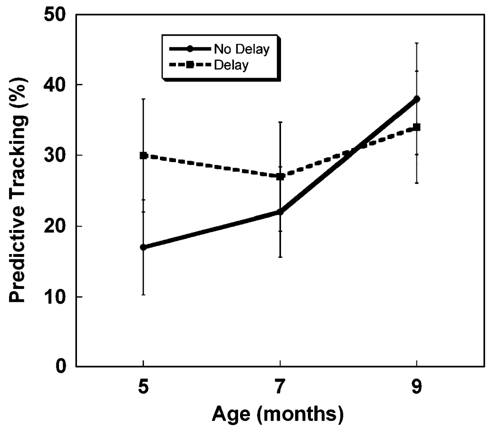

Figure 6. Mean percent predictive tracking as a function of age and stimulus condition (occlusion, instantaneous disappearance, implosion, virtual occlusion). Error bars represent standard errors of the mean.

showing either no difference or faster gaze shifts in the delay condition.

Percent Predictive Tracking

A second mixed design analysis of variance (ANOVA) was conducted with percent predictive tracking as the dependent variable. There was a significant effect of condition, $F(3, 97) = 3.14$, $p < .03$ (see Figure 5). Planned comparisons revealed that infants showed a higher percentage of predictive tracking trials in the occlusion condition relative to the other three conditions, $t(35) = 2.60$, $p < .01$, as well as relative to just the disappearance and implosion conditions, $t(35) = 2.11$, $p < .025$. (Note, however, that these planned comparisons did not include the 5-month-old data because a significant number of infants at this age failed to show predictive tracking in one or more conditions, which skewed the data.) There was also a significant age by condition by delay interaction, $F(6, 97) = 2.21$, $p < .05$. The primary reason for this three-way interaction was that the difference in the percentage of predictive tracking as a function of delay decreased between 5 and 7 months of age, and by 9 months of age the percentage of predictive tracking was greater with no delay than with a delay; this trend was especially apparent in the occlusion condition (see Figure 6).

Fixation Duration

A mixed design ANOVA showed a trend toward an increase in fixation duration as a function of age, $F(2, 29) = 2.79$, $p < .08$, and an effect of stimulus condition, $F(3, 95) = 4.14$, $p < .01$. Planned comparisons revealed that fixation times were shorter in the occlusion condition than in the other three conditions, $t(35) = 2.42$, $p < .02$, $t(35) = 2.81$, $p < .005$, $t(35) = 2.81$, $p < .005$, for disappearance, implosion, and virtual occlusion, respectively (see Figure 7). The age by condition interaction was not significant, $F(6, 95) = 1.34$, *ns*, but there was a main effect of delay, $F(1, 29) = 13.70$, $p < .001$, with longer fixations in the delay condition, presumably reflecting the greater amount of time available for fixation before the ball's reappearance elicited a reactive saccade.

In order to determine whether longer fixation times were related to less predictive tracking in the disappearance, implosion, and virtual occlusion conditions, correlation coefficients were computed. Contrary to this prediction, the mean correlations between gaze shift and duration of fixation were 0,

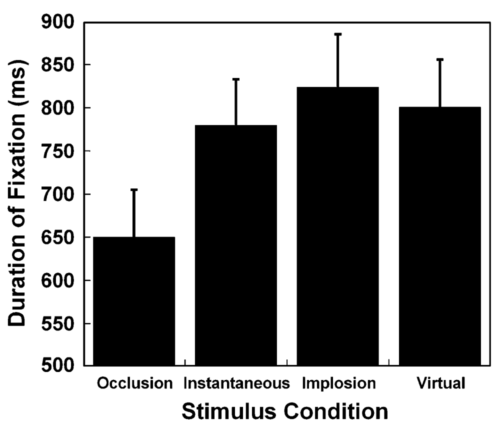

Figure 7. Mean duration of fixation at the forward edge of the occluding surface as a function of stimulus condition (occlusion, instantaneous disappearance, implosion, virtual occlusion). Error bars represent standard errors of the mean.

− .09, and .10, for disappearance, implosion, and virtual occlusion, respectively. Similarly, the mean correlations between percent predictive tracking and duration of fixation were − .29, − .04, and .28, for disappearance, implosion, and virtual occlusion, respectively. By contrast, the mean correlations between gaze shift and percent predictive tracking were .81, .85, and .62 for disappearance, implosion, and virtual occlusion, respectively.

Effects of Practice

On every block of trials, infants were presented with each of the four stimulus types twice (delay and no delay). Although a few infants were missing data from one or more trials, no infant was missing data from both delay and no-delay trials in the same stimulus by block condition. It was thus possible to compare mean gaze shift performance across blocks by collapsing across delay condition. An ANOVA was conducted to determine whether gaze shift performance improved from the repetition of the trials across the first two blocks. The results revealed no difference in gaze shift performance as a function of block, $F(1, 31) = 1.52$, *ns*. A subset of infants ($n = 17$) completed three blocks of trials, but the results assessing the effect of three blocks on gaze shift performance were also nonsignificant, $F(2, 30) = 1.52$, *ns*.

Responses Following Reappearance of Ball

On trials when infants shifted their fixation to the far side of the occluding surface before the reappearance of the ball, they could wait until the ball reappeared, look back at the location where the ball disappeared, or look somewhere else. As summarized in Table 1, 5-month-old infants were more likely to look back or look somewhere else than to wait for the reappearance of the ball; 7-month-old infants waited for the reappearance of the ball on approximately 50% of the predictive trials; and 9-month-old infants waited for the reappearance of the ball on a majority of trials. A chi-square analysis revealed that these different responses as a function of age were significant, $\chi^2(4) = 9.47$, $p = .05$.

Table 1
Number of Trials on Which Infants Executed One of Three Responses Before the Reappearance of the Ball as a Function of Age[a]

Age (years)	# Predictive trials	Responses: Wait for ball	Look at prior location	Look at new location
5	48	19	20	9
7	59	30	18	11
9	75	49	14	12

Note.
[a]Limited to trials on which predictive tracking occurred.

Discussion

Three different measures converged to show that infants were sensitive to the accretion and deletion of texture at an edge as specifying the persistence of the occluded moving object. As reported in previous studies, infants stopped tracking and briefly fixated the edge of the occluding surface when the moving object disappeared. If the ball disappeared via kinetic occlusion, infants fixated the edge of the occluding surface for a shorter period of time than if the ball disappeared via instantaneous disappearance, implosion, or virtual occlusion. Infants in the occlusion condition also executed earlier saccades (i.e., gaze shifts) to the location where the ball would reappear, and showed predictive tracking on a greater percentage of trials. Taken together, these results suggest that infants' predictive tracking is based on more than extrapolating the trajectory of the previously visible target. It appears that the manner by which the target disappears also affects predictive tracking.

Relation Between Occlusion and Predictive Tracking

There are a number of reasons why infants might have shown more predictive tracking in the occlusion condition than in any of the other three conditions, including: (1) they interpreted instantaneous disappearance or implosion as specifying that the ball was annihilated or at least followed a discontinuous spatiotemporal trajectory, (2) they interpreted kinetic occlusion as specifying the continuity of the rolling ball, or perhaps (3) they were sensitive to both optical transformations. In order to address the first possibility that infants were sensitive to the optical information specifying the spatiotemporal discontinuity of the ball, it is first necessary to establish that infants' predictive tracking was not merely disrupted in the nonocclusion conditions.

An unintended reason why instantaneous disappearance might interfere with predictive tracking is that it introduces a visual transient into the optic array (Jonides & Yantis, 1988). This explanation is unlikely, however, given that a similar decrement in performance was obtained in the implosion condition, which was equivalent to the occlusion condition in terms of the rate of the ball's disappearance. The one difference between implosion and occlusion is that accretion and deletion of texture do not occur along a fixed contour in the former condition, but this difference does not introduce a visual transient into the event.

A second reason why predictive tracking may have been disrupted in the disappearance and implosion conditions was suggested by one of the reviewers. Unlike the visual event associated with the occlusion condition, the visual event associated with the disappearance and implosion conditions is completely unfamiliar and discrepant to infants. Previous research (e.g., Aguiar & Baillargeon, 1999; Spelke et al., 1995; Xu & Carey, 1996) suggests that infants tend to look longer at events that are novel or represent violations of possible events. In the case of the disappearance and implosion conditions, infants looked longer at the locus of the ball's disappearance than they did during the occlusion condition. It is thus possible that infants showed less predictive tracking in these conditions because they looked longer at the location of the disappearance and were consequently less likely to saccade to the far side of the occluder before the ball reappeared. Although plausible, the data revealed that longer looking times at the occluder edge are not responsible for infants showing less predictive tracking in the disappearance and implosion conditions, because the correlations between fixation times and predictive tracking were low and nonsignificant. Moreover, it is questionable as to whether or not infants even perceived the disappearance event as discrepant: A sample of 10 adults viewing this same event did not notice anything unusual about the ball's disappearance until they were explicitly instructed to evaluate the naturalness of the event. Although it is possible that infants might detect the abrupt disappearance event as discrepant even though it was not explicitly detected by adults, we suspect that it is quite unlikely given that the temporal duration differentiating the disappearance and occlusion events was a mere 300 ms.

If predictive tracking did not decline because of some novelty effect or visual transient associated with instantaneous occlusion or implosion, it is conceivable that infants were sensitive to the spatiotemporal discontinuity associated with the disappearance of the ball. In fact, infants, like adults, may have perceived these transformations as specifying that objects were going out of existence. This interpretation would decrease infants' likelihood to continue to track the ball, and indeed, this is the result that was obtained. Converging evidence for this interpretation comes from previous studies suggesting that infants are sensitive to the spatiotemporal discontinuity of moving objects (Spelke et al., 1995; Xu & Carey, 1996). Nevertheless, the interpretation for the current finding remains somewhat tentative because it is difficult to determine whether impaired tracking performance was directly a function of interpreting instantaneous disappearance or implosion as a discontinuous event or whether performance appeared impaired only because it was facilitated by the occlusion condition. In order to disentangle these two possibilities it would be necessary to include a baseline condition to determine whether instantaneous disappearance and implosion specifically impaired performance or simply did not facilitate performance.

Let us now consider whether infants' predictive tracking was sensitive to the occlusion information specifying the spatiotemporal continuity of the moving ball. The findings from the current experiment suggest that the presence of occlusion information, in the form of accretion and deletion of texture at an edge, facilitates predictive tracking. It is not entirely clear, however, whether this information alone is sufficient to support predictive tracking. In the previously cited study by Kaufman et al. (2005), infants showed similar EEG responses to objects disappearing via kinetic occlusion and virtual occlusion. By contrast, tracking in the current study was less likely following virtual occlusion than following kinetic occlusion. This difference may be attributable to different task demands. In the former study, infants simply observed a stationary object that was gradually occluded, whereas infants in the current study were required to use this optical transformation to anticipate the reappearance of a moving object and thereby control predictive tracking. The visibility of the near and especially the far edge of the occluder may have been necessary for the infant to anticipate the location at which the ball would reappear. A somewhat different interpretation for the difficulty presented by the current virtual occlusion condition is that a stimulus conflict was created by the virtual occluder appearing continuous with the wooden floor. As the ball was gradually occluded, it appeared to be covered by the patterned floor, which may have interfered with the continued tracking of the ball. This anomaly was avoided in the studies of Kaufman et al. (2005) and Scholl and Pylyshyn (1999), because the background and the occluder both consisted of a flat homogeneously textured surface. Additional research is necessary to assess whether either factor contributes to poorer predictive tracking with a virtual occluder.

Although performance in the virtual occlusion condition reveals a limitation in infants' perception of occlusion information, the virtual occlusion condition also provides a baseline condition for evaluating whether the fully specified occlusion stimulus facilitates predictive tracking. In essence, the two conditions were equivalent except for the presence of a visible occluding surface in the occlusion condition. Thus, improved performance in this condition relative to the virtual condition must have been attributable to the facilitating effects of fully specified occlusion.

Development of Predictive Tracking

Consistent with previous studies on infants' predictive tracking, all three measures of predictive tracking revealed that this behavior improved between 5 and 9 months of age. Intriguingly, this improvement did not interact with stimulus condition, suggesting that infants were sensitive to the occlusion information for facilitating predictive tracking by 5 months of age. It is not entirely clear, however, that predictive tracking reflected the same level of object knowledge at each of the three ages. At 5 months of age, infants did not wait for the reappearance of the ball following occlusion on a majority of the trials. By 7 months of age, infants waited for the reappearance of the ball on about half of the trials, but it was not until 9 months of age that infants waited for the reappearance of the ball on a clear majority (75%) of the trials. This finding suggests that the perceived continuity of the object was quite fragile at 5 months of age, and that the expectation for the reappearance of the ball following gaze shift had a very brief refractory period. Apparently, this refractory period continues to increase from 5 to 9 months of age and might be attributable to the increasing strength of the object representation (Munakata, 2001).

What factors contribute to these developmental improvements? Between 5 and 9 months of age infants develop the capacity for visually directed grasping, sitting without support, and locomoting independently (Bertenthal & von Hofsten, 1998). All of these skills provide infants with increasing opportunities to experience more and different kinds of visual events. Most of these events include spatiotemporal transformations, and thus the visual experience accumulated from these events contributes to infants' knowledge of briefly occluded moving objects. Unlike the hypothesized effects of long-term visual experience, short-term experience provided by the presentation of multiple blocks of trials did not lead to an improvement in predictive tracking. Although somewhat surprising, given the evidence for improved predictive tracking following 2 min of tracking without an occluder (Johnson, Amso et al., 2003), this finding is consistent with other reports suggesting that infants do not show evidence of learning to predict the reappearance of moving objects across multiple trials of an experiment (Gredebäck et al., 2002; Rosander & von Hofsten, 2004). (This type of learning should be distinguished from the within-trial learning that did occur in the study reported by Rosander and von Hofsten (2004). In the case of the current experiment, there was no opportunity to assess within-trial learning because each trial consisted of the ball moving behind the occluder once rather than oscillating back and forth.) One striking difference between these studies is that the one showing learning involved only a single stimulus condition, whereas the others involved multiple conditions demanding different responses to different conditions. Conceivably, the need to modify responses from trial to trial or across blocks interfered with any improvement that might have accrued through learning.

Another candidate for explaining developmental improvements in predictive tracking involves the reaction times associated with programming a saccade following the disappearance of a moving target. Infants showed greater predictive tracking in the delay condition when they had additional time to anticipate the reappearance of the ball. It is unlikely that this increase in predictive tracking was simply a function of more time to execute a random saccade, because in that case we would have expected a main effect of delay and no interactions. Instead, delay interacted with age and condition for both gaze shift and percent predictive tracking, suggesting that the effect of the delay was more systematic than what would be expected by random improvements attributable to more time. This finding, thus, suggests that infants sometimes expected the ball to reappear, but were simply too slow to disengage from the edge of the occluder or too slow to respond to the stored motion information specifying the perceived direction of the occluded ball. Interestingly, infants have shown predictive tracking when targets are occluded for as little as 300 ms (e.g., Rosander & von Hofsten, 2004). Thus, the probability of executing a saccade before the object reappears does not depend exclusively on occlusion exceeding some minimum time span, but instead is most likely a function of multiple factors, including the velocity of the ball, the width of the occluder, and the nature of the disappearance. In sum, the results from this analysis suggest that predictive tracking should not be interpreted as a definitive measure of infants' anticipations of the reappearance of a briefly occluded object, as it can sometimes underestimate infants' expectations of the continuity of moving objects.

Predictive Tracking and Object Knowledge

Previous findings from experiments on the perception of spatiotemporal displacements of objects and predictive tracking have been used to draw conclusions about the development of the object concept or object permanence (e.g., Aguiar & Baillargeon, 1999; Johnson, Amso et al., 2003; Spelke et al., 1992; von Hofsten et al., 2000). Both of these terms imply that infants possess specific knowledge about the properties of objects, but it is rarely stated whether this knowledge is embodied in the actions of infants or instead constitutes explicit and generalizable knowledge. In the case of the current results, this distinction seems highly relevant because infants showed better predictive tracking when the ball disappeared via kinetic occlusion than via the other optical transformations, suggesting some knowledge of the permanence of objects. Yet, it is not clear whether this knowledge was associated exclusively with the control of visual tracking or whether this knowledge was independent of the task and could be accessed and generalized to other tasks.

One important source of evidence for addressing this question is to consider how adults visually track moving objects that are briefly occluded. Of central importance to understanding adults' performance is the finding that visual pursuit cannot typically be initiated or maintained in the absence of a visual target (Barnes, Donnelly, & Eason, 1987). Thus, tracking should be impaired if objects become invisible during visual pursuit, and indeed disruptions in tracking occur if objects blink off for as little as 200 ms. If, however, the disappearance is the result of an occluding surface, then visual pursuit continues with a negligible loss in velocity for durations ranging between 200 and 1,200 ms (Churchland, Chou, & Lisberger, 2003). For very brief occlusion durations, observers do not have sufficient time to (1) detect the occlusion or blinking, (2) interpret its meaning, and (3) then adjust their tracking accordingly. Instead, this process must occur automatically, suggesting a more direct mapping between the perception of the optical transformation and the control of visual tracking. Bennett and Barnes (2006) suggest that a veridical representation of extrapolated object velocity could be obtained from persistent neural activity in the frontal eye fields (FEF), but this occurs only for visible and briefly occluded object motion, and not for object motion that blinks off. This stimulus-driven maintenance of occluded object motion would explain why transient occlusions cause minimal disruptions to object tracking.

Such evidence suggests that the visuomotor system for adults *automatically* interprets a transient occlusion as specifying object persistence. Given that adults do not have sufficient time while tracking an object to cognitively evaluate the meaning of the optical transformation, it is even less likely that infants would be able to control their predictive tracking in a more explicit fashion. Two implications follow from these conclusions:

(1) The visuomotor system is specifically organized to maintain a representation for transiently occluded objects, and thus this sensitivity to kinetic occlusion is embodied in the functioning of predictive tracking. Conversely, the visuomotor system is not organized to maintain a representation for objects that abruptly disappear or implode, and thus predictive tracking performance is disrupted in these conditions. It is thus reasonable to conclude that infants possess some embodied knowledge of the optical transformations that support or do not support object continuity. This knowledge is operationalized in terms of whether or not the disappearing object maintains a representation that the visuomotor system then uses to control visual tracking.

(2) The object knowledge embodied in predictive tracking does not necessarily generalize to more explicit knowledge about objects. More direct evidence for this conclusion was reported by Berthier et al. (2001) in a study testing predictive reaching by 9-month-old infants. Although these infants predictively reached for a briefly occluded moving ball, they were not able to find the ball behind the occluder when it did not reappear. Presumably, the retrieval of the ball from behind the occluder required explicit recall of the ball's location, whereas predictive reaching did not require any explicit recall, only prospective control within a very brief time span. Thus, it is prudent to remain cautious in interpreting the implications of the current findings for understanding infants' explicit knowledge about objects.

In sum, the current evidence suggests that infants are sensitive to the optical transformations involved in the appearance and disappearance of objects for specifying continuity and use this information for predictive tracking. It is not, however, necessary for them to understand explicitly how these object transformations relate to the continuing existence of objects. The task of predictive tracking requires neither recall nor offline reasoning about objects or events. This conclusion is not meant to imply that infants are incapable of explicitly representing object continuity, only that this understanding is unnecessary for predictive tracking. It remains an open question as to when infants develop explicit knowledge of the object transformations used in the current research and whether the embodied knowledge associated with these transformations is used to bootstrap a more explicit understanding at some later time.

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