Differential Contributions of Development and Learning to Infants’ Knowledge of Object Continuity and Discontinuity

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Sixty infants divided evenly between 5 and 7 months of age were tested for their knowledge of object continuity versus discontinuity with a predictive tracking task. The stimulus event consisted of a moving ball that was briefly occluded for 20 trials. Both age groups predictively tracked the ball when it disappeared and reappeared via occlusion, but not when it disappeared and reappeared via implosion. Infants displayed high levels of predictive tracking from the first trial in the occlusion condition, and showed significant improvement across trials in the implosion condition. These results suggest that infants possess embodied knowledge to support differential tracking of continuously and discontinuously moving objects, but this tracking can be modified by visual experience.

Infants’ knowledge of objects is often conceptualized in terms of existence constancy—Does the infant believe that an object that disappears from sight goes out of existence? According to Piaget (1937/1954), infants’ knowledge of objects is restricted to their actions until approximately 9 months of age, and thus out of sight is out of mind. Although this claim has been challenged by numerous researchers in the past two decades (e.g., Baillargeon, 1987; Meltzoff & Moore, 1998; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Wynn, 1992), virtually all of the research has focused exclusively on showing infants’ knowledge of occluded objects, that is, objects that continue to exist, but are temporarily not visible.

This focus on only occlusion is somewhat misleading, because objects also disappear when they are no longer illuminated or when they fade into the distance. Moreover, there are exceptions to the persistence of objects, such as when they go out of existence because their substance dissolves, disintegrates, or evaporates (Gibson, 1979). Unlike the preceding transformations that are all perceptually reversible, these latter change are irreversible. Currently, little is known about infants’ sensitivity to these phenomenally discontinuous and irreversible changes in objects.

For adults, the continuing existence of objects is specified by the lawful manner in which they disappear and reappear behind occluding surfaces (Gibson, Kaplan, Reynolds, & Wheeler, 1969; Michotte, 1950; Michotte, Thines, & Crabbe, 1964/1991). The disappearance of a surface by dissolution, for example, can be distinguished from its disappearance by occlusion if the observer is sensitive to the differences in the optical transformations at the occluding edges. In general, continuity is specified by the progressive deletion of texture at the leading edge of an occluder and the subsequent accretion of texture at the trailing edge, whereas discontinuity is specified by the abrupt disappearance or the deletion of texture that does not proceed along a fixed contour, such as would occur during implosion (Gibson et al., 1969; Scholl & Pylyshyn, 1999).

Empirical evidence reveals that adult observers respond differently to objects that disappear via occlusion than via abrupt disappearance or implosion.

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Scholl and Pylyshyn (1999), for instance, tested adult observers in a multiple object tracking task, and reported that performance was not impaired when the objects were briefly occluded during their movement on the screen. By contrast, performance was significantly impaired when moving objects disappeared for equivalent amounts of time but the optical transformation did not specify continuity. Similarly, Churchland, Chou, and Lisberger (2003) report no disruption in adults’ visual pursuit of a moving target if it disappears and reappears via occlusion-disocclusion for durations ranging between 200 and 1,200 ms, but significant disruptions if objects blink off for as little as 200 ms. In both these tasks, observers are not necessarily aware of the differences in the optical transformations, but respond very differently, suggesting that the interpretation of this information is based on embodied knowledge within the visuomotor system. Given the adaptive importance of tracking objects via the visuomotor system, it is conceivable that this knowledge for detecting continuous versus discontinuous movements develops at a very young age.

An early study conducted by Bower (1967) examined infants’ sensitivity to the optical transformations specifying object continuity and discontinuity, but methodological problems rendered the results difficult to interpret. More recently, 6-month-old infants revealed oscillatory electroencephalogram (EEG) activity recorded over right temporal channels while viewing an object that was occluded gradually, but not while viewing the same object disintegrate as an occluding edge moved over it (Kaufman, Csibra, & Johnson, 2005). Increased gamma oscillations are associated with object maintenance, which has been interpreted as consistent with infants perceiving objects as persisting (cf. Kaufman, Csibra, & Johnson, 2003). This evidence converges with recent neurophysiological findings in nonhuman primates showing greater neural activity in the superior temporal sulcus when a target disappears and reappears via gradual occlusion and disocclusion rather than via an abrupt optical transformation inconsistent with its continued existence (Baker, Keyser, Jellema, Wicker, & Perrett, 2001).

Although the preceding EEG studies are suggestive of infants’ knowledge of the continuity or discontinuity of briefly occluded objects, behavioral evidence is necessary to confirm that they use this knowledge. One paradigm used successfully for testing infants’ representation of moving objects involves measuring their predictive tracking (e.g., Gredebäck & von Hofsten, 2004; Johnson, Amso, & Slemmer, 2003; Kochukhova & Gredebäck, 2007; Rosander & von Hofsten, 2004; Von Hofsten, Kochukhova, & Rosander, 2007). In most studies, infants track a linearly moving object that disappears briefly behind an occluder. After tracking is interrupted at the occluding edge, infants execute one or more saccades to relocate the object. If infants saccade to the far edge of the occluder in anticipation of the object’s reappearance, they are credited with predictive tracking. The consensus from these studies is that infants predictively track objects by 4–6 months of age, presumably because of knowledge of object continuity. In spite of the empirical evidence supporting this conclusion, critics caution that predictive tracking could be simply a function of some form of contingency learning (Bremner et al., 2007; Goldberg, 1976). This interpretive issue concerning predictive tracking has yet to be completely resolved, and thus, age differences could be a function of development or learning or both.

Consider, for example, a recent study by Bertenthal, Longo, and Kenny (2007) testing whether or not 5- to 9-month-old infants were more likely to predictively track an object occluded via deletion and accretion of texture than via other stimulus transformations that were not consistent with object continuity (Bertenthal et al., 2007). Although the results revealed that infants were more likely to predictively track the object following its disappearance via the gradual deletion of its texture and that this difference increased with age, it is not clear whether age changes are a function of development or learning during the experiment. In this study, four stimulus conditions were randomly presented from 1 trial to the next for up to 32 trials. Thus, age differences may have reflected developmental changes in infants’ knowledge of object continuity, or instead changes in learning to expect the reappearance of the occluded object. The design of this study precluded a definitive conclusion because changes in learning could have interacted with developmental changes in sensitivity to the different stimulus transformations from one trial to the next.

The following predictive tracking study was conducted to clarify whether or not age changes in infants’ knowledge of deletion and accretion of an object’s surface texture for specifying object continuity and discontinuity is a function of development or learning or both. By presenting infants with as many as 20 repetitions of the same stimulus transformation, we were able to carefully assess whether infants learned about the reappearance of the object from previous trials via contingency learning or were already predisposed to represent...
the object when it was first occluded from view. Five- and 7-month-old infants were tested for predictive tracking of a ball that rolled across the screen, and then reversed direction and continued until it returned to its starting location. Unlike previous studies that used two-dimensional stimuli appearing to move on a flat screen, the stimulus display included the projection of a three-dimensional scene with perspective and cast shadows to provide relative depth information as the ball rolled back and forth (see Figure 1). The moving ball disappeared and then reappeared from view in the middle of its path via occlusion–disocclusion or implosion–explosion. As previously discussed, the former stimulus transformation is perceived by adults as specifying that the object continues behind the occluder, whereas the latter is perceived as specifying that the object rapidly shrinks to nothing or rapidly expands from nothing to a bounded object.

Method

Participants

Sixty healthy full-term infants participated in this study. Thirty infants were tested at 5 months of age (12 girls, 18 boys); 15 were tested in each of the two stimulus conditions ($M = 5$ months 1 day, $SD = 1.6$ days for the occlusion–disocclusion condition; $M = 5$ months 1 day, $SD = 3.0$ days in the implosion–explosion condition). An equivalent number of infants were tested in both conditions at 7 months of age (19 girls, 11 boys; $M = 7$ months 1 day, $SD = 2.5$ days in the occlusion–disocclusion condition; $M = 7$ months 1 day, $SD = 1.9$ days in the implosion–explosion condition). Four additional infants were tested in the occlusion–disocclusion condition and eight additional infants were tested in the implosion–explosion condition but were excluded from the analysis because the eye tracker was unable to record a stable corneal reflection (3), computer problems (3), or lack of attention (6). Participants were primarily from middle-class families and were Caucasian. They were contacted by mail based on birth and medical records, and parents signed a consent form before the study began.

Stimuli and Apparatus

Gaze was measured using a Tobii ET-17 eye tracker (Stockholm, Sweden). The system tracked gaze of both eyes with an infrared eye tracker integrated in a 17-in. monitor (measurement error $< 1^\circ$ of visual angle). During calibration of the infant’s eye gaze, a blue and white sphere (extended diameter $= 3.3^\circ$) expanded and contracted in synchrony with a sound at each of 16 calibration points on the screen.

Infants were tested with one of two movies displaying a multicolored ball (diameter $= 3.1^\circ$) appearing to roll horizontally on the floor of a projected three-dimensional room (horizontal extension $= 47.5^\circ$), designed with multiple depth cues (see Figure 1). The ball rolled at a velocity of $6.4^\circ$/s. In the middle of its trajectory, the ball was completely hidden by an occluder (horizontal extension $= 12.7^\circ$) for 1,500 ms. The transition from fully visible to invisible or vice versa lasted approximately 480 ms. Initially the ball moved from the left side of the room, then bounced off the right wall and rolled back to the starting position (see Figure 1). Each infant was presented with one of the two stimulus events: In the occlusion–disocclusion condition, the ball gradually disappeared behind the edge of the occluding screen and gradually reappeared at the opposite edge (see Figure 1A). In the implosion–explosion condition, the ball rapidly shrunk in size (as it continued to move) and disappeared as it reached the edge of the occluder and rapidly expanded in size as it reappeared at the opposite edge of the occluder (see Figure 1B). Both stimulus transformations occurred while the ball continued to translate and involved the deletion and accretion of texture, except that the former transformation occurred along the occluder edge whereas the latter

Figure 1. A single frame from the stimulus movie showing a multicolored ball rolling across the screen.

Note. Pictorial depth cues depict the ball as rolling behind the occluding screen. Panels (A) and (B) depict screen shots during the ball’s disappearance in the occlusion–disocclusion and implosion–explosion conditions, respectively. Panels (C) and (D) represent the area of interest for scoring the fixations.
transformation corresponded to either a radial contraction or expansion of the texture. These stimuli were rendered with 3ds Max (Autodesk Inc., San Rafael, CA) and assembled as a movie with Macromedia Director. The movies were silent with the exception of two “bouncing sounds” occurring once at the beginning of each trial when the ball bounced up and down at its starting location, and a second time when the ball changed direction. After the conclusion of each trial, infants were presented with one of six different movies with sound to attract their attention to the middle of the screen before the next trial began.

Procedure

Infants sat in a safety car seat with their eyes approximately 60 cm from the Tobii monitor. They were presented with the stimulus alternately translating from left to right or right to left for 20 trials. One group of infants was presented with the occlusion–disocclusion stimulus and the other group with the implosion–explosion stimulus. The entire procedure lasted no more than 15 min.

Data Analysis

The eye tracker stored coordinates of gaze for both eyes, a measurement of data quality (5-point scale), a time stamp, and a record of the stimuli. The data were analyzed using the average of the two eyes weighted by the quality indicator (only highly accurate data points for each eye were included). A trial was only included in the analysis if infants attended to the moving ball both before and after the occlusion event. Fixations were recorded as predictive if they occurred within 200 ms of the ball’s reappearance (see below for the justification of this criterion) and were located within an area of interest (AOI) defined by the top and bottom edges of the occluder in the vertical direction and within an 9.3° wide area (3 times the diameter of the ball) in the horizontal direction. This area began 3.1° inside the occluding edge and extended to 6.2° beyond the edge (see Figures 1C and D).

Three different measures of infants’ performance were analyzed. The first was gaze shift, calculated as the time difference between the ball’s reappearance and the infant’s redirection of gaze to that previously defined AOI. 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 ball’s reappearance. The second measure was percent predictive tracking, calculated as the percentage of trials on which gaze shift was > −200 ms. This criterion for categorizing a gaze shift as predictive is based on the average reactive saccadic latency to moving targets by adults (197 ms, SD = 28 ms; Engel, Anderson, & Soechting, 1999), and has been used previously to distinguish reactive from predictive saccades in occlusion tasks (Bertenthal et al., 2007; Gredebäck & von Hofsten, 2004). The final measure was duration of fixation at the location where the ball disappeared. As previously mentioned, infants’ smooth tracking of the rolling ball is interrupted by the occluder. The duration of fixation is a measure of infants’ interest in the stimulus transformation.

Results

An analysis of variance was conducted with each of the three dependent measures (gaze shift, percent predictive tracking, duration of fixation) to assess the effects of age (5 and 7 months) and stimulus type (occlusion–disocclusion, implosion–explosion) in a 2 × 2 between-subjects design. The first analysis with gaze shift as the dependent variable revealed that saccadic latencies to the AOI were shorter in the occlusion–disocclusion than in the implosion–explosion condition, \( F(1, 56) = 31.97, p < .0001, \eta^2_p = .36 \), and decreased with age, \( F(1, 56) = 40.70, p < .0001, \eta^2_p = .42 \) (see Figure 2). Similarly, the second analysis with percent predictive tracking as the dependent variable revealed more predictive tracking in the occlusion–disocclusion condition than in the implosion–explosion condition, \( F(1, 56) = 54.14, p < .0001, \eta^2_p = .49 \).

![Figure 2. Mean gaze shift for 5- and 7-month-old infants as a function of stimulus type.](image-url)

Note. Positive values indicate that infants anticipated the reappearance of the ball; negative values indicate that infants’ redirection of gaze lagged behind the reappearance of the ball. Error bars represent standard errors of the mean.
percent predictive tracking also improved with age, \(F(1, 56) = 41.73, p < .0001, \eta^2_p = .43\) (see Figure 3). The final analysis with duration of fixation as the dependent measure revealed that 5-month-old infants fixated the occluding edge for less time than 7-month-old infants, \(F(1, 56) = 24.81, p < .0001, \eta^2_p = .31\), but, unlike the preceding two analyses, there was no effect of stimulus type, \(F(1, 56) = .004, p = .95, \eta^2_p = .006\) (see Figure 4). None of the interactions between stimulus type and age were significant.

At a more descriptive level, Figure 5 shows the distribution of gaze points before, during, and after the occlusion event for 5- and 7-month-old infants. It is noteworthy that this distribution is more variable for the older infants, which could be attributable to their predicting the reappearance of the ball more frequently and earlier, but then not waiting for the ball to reappear and instead searching around the occluder. Bertenthal et al. (2007) reported that it was not until 9 months of age that infants waited on a majority of trials for the reappearance of the ball. Although this interpretation for explaining the distribution of gaze points is somewhat speculative, it is supported by the histogram of fixations for both 5- and 7-month-old infants (see Figure 6). As can be seen, 7-month-old infants predict the reappearance of the ball earlier and more frequently than do 5-month-old infants. In addition, it should be noted that 5-month-old infants often looked away from the occluder during the time that the ball was behind it; thus many of their gaze points would not appear on the occluder.

The final analysis was designed to explore whether infants’ performance was partly or completely attributable to learning to expect the reappearance of the ball at the far occluder edge before it appeared there. Infants tracked the rolling ball for a mean of 16.7 trials (\(SD = 3.71\) trials). If infants learned from previous experience, then the percent predictive tracking should increase with the number of trials. A mixed model analysis of variance (ANOVA) with age and stimulus type as between-subjects variables, and trials as the repeated measure (missing data were replaced with group means, and degrees of freedom were reduced accordingly) revealed no significant linear trend for percent predictive tracking as a function of trials, \(F(1, 56) = .003, p = .954, \eta^2_p < .001\). Trials did, however, interact with stimulus type, \(F(1, 56) = 5.11, p = .028, \eta^2_p = .08\), but not with age, \(F(1, 56) = .029, p = .87, \eta^2_p = .001\) (see Figure 7). Kochukhova and Gredebäck (2007) reported that 6-month-old infants learn to predict the reappearance of a nonlinearly moving stimulus within three trials. To assess whether or not the rate of learning was comparable here, we conducted a second mixed model ANOVA restricted to the first three trials. The results revealed that predictive tracking interacted with the stimulus condition, \(F(1, 56) = 6.32, p = .015, \eta^2_p = .10\), and improved rapidly with the implosion stimulus, \(F(2, 55) = 3.50, p = .04, \eta^2_p = .11\), but not with the occlusion stimulus, \(F(2, 55) = .43, p = .65, \eta^2_p = .02\).

Discussion

Infants showed significantly greater predictive tracking in the occlusion–disocclusion condition than in the implosion–explosion condition. This
finding is significant because all other variables that were previously hypothesized to facilitate predictive tracking (e.g., smooth and linear trajectories, width of occluding screen, duration of disappearance) were held constant in the two conditions. It thus appears that infants, like adults, are sensitive to the subtle differences in the way that an object disappears from view, and occlusion–disocclusion, but not implosion–explosion, supports predictive tracking.

These results are especially important for helping to clarify the role of contingency learning in predictive tracking. As discussed in the Introduction, critics claim that predictive tracking can be explained simply as contingency learning (e.g., Bremner et al., 2007), but the current results suggest that learning is not necessary when objects disappear via occlusion. Contingency learning should be independent of how objects disappear from view. Indeed, the typical evidence for this sort of learning does not even involve a moving stimulus, but rather a stimulus that first appears on one side of the viewing screen and then after a brief disappearance appears on the other side (e.g., Haith, 1994). In the current experiment, infants were clearly sensitive to more than the temporal contingency (i.e., they were sensitive to the stimulus differences specifying object continuity and discontinuity). Moreover, there was no evidence of learning in the occlusion–disocclusion condition after as many as 20 trials, and the likelihood of predictive tracking was very high from the first trial. By contrast, the analysis of

**Figure 5.** Color maps showing the location of each gaze sample from each infant (each sample represents 20 ms for 7-month-old and ~33 ms for 5-month-old infants).

*Note.* The data are divided into three panels: ball visible before its disappearance (left panel), ball not visible (center panel), and ball visible upon its reappearance (right panel). Top panels display 5-month-old data; bottom panels display 7-month-old data.

**Figure 6.** Histogram of saccades occurring before the ball reappears (positive values) or after the ball reappears (negative values).

*Note.* Reactive saccades are located to the left of the dark vertical line, and predictive saccades are located to the right of the dark vertical line.
infants’ performance on the implosion–explosion trials suggests that predictive tracking was initially not very likely, but there was some evidence of learning. Even though the stimulus transformation specified that the ball should cease to exist, the infant’s phenomenal experience was that it reappeared on the other side of the occluder shortly after it disappeared. The finding that infants showed some evidence of learning this contingency within the first three trials suggests that even if infants were sensitive to the stimulus transformation they were capable of modifying their behavior in response to recent visual experience.

A similar result was reported by Kochukhova and Gredebäck (2007), who studied predictive tracking of linear and nonlinear trajectories by 6-month-old infants. Although infants correctly predicted the reappearance of a linearly moving object from the first trial by extrapolating its path of motion, they also mistakenly predicted the reappearance of an object that changed its trajectory while occluded as if it would continue to follow a linear trajectory. In spite of this initial error, infants learned within three trials to correctly predict the new location of the moving object’s reappearance. According to Kochukhova and Gredebäck (2007), infants learned to inhibit their prepotent response when recent experience taught them that the object would reappear in a different location than expected based on the perceptual information alone.

In the current study, infants also learned that the ball would reappear on the opposite side of the occluder, even though the stimulus information associated with its disappearance specified that it should not. Yet, unlike the findings from the previous study, this improvement was not continuous after the first three trials. Instead, the likelihood of predictive tracking varied across trials, suggesting that learning to expect the reappearance of the ball interacted with other factors; otherwise, predictive tracking should have shown a more steady increase. Although a complete explanation for this difference in the rate of learning will require further research, it is interesting to note that the current study included stimulus information that directly conflicted with the expectation of the ball reappearing whereas the study conducted by Kochukhova and
Gredebäck (2007) did not. Thus, the discontinuous learning displayed by infants is suggestive of their appreciating that implosion information specifies object discontinuity. In sum, these results suggest that infants possess embodied knowledge to support differential tracking of continuously and discontinuously moving objects, but this tracking can be modified somewhat by recent visual experience.

Two additional issues merit some discussion. First, previous studies testing infants’ predictive tracking were not designed to optimize the perception of accretion and deletion of texture at the occluder boundary. In most of these studies, infants predictively tracked moving objects on < 50% of the trials. By contrast, 5- and 7-month-old infants in the current study showed predictive tracking on 60% and 80% of the trials, respectively, suggesting that the greater salience of the stimulus transformation increased infants’ perception of object continuity as the ball disappeared behind the occluder.

Second, unlike the occlusion–disocclusion condition, infants’ interpretation of implosion at the occluding edge is somewhat ambiguous. Although the implosion–explosion condition specifies object destruction to adults, the lack of a significant response by infants to this information renders the interpretation of these results less conclusive. One alternative interpretation for less predictive tracking in the implosion–explosion condition is that infants perceived the ball’s rapid shrinkage as novel, which recruited greater attention at the locus of its disappearance. This increased attention would likely have interfered with infants shifting gaze in a timely fashion to anticipate the ball’s reappearance. Although this is a plausible interpretation, the results from the duration of fixation data revealed no difference in looking time as a function of stimulus condition. Thus, it is unlikely that less predictive tracking in the implosion condition is attributable to a novelty effect.

In conclusion, infants show a developmental improvement in their sensitivity to accretion and deletion of texture for specifying object continuity and discontinuity between 5 and 7 months of age, and they show little evidence of learning across trials. By contrast, the finding that predictive tracking following implosion showed some improvement across trials suggests that real-time learning also contributes to how infants respond to briefly disappearing objects. Taken together, these results offer a compelling example of how both development and learning contribute to infants’ object knowledge revealed through predictive tracking. It remains an empirical question as to whether or not this knowledge generalizes to other tasks.

References


