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Infants' representations of three-dimensional occluded objects

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ABSTRACT

Infants' ability to represent objects has received significant attention from the developmental research community. With the advent of eye-tracking technology, detailed analysis of infants' looking patterns during object occlusion have revealed much about the nature of infants' representations. The current study continues this research by analyzing infants' looking patterns in a novel manner and by comparing infants' looking at a simple display in which a single three-dimensional (3D) object moves along a continuous trajectory to a more complex display in which two 3D objects undergo trajectories that are interrupted behind an occluder. Six-month-old infants saw an occlusion sequence in which a ball moved along a linear path, disappeared behind a rectangular screen, and then a ball (ball–ball event) or a box (ball–box event) emerged at the other edge. An eye-tracking system recorded infants' eye-movements during the event sequence. Results from examination of infants' attention to the occluder indicate that during the occlusion interval infants looked longer to the side of the occluder behind which the moving occluded object was located, shifting gaze from one side of the occluder to the other as the object(s) moved behind the screen. Furthermore, when events included two objects, infants attended to the spatiotemporal coordinates of the objects longer than when a single object was involved. These results provide clear evidence that infants' visual tracking is different in response to a one-object display than to a two-object display. Furthermore, this finding suggests that infants may require more focused attention to the hidden position of objects in more complex multiple-object displays and provides additional evidence that infants represent the spatial location of moving occluded objects.

1. Infants' representations of three-dimensional occluded objects

Scientists have long puzzled over the nature of the naïve human mind prior to extensive experience in the physical world. There is now substantial evidence that young infants represent the existence and physical properties of objects (e.g., Aguiar & Baillargeon, 2002; Baillargeon, 1987, 2004; Baillargeon & DeVos, 1991; Clifton, Rochat, Litovsky, & Perris, 1991; Hood & Willatts, 1986; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Wilcox, Nadel, & Rosser, 1996). One capacity that has received a great deal of attention is that of representing object motion during occlusion. With improvements in technology, the use of eye-tracking has converged with other methods to provide evidence of infants' representational capacities and has provided new insights into the nuances of infants' tracking abilities. These studies have demonstrated that infants are relatively good at tracking occluded objects and making predictions about where objects will next appear. For example, when viewing an object moving along a linear or curvilinear path that is partially occluded, infants aged 4–12 months

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predict where an object will next become visible (Gredebäck & von Hofsten, 2004; Gredebäck, von Hofsten, & Boudreau, 2002; Gredebäck, von Hofsten, Karlsson, & Aus, 2005; Johnson, Amso, & Slemmer, 2003; Kochukhova & Gredebäck, 2007; McMurray & Aslin, 2004; Rosander & von Hofsten, 2004; von Hofsten, Kochukhova, & Rosander, 2007), shifting their gaze during the occlusion interval to the appropriate edge of the occluder. Infants demonstrate predictive looking across a wide range of occluder widths and occlusion intervals and scale the latency of their gaze across the occluder to the duration of the occlusion interval (Gredebäck & von Hofsten, 2004; Gredebäck et al., 2002; von Hofsten et al., 2007).

These and other studies have also revealed that infants base their anticipation of emergences of moving occluded objects upon a number of different factors. One source of information infants draw on is their physical knowledge. Even very young infants possess basic expectations about how physical objects move and interact and use this information to predict the outcome of occlusion events (Aguiar & Baillargeon, 2002; Spelke et al., 1992; Spelke, Katz, Purcell, & Ehrlich, 1994; Spelke, Kestenbaum, Simons, & Wein, 1995). For example, infants extrapolate when and where a moving occluded object will next appear on the basis of pre-occlusion motion (Gredebäck & von Hofsten, 2004; Gredebäck et al., 2002; von Hofsten et al., 2007) and the expectation that objects move on continuous paths even when occluded (Kochukhova & Gredebäck, 2007). Infants can also predict the trajectory of a moving occluded object on the basis of its physical characteristics (e.g., the red square moves left) and anticipate the final orientation of an object as it rotates during the occlusion interval (Hespos & Rochat, 1997; McMurray & Aslin, 2004). At the same time, infants are able to adapt their anticipatory looking on the basis of recent experience (Kochukhova & Gredebäck, 2007). For example, when presented with fixed but non-linear paths (e.g., an object changes its direction of motion when occluded), initially infants fail to correctly predict where the object will next appear, typically looking to the edge of the screen at which the object would appear if it had followed a linear path. However, infants quickly learn non-linear but fixed paths and after two or three presentations of the occlusion sequence can accurately predict the point of emergence (Kochukhova & Gredebäck, 2007). These and related findings (Johnson et al., 2003; Wilcox, 2003) indicate that recent experiences can influence infant's interpretation of occluded motion and trial-related changes in behavior can be observed.

2. New directions

In sum, much has been learned about infants' capacity to represent objects as they move behind an occluder by means of detailed analysis of infants' visual behaviors. These investigations of infants' ability to track briefly occluded objects using an eye tracker typically measure predictive or anticipatory looking. While this measure has been informative, other looking behaviors may provide additional and potentially more detailed evidence of the representations infants' maintain concerning object motion and therefore warrant investigation.

What's more, assessment of infants' representations of complex occlusion events using eye tracking has been relatively understudied. The spatiotemporal parameters of occlusion events involving a single object moving along an unobstructed path are rather simple. In the physical world, however, occlusion events are often more complex. Paths of motion are sometimes obstructed and occlusion events can involve multiple objects. To what extent can infants represent these more complex events? There is evidence that infants expect a moving occluded object to stop or alter its path of motion after hitting an impenetrable barrier (Spelke et al., 1992, 1994) or to cause a stationary object to move upon contact (Kotovsky & Baillargeon, 1994, 2000). In addition, infants recognize when the spatiotemporal or featural properties of an event require the presence of more than a single object (Aguiar & Baillargeon, 2002; Spelke et al., 1995; Wilcox & Schweinle, 2002, 2003). It is possible that using an assessment measure as sensitive as eye-tracking will reveal looking patterns other than anticipatory looks that provide information about the nature of infants' object representations in complex occlusion events. The present research investigated infants' response to events involving one object as compared to two objects.

Finally, eye-tracking studies assessing infants' ability to track moving objects during an occlusion sequence have made use primarily of two-dimensional displays. The present research sought to build on these findings by using three-dimensional displays.

3. The present research

Given these gaps in current studies of infants' ability to track objects as they undergo occlusion, the purpose of the current research was to investigate infants' capacity to represent simple and complex occlusion sequences within a three-dimensional display. Infants looking patterns to multiple areas of the display were assessed using an eye-tracking system. Infants aged 6 months saw one of two events, ball–box or ball–ball (Fig. 1) and a corneal reflection eye tracker was used to assess looking patterns. Previous research indicates that infants 4.5 months and older interpret a ball–box event as involving two separate and distinct objects and a ball–ball event as involving a single object (McCurry, Wilcox, Woods, & Armstrong, 2009; Wilcox & Baillargeon, 1998a, 1998b; Wilcox & Chapa, 2002; Wilcox & Schweinle, 2002). However, 4.5 month olds' perception of depth is limited. It is not until around 5 or 6 months that infants' visual capacities and experiences have given them an understanding of the significance of depth (Birch, 1993; Brown & Miracle, 2003; Fox, Aslin, Shea, & Dumais, 1980; Gordon & Yonas, 1976; Kavšek, 2003), therefore infants in the current study were tested at about 6 months.

We hypothesized that if infants represent occluded paths of motion and if infants were given sufficient time to examine the display during occlusion, they should evidence three types of looking patterns that are consistent with the objects' path of motion. First, the infants in both conditions should demonstrate anticipatory looking. This outcome would build and extend

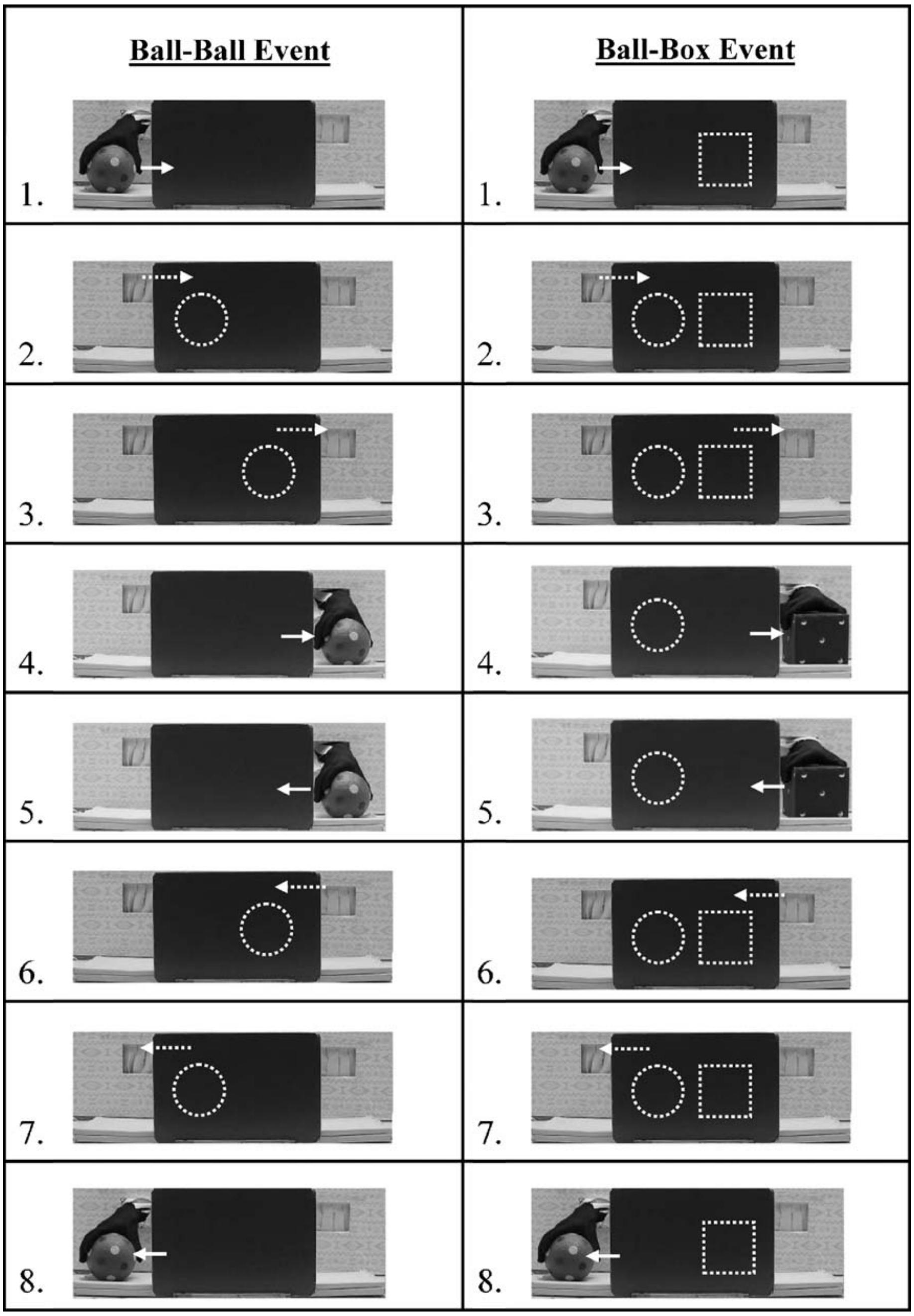

Fig. 1. One cycle of the event sequence (2 full trajectories) for the ball–ball and the ball–box events. Arrows represent the direction of object motion and dotted lines represent the location of the objects while they are hidden behind the screen.

on results obtained with one-object events in 2-D displays (Gredebäck & von Hofsten, 2004; Gredebäck et al., 2002; Johnson et al., 2003; Kochukhova & Gredebäck, 2007; Rosander & von Hofsten, 2004; von Hofsten et al., 2007) to one- and two-object events in 3D displays. Second, during occlusion when not engaging in anticipatory looking, we expected infants to direct looking to the portion of the occluder that currently hides the object as it moves along a hidden trajectory. However, given evidence (Schweinle & Wilcox, 2004; Wilcox, 2003, 2007; Wilcox & Baillargeon, 1998a) that it is more difficult for infants to represent two-object occlusion events (i.e., the objects' motion paths stop and start while they are hidden behind the screen) than one-object occlusion events (i.e., a single object moves continuously behind the screen), we expected group differences in tracking behavior. Third, during occlusion and when objects were visible, we examined where infants looked when they were not looking at the moving object. We expected that if infants focus on identifying and tracking the motion paths of objects, they would shift their attention in the direction of object motion throughout the event. That is, we expected most shifts of gaze away from the moving object, regardless of whether the object was visible or occluded, to be in the direction of object motion.

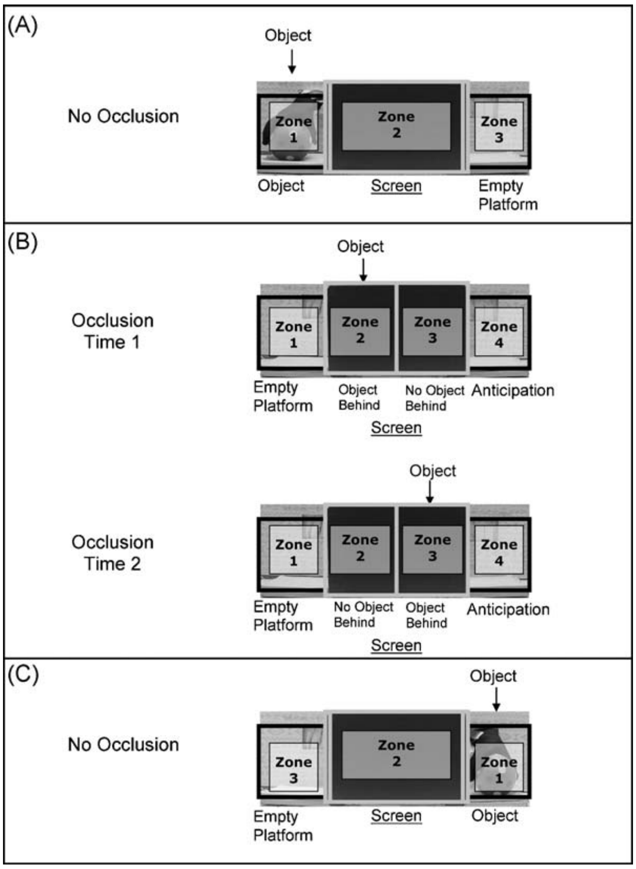

Fig. 2. Look zones during one trajectory of the event sequence for the ball–ball event. During occlusion, four zones of interest were identified (B): zone 1 (the place where the object was last seen), zone 2 (the side of the screen behind which the object had just disappeared), zone 3 (the side of the screen from behind which the object would next emerge), and zone 4 (the empty platform where the object would next be seen). During *no-occlusion*, three zones of interest were identified (A and C). These included zone 1 (looks to the object), zone 2 (looks to the screen), and zone 3 (looks to the opposite and empty platform).

4. Methods

4.1. Participants

Twenty healthy, term infants participated, 9 males, 11 females (M age = 6 months, 18 days; range 5 months, 7 days to 7 months, 19 days). Nineteen parents reported their infant's race/ethnicity: Caucasian (N = 11), Hispanic (N = 7) and Native American (N = 1). Five additional infants were tested but eliminated from analyses because of fussiness (N = 4) or failure to look at the display once testing began (N = 1). Infants were pseudo-randomly assigned to one of two groups: ball–box (N = 10) or ball–ball (N = 10).

4.2. Apparatus and stimuli

The events were presented in a puppet-stage apparatus; the stage was 85 cm wide × 38 cm high × 42 cm deep. The area of the stage within which tracking was monitored was approximately 60 cm wide and 20 cm high (see Fig. 2), corresponding to visual angles of 53° and 19°, respectively. A muslin shade concealed the stage and was raised at the beginning of each trial. The infant was isolated from the testing room by a cloth curtain. The stage was illuminated but no other lighting was used.

A blue screen, used in the test, events was 30 × 20 cm (28° × 19°) and centered on the stage. The green ball was 10.25 cm in diameter with red, blue, and yellow dots. The red box was 10.25 cm square and decorated with silver thumbtacks. Both objects subtended an angle of approximately 9.8°. To equate the events as much as possible, the ball–ball event was produced using two identical balls. The objects were moved by a gloved hand which entered the apparatus through a concealed slit in the back wall of the apparatus.

4.3. Events

4.3.1. Ball–box condition

To capture the infant's attention at the start of each test trial, Experimenter 1 (E1) danced the ball back and forth on its central axis in a rotating motion to the left of the test screen (the box was hidden behind the screen). Once the infant looked at the ball, E1 placed the ball on the platform, paused (1 s), then moved the ball right until it was fully hidden behind the screen (2 s); E1 then moved the box until it emerged from behind the screen and moved to the right edge of the platform (2 s). The box paused (1 s) and then the 5 s sequence was seen in reverse. The entire 10 s sequence (see Fig. 1) was repeated twice for a total of three cycles. Objects moved at a rate of 12 cm/s (11.4°/s) and the occlusion interval was 1.8 s.

4.3.2. Ball–ball event

The ball–ball event was identical to the ball–box event except that the second, identical ball was substituted for the box.

4.4. Automated eye tracking

Eye movements were assessed using an ASL Pan/Tilt Model R6 remote optics corneal reflection eye tracker (Applied Science Laboratories, Bedford, MA). A scene camera recorded the 3D event and imported it into the eye tracking system. Gaze points were superimposed on the video image by *Gazetracker Premium Academic* software. Another camera was focused on the infant and recorded looking behavior during the test trials; these recordings were time-locked to the recordings obtained with the scene camera. Data were coded offline.

4.5. Procedure

4.5.1. Calibration

Infants sat 60 cm from the display in a car seat centered in front of the apparatus. The eye tracker was located directly underneath the stage. An external magnetic head tracker (MHT) was affixed to a headband and placed on the infant's head just over the left eye. To calibrate looking, a hand-held blinking light (2 cm or 1.9° in diameter) was used to capture infants' attention at each of three successive points in the apparatus. The points were top left, lower right, and lower left (i.e., points 1, 7, and 9 of a nine-point array) and an eye-tracker operator set the system to correspond. These three calibration points were located in different horizontal and depth planes and were chosen because they yielded the most precise calibration in our three-dimensional display. Calibration accuracy for each infant was then assessed by re-capturing the infant's gaze at each of the three calibration points and then by moving first the blinking light and then a bright orb (6 cm or 5.7° in diameter) throughout the display. If calibration was not accurate, the procedure was repeated.

4.5.2. Test trials

After calibration, infants saw two test trials appropriate for their condition. Each trial consisted of three full cycles of the event, resulting in a total of 12 alternating trajectories (2 trajectories per cycle). Each trial lasted 30 s (M = 29.68, SD = 1.32; range 27.47–33.45). To keep the infants' eyes directed toward the apparatus between trials a *Muppet Show* video was projected onto the lowered muslin shade using a Dell DLP front projector.

4.6. Coding

Digital files were subjected to frame by frame analysis using *The Observer 5.0* software by *Noldus*. Coders determined infants' gaze position from crosshairs superimposed on the display image by the eye tracker. Two time periods of interest were identified. These were *full occlusion* (i.e., the time during which the objects were entirely occluded) and *no occlusion* (i.e., the time during which any object was visible). Infants' looking during these two periods was assessed as follows.

4.6.1. Full-occlusion look zones

Four zones of interest were identified (see Fig. 2B). Anticipatory eye movements, or *anticipations*, were assessed by coding the number of trajectories in which infants looked at least once to the area in which the object would next appear during the occlusion interval (zone 4). These included the looks to the edge of the screen at the boundary of zones 3 and 4. To assess *looking to screen*, two scores were calculated for each infant: (1) looking to the screen where an object was hidden (i.e., zone 2 at time 1, and zone 3 at time 2) and (2) looking to the screen where no object was hidden (i.e., zone 2 at time 2, and zone 3 at time 1). Ambiguous looks to the center of the screen (the boundary of zones 2 and 3) were not included in these measures, but were included in total looks to the screen. A percentage score was calculated by dividing the amount of time that the infant looked to the *object-hidden* and the *no-object-hidden* side of the screen of compared to the infants' total looking during occlusion. Full occlusion times averaged 1.5 s (M = 1.57, SD = 0.18; range 1.05–2.4).

4.6.2. No-occlusion look zones

Three zones of interest were identified (see Fig. 2A and C). To assess *duration of looking*, a percentage score for each zone was obtained by dividing the duration of looking to each zone by the total time that the object was visible. This resulted in

Table 1
Looking duration (s).

	Trial 1		Trial 2	
	M	*SD*	*M*	*SD*
Occlusion				
Ball–box	7.42	2.08	6.12	1.92
Ball–ball	6.92	2.56	6.37	3.53
Non-occlusion				
Ball–box	16.47	3.43	15.95	5.13
Ball–ball	16.34	3.99	15.94	5.83

Note: Each trial was 30 s and of this time the objects were occluded for 9 s and visible for 21 s.

three scores for each infant: (1) the proportion of time spent tracking the object; (2) the proportion of time spent looking at the screen; and (3) the proportion of time spent looking at the opposite, and empty, side of the platform.

4.6.3. Direction of gaze

Infants' direction of gaze was coded by identifying the number of times the infant shifted gaze from one zone to another. Four look zones identical to those used during the occlusion time period (Fig. 2B) were used. Each trajectory was separated into two intervals: occlusion and no-occlusion. Zone shifts were identified as being in the direction of object motion or contrary to the direction of object motion during the two intervals. For example, if the ball in the ball–ball condition was moving left to right across the platform, and was currently located in zone 3 (an occlusion interval) a shift to zone 4 would be considered a shift in the direction of motion (DOM), whereas a shift to zone 1 or 2 would not be considered a shift in DOM.

5. Results

Unless otherwise stated, the data analyses reported below were conducted on percentage of time infants' spent looking during occlusion or non-occlusion intervals of the test events. Raw scores of mean total looking durations by trial (trial 1 or 2), condition (ball–ball and ball–box), and by interval (occlusion and no-occlusion) are included for reference and will be discussed in subsequent sections (see Table 1).

5.1. Full occlusion

5.1.1. Anticipations

Infants made at least one anticipatory look on 75 (31%) of the 240 trajectories (20 infants were presented with 2 trials and each trial contained 6 trajectories). This percentage is consistent with the percentage of anticipations reported during occlusion events by other researchers, which range from 20 to 50% (e.g., Gredebäck & von Hofsten, 2004; McMurray & Aslin, 2004), although under some conditions anticipatory looks can be higher (e.g., Johnson et al., 2003). A 2 × 2 mixed analysis of variance (ANOVA) with trial (1 or 2) as a within-subjects factor and condition (ball–ball or ball–box) as a between-subjects factor revealed a significant main effect of trial, $F(1, 18) = 5.87$, $P < 0.03$, $\eta_p^2 = 0.25$. The infants made more anticipatory looks in trial 1 ($M = 2.20$, $SD = 1.36$, 37% of the trajectories) than trial 2 ($M = 1.45$, $SD = 1.47$, 24% of the trajectories), Cohen's $d = .53$.

5.1.2. Looking to screen

Percentage of looking to the occluder was calculated by dividing the amount of time that the infant looked to the *object-hidden* and the *no-object-hidden* side of the screen compared to the infants' total looking during occlusion. Mean percentage scores were subjected to a 2 × 2 × 2 mixed ANOVA with side of screen (object hidden or no object hidden) and trial (1 or 2) as within-subjects factors and condition (ball–ball or ball–box) as the between subjects factor. The main effect of screen was significant, $F(1, 18) = 12.37$, $P = 0.002$, $\eta_p^2 = 0.41$ (*object-hidden*, $M = 20.70$, $SD = 10.02$; *no-object-hidden* $M = 14.28$, $SD = 8.46$), indicating that the infants looked a greater percentage of time to the side of the screen behind which the object was hidden than the other side of the screen. More importantly, there was a significant screen × condition interaction, $F(1, 18) = 5.73$, $P = 0.03$, $\eta_p^2 = 0.24$. Follow-up analysis revealed that the infants who saw the ball–box event looked a greater proportion of time to the side of the screen that hid the object ($M = 23.35$, $SD = 12.56$) than to the side of the screen that did not hide the object ($M = 12.55$, $SD = 6.80$), $t(9) = 4.35$, $P = 0.002$, Cohen's $d = 1.07$. All ten infants looked longer to the side of the screen that hid the object. In contrast, the infants who saw the ball–ball event had approximately equal proportions of looking to either side of the screen, $t(9) < 1$ (*object-hidden*, $M = 18.05$, $SD = 6.22$; *no-object-hidden*, $M = 16.00$, $SD = 9.92$) and only seven of the ten infants looked longer to the side of the screen that hid the object. Further inspection of the data revealed, however, that this effect was led largely by performance in the second trial (see Fig. 3). In trial 1, the ball–ball infants tended to look longer to the side of the screen that hid the object, $t(9) = 2.53$, $P = 0.015$ (one-tailed), Cohen's $d = .85$, but in trial 2 showed a reverse pattern of looking; they tended to look longer to the side of the screen that *did not* hide the object, $t(9) = -0.65$, $P = .27$ (one-tailed), Cohen's $d = .26$. In contrast, the infants in the ball–box condition looked longer to the side of the screen that hid

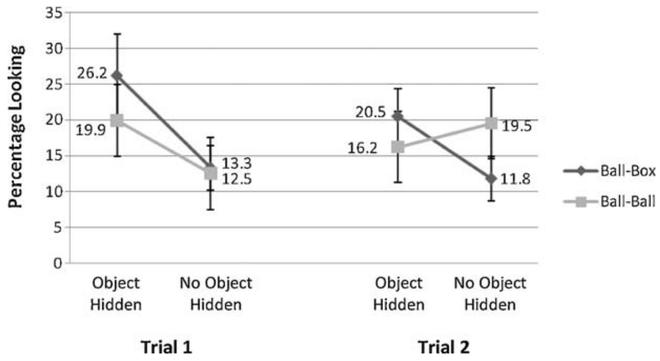

Fig. 3. Percentage of looking to the occluder calculated by dividing the amount of time that the infant looked to the *object-hidden* and the *no-object-hidden* side of the screen of compared to the infants' total looking during occlusion.

the moving object in trial 1, $t(9) = 3.64$, $P = 0.0025$ (one-tailed), Cohen's $d = .88$, and trial 2, $t(9) = 2.21$, $P = 0.0275$ (one-tailed), Cohen's $d = 79$.

Given the range in infants' age, we thought it important to establish whether the same results would be obtained after adjusting for differences in age. To this end, looking to screen data were also subjected to an analysis of covariance (ANCOVA); the factors were the same as in the ANOVA and the covariate was the infants' age in days. The results of the ANCOVA replicated those of the ANOVA: the screen × condition interaction was significant, $F(1, 17) = 5.60$, $P = 0.03$, $\eta_p^2 = 0.25$.

5.2. *No occlusion*

5.2.1. *Duration of looking*

Mean percentage of total looking time during the period in which the object was visible was subjected to a 3 × 2 × 2 mixed ANOVA with look zone (screen, object, or empty platform) and trial (1 or 2) as the within-subjects factors and condition (ball–ball or ball–box) as a between subjects factor. The main effect of look zone was significant, $F(2, 36) = 120.87$, $P < 0.001$, $\eta_p^2 = 0.87$. When the object was visible, infants looked a greater percentage of time at the object ($M = 63.45$, $SD = 19.51$) than to the screen ($M = 11.30$, $SD = 7.83$) or empty platform ($M = 6.25$, $SD = 3.31$).

5.3. *Direction of gaze*

The percentage of gaze shifts that were in the direction of object motion (%DOM) was calculated for the occlusion and the non-occlusion intervals. The data were then subjected to a mixed-model ANOVA with trial (1 or 2) as the within-subjects factor and condition (ball–box or ball–ball) as the between subjects factor. For the non-occlusion intervals the main effects and interaction were not significant. In both the ball–box condition ($M = 76\%$, $SD = 9\%$), $t(9) = 9.22$, $P < 0.001$, and the ball–ball condition ($M = 78\%$, $SD = 12\%$), $t(9) = 7.66$, $P < 0.001$, infants' gaze shifts were in the direction of motion a greater percentage of time than expected by chance. For the occlusion intervals, the main effect of Condition approached significance, $F(1, 18) = 4.15$, $P = .057$, $\eta_p^2 = 0.19$. In the ball–box condition the infants shifted their gaze in the direction of motion more often than expected by chance ($M = 58\%$, $SD = 7\%$), $t(9) = 3.41$, $P = .008$. In contrast, in the ball–ball condition the mean %DOM did not differ significantly from 50% ($M = 50\%$, $SD = 5\%$), $t(9) < 1$.

6. Discussion

One question central to understanding the ontogeny of human knowledge is the extent to which infants represent occlusion events and how this changes with experience. The current research, using eye-tracking technology, reveals three important findings that bear on this question. First, the results indicated that when viewing a ball–ball or ball–box event, infants engaged in anticipatory looking. These data provide converging evidence that 6.5-month-olds represent paths of object motion through occlusion and extend previous anticipatory looking results (Gredebäck & von Hofsten, 2004; Johnson et al., 2003; Kochukhova & Gredebäck, 2007; McMurray & Aslin, 2004; Rosander & von Hofsten, 2004) to 3D multiple-object displays. Furthermore, the infants were more likely to make anticipatory looks during the first than the second test trial. These data suggest that once infants identify paths of motion – they have a clear depiction of the basic structure of the event (e.g., a ball moves behind the left side of the screen and a box emerges from behind the right) – and they experience success in their predictions of a fixed event, they are less likely to produce anticipatory looks. They no longer need to see the emergence of the object to confirm their interpretation of the event. Although it is possible that the trial-related decrease in anticipations reflects decreased attention to the task, overall, other data argue against this interpretation. Recall that as the test session advanced infants continued to watch the event (see Table 1) and there were no significant effects of trial on duration of looking to the screen during the occlusion interval or to the objects were they were visible, even though infants evidenced significantly fewer anticipatory looks.

Second, the results indicated that during the occlusion interval infants directed their looks to the side of the screen that currently hid the object, shifting attention from one side of the screen to the other as the objects moved behind the screen. Systematic, focused attention to the side of screen that hid the moving object suggests that the infants were tracking the movement of the ball (and the box) throughout the occlusion interval. This is particularly interesting when considering that infants who saw the ball–box event tracked both objects as they moved through the display rather than spending time looking at the side of the screen that hid the stationary object. These novel results are intriguing because they suggest that not only do infants anticipate the point where the next emergence will occur, but they represent the entire path of motion and their attention is captured by object movement even when objects are hidden just as it is when objects are visible. This is particularly evident when two objects are involved in an event.

Furthermore, these results reveal that not all occlusion events are created equal: the ball–box infants demonstrated this tracking behavior on both trials, whereas the ball–ball infants only demonstrated it on the first trial. One interpretation of these group differences is that the ball–ball infants found it easier to represent the occlusion event than the ball–box infants. After tracking the ball during the first trial, and seeing that the ball continued to emerge to both sides of the screen throughout the event, the ball–ball infants were confident as to the path that the ball followed when behind the screen. Hence, particularly on the second trial infants were not compelled to track the ball as it moved along its occluded trajectory. In contrast, the infants who saw the ball–box event found it more difficult to represent the occlusion sequence. Although the point at which an object would next emerge was relatively easy to predict, it was more challenging to draw inferences about the path that the ball and the box followed when behind the screen. For example, the ball stopped its motion once it was occluded and when it once again began to move, after the appearance of the box, it moved in the opposite direction. Infants who saw the ball–box event were more likely than infants who saw the ball–ball event to focus attention on the spatiotemporal coordinates of the object(s) during occlusion. Although this interpretation is consistent with evidence that infants find it more difficult to represent two-object than one-object occlusion events (Schweinle & Wilcox, 2004; Wilcox, 2003, 2007; Wilcox & Baillargeon, 1998a), further research will be needed to assess this and other interpretations.

Finally, the current research indicates that when infants were not attending to the location of the moving object, the infants tended to look in the direction of object motion. For example, during no-occlusion intervals when the object was visible, both the ball–box and the ball–ball infants were more likely to look forward to a zone in which the object was moving towards, than to look backward to a zone in which the object had once been. These data indicate that infants reliably tracked a visible moving object, and when they shift attention away from the object they tend to shift in the direction of motion. This pattern of behavior provides infants with ample opportunity to view the trajectories of visible moving objects and to make and confirm predictions about where the object will be next. When objects were no longer visible, during the occlusion intervals, a similar pattern of results was obtained for infants in the ball–box condition. The ball–box infants shifted their gaze in the direction of motion and, although the effect was not as strong as that observed when the objects were visible during the non-occlusion interval of the test event, it was significantly greater than expected by chance. These data suggest that even when the ball and the box were fully occluded, the infants attended to the objects' paths of motion. Even when the infants were not directing their gaze to the current location of the object, they were shifting their gaze in the direction in which the object was moving. In contrast, the ball–ball infants were random in the direction in which they shifted their gaze during the occlusion interval. Sometimes they looked forward; sometimes they looked backward.

This novel outcome cannot be explained by decreased interest to the ball–ball as compared to ball–box event. There were no differences, overall, in the amount of time infants spent watching the two events (see Table 1). More likely, this result reflects the ease with which infants interpret and represent one-object (ball–ball) as compared to two-object (ball–box) occlusion events. When viewing the ball–ball event infants can quickly identify the trajectory of the ball as it moves back and forth behind the screen and recognize that the ball follows a simple and predictable path of motion throughout the event. Hence, infants turn their attention to other aspects of the event. In contrast, when viewing the ball–box event it is more challenging for infants to identify the trajectory that each of the two objects follow as they move back and forth behind the screen. In an attempt to identify and represent these trajectories, infants are compelled to follow the moving occluded trajectories, attending to where the moving object currently is, and where it will be next, as the event unfolds before them.

This interpretation of the %DOM results is consistent with the occlusion data. During the occlusion interval, the ball–box infants were more likely to look at the side of the screen that currently hid the moving object than at the opposite side of the screen. The ball–ball infants demonstrated this pattern of looking on trial 1, but failed to look longer at the side of the screen that hid the ball on trial 2. That is, the infants were more likely to track paths of motion throughout occlusion, shifting gaze from one side of the occluder to the other, when the event involved two objects than when it involved a single object.

Collectively, these data provide converging evidence for the idea that infants not only represent hidden objects, but also represent the motion paths objects undergo when occluded. Using this novel assessment of looking behaviors, we have revealed new information about infants' representations of three-dimensional, complex occlusion events that would not have been available using traditional global-look-time measures (i.e., overall, infants looked equally to the one-object and two-object events). Furthermore, results indicated that object motion, whether the objects were visible or occluded, captured infants' attention. This finding is particularly interesting because it provides a mechanism for infants' learning about the nature of events that are not directly observed. For example, it is possible that infants' looking to the occluder itself may assist them in forming and maintaining representations of objects and object motion paths during occlusion. This possibility is particularly intriguing given the differences seen in looking behaviors of infants who saw the one-object compared to the two-object event. Future studies will continue to investigate these and other methods for assessing infants' representations of objects in simple and complex occlusion events.

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