

Orientation Effects in the Development of Linear Object Tracking in Early Infancy

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Infants' oculomotor tracking develops rapidly but is poorer when there are horizontal and vertical movement components. Additionally, persistence of objects moving through occlusion emerges at 4 months but initially is absent for objects moving obliquely. In two experiments, we recorded eye movements of thirty-two 4-month-old and thirty-two 6-month-old infants (mainly Caucasian-White) tracking horizontal, vertical, and oblique trajectories. Infants tracked oblique trajectories less accurately, but 6-month olds tracked more accurately such that they tracked oblique trajectories as accurately as 4-month olds tracked horizontal and vertical trajectories. Similar results emerged when the object was temporarily occluded. Thus, 4-month olds' tracking of oblique trajectories may be insufficient to support object persistence, whereas 6-month olds may track sufficiently accurately to perceive object persistence for all trajectory orientations.

In research on infants' perception and understanding of the world, it is generally assumed that infants are able to process the displays presented to them, at least at the level of detecting the visible events contained in them. However, particularly in the case of research with young infants, this assumption may not be safe. For instance, in the case of stationary objects, we know that 1- to 2-month-old infants localize targets through a series of undershoot saccades in the direction of the stimulus rather than in a single accurate saccade (Aslin & Salapatek, 1975). This has implications for the speed at which they foveate stationary targets and raises questions about their ability to localize targets in space (Aslin, 1993). Infants' ability to track moving objects develops rapidly, with smooth tracking of horizontally moving objects emerging between 2 and 5 months of age (von Hofsten & Rosander, 1996, 1997). However, vertical tracking is poorer than horizontal tracking in 5- to 9-month-

old infants (Grönqvist, Gredebäck, & von Hofsten, 2006) and remains so in adults (Rottach et al., 1996). Infants of 5–9 months of age also show poorer circular tracking (Grönqvist et al., 2006), which involves coordination of intraocular muscles controlling vertical and horizontal eye movements (Schiller, 1998). The errors in circular tracking are greater than would result from simply summing vertical and horizontal tracking errors, suggesting that the difficulty here involves the coordination of vertical and horizontal tracking components.

Although research on infants' ability to localize stationary objects and track moving objects is important in its own right, the findings may also have far-reaching implications for infants' perceptual and cognitive development. Specifically, findings regarding infants' accuracy at tracking objects on different trajectories may have implications for their perception of the persistence of moving objects. Perception of object persistence in moving object occlusion events emerges at around 4 months

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of age (Johnson et al., 2003). In this method, infants are habituated to an event in which an object cycles back and forth, passing behind an occluder in the middle part of its trajectory. Infants are then presented with either continuous or discontinuous object trajectories in the absence of the occluder. Longer looking at the discontinuous trajectory is taken as evidence that they perceived the habituation display as composed of a continuous movement, and that the object persists when it is hidden. However, 4-month olds only perceive object persistence when the gap in perception is short spatially (Bremner et al., 2005; Johnson et al., 2003) or temporally (Bremner et al., 2005). On the basis of evidence for a number of perceptual constraints on early perception of object persistence, Bremner, Slater, and Johnson (2015) proposed a model in which perception of object persistence is initially heavily dependent on perceptual cues to occlusion, and develops through a reduction of the number of cues required for veridical perception.

One somewhat unexpected perceptual constraint is that 4-month olds have difficulty perceiving persistence of objects moving on oblique trajectories (Bremner, Slater, Mason, Spring, & Johnson, 2017; Bremner et al., 2007). Bremner et al. (2017) suggested that the problem with oblique trajectories arose from the need to coordinate intraocular muscles controlling vertical and horizontal eye movements to produce oblique eye movements (Schiller, 1998). Specifically, 4-month olds are unable to perceive object persistence in oblique trajectories because their tracking is not sufficiently accurate, even when the object is fully visible. In the extreme, poor tracking of the object while it is in sight could result in infants failing to detect the occlusion event at the occluder edge that specifies the object's persistence (cf. Bertenthal, Longo, & Kenny, 2007). The possibility that oblique tracking might be particularly inaccurate is in keeping with the finding with older infants that predictive tracking is poorer for objects moving on a circular trajectory than on a horizontal or vertical trajectory (Grönqvist et al., 2006) because circular tracking also involves coordination of vertical and horizontal components of tracking. However, Bremner et al. (2017) found that 6-month olds had overcome the problem with oblique trajectories to the extent that they detected persistence of objects moving obliquely.

If the object tracking interpretation of 4-month olds' difficulties with objects moving on oblique trajectories is correct, it should be possible to demonstrate less accurate tracking by this age group for objects moving on oblique trajectories. Furthermore,

we would predict that by 6 months of age, tracking of obliques would have improved, either to the same level as horizontal or vertical tracking, or to a threshold level that permits detection of object persistence. Although some research has investigated predictive tracking of an object moving on a circular trajectory by infants of 6 months and older (Gredebäck & von Hofsten, 2004; Gredebäck, von Hofsten, & Boudreau, 2002) and has compared vertical, horizontal, and circular tracking by 5- to 9-month olds (Grönqvist et al., 2006), to our knowledge there has been no direct comparison of young infants' horizontal, vertical, and oblique tracking.

The aim of the present work is to fill this gap in knowledge, with the primary goal of providing a plausible basis for the oblique object persistence deficit in poorer object tracking. In contrast with other work that has looked at predictive tracking across occlusion, the present work tackles the simpler question of whether 4-month olds' tracking of a constantly visible object is poorer for oblique than other trajectories, and whether any deficit is reduced by 6 months of age. There are several measures of tracking accuracy (e.g., Mareschal, Harris, & Plunkett, 1997), but for our purposes measures of the average distance between gaze and the center of the target and time on target seemed appropriate, the former because it is one of the primary measures used in other work on object tracking, and the latter because it provides a measure of the extent to which infants' gaze was sufficiently on target to detect an occlusion event in object persistence tasks. We obtained both of these measures with an eye-tracker. In addition, rather than optimizing the conditions for tracking accuracy, we aimed to present a task in which the object movements mimicked those presented in the object persistence work. Although infants track more accurately when the object moves sinusoidally (von Hofsten & Rosander, 1997), slowing down before reversal and speeding up afterwards, to replicate the object persistence work, we presented "triangular" object motion in which the object moved at a constant speed, reversing abruptly at the end points.

Experiment 1

Method

Participants

With an alpha level = .05 and power = .8, using GPower (Faul, Erdfelder, Lang, & Buchner, 2007),

we calculated that an $N = 14$ per group was needed to detect a medium effect size, and thus we set the N per group at 16 to equate the number of infants in subgroups. Sixteen 4-month-old infants ($M = 126.6$ days, range = 115–138 days; 5 girls) and sixteen 6-month-old infants ($M = 186.9$ days, range = 176–196 days; 7 girls) took part in the experiment. A further seven 4-month olds and three 6-month olds did not complete testing due to fussiness ($n = 6$) or failure to calibrate ($n = 4$). Participants in both experiments were predominantly Caucasian-White infants of mainly middle-class parents. The exceptions were one infant of Asian parentage, and one of mixed race Asian-Caucasian parentage. Infants were recruited during 2017–2018 through Lancaster University Babylab database.

Apparatus and Stimuli

Adobe Animate software was used to create the visual displays. The stimuli consisted of an image of a 4.5 cm sphere (3.2°) on a black background that translated back and forth on a linear horizontal, vertical, 45° oblique, or 135° oblique trajectory (see Figure 1). The frame rate was 48 frames per second. The length of the trajectory was 27.5 cm and the rate of motion was 11 cm/s ($7.9^\circ/s$), comparable to the $9.4^\circ/s$ rate of motion in object persistence work (Bremner et al., 2017). To maximize the attention, the color of the ball morphed to a new color every second (cycling from green to red to blue). Each translation lasted for 5 s and the ball translated twice for each animation. A 60×33.5 cm monitor was used for the presentation of stimuli. A Tobii x60 eye-tracker (Tobii Group, Stockholm, Sweden) was positioned below the display. Eye-tracker calibration was accomplished by 5-point stimulus presentation on the display screen.

Procedure

Infants were seated on their caregiver's knee, and viewed the display from a distance of 80 cm. Caregivers were asked not to interact in any way with their infant during the session. Once eye-tracker calibration was achieved, eight tracking trials followed. Prior to each trial, to attract infants' attention a sounding image of a rotating toy dinosaur about the size of the ball was shown at the position at which the subsequent ball trajectory would commence. The trial began as soon as the infant directed his/her gaze to the location of the dinosaur. A trial consisted of the object cycling back

and forth for 10 s. There were two blocks of four trials. Each block consisted of a horizontal (0°), vertical (90°), 45° oblique, and 135° oblique trajectory. A Latin square ordering resulted in four different trajectory orders ($0^\circ:90^\circ:45^\circ:135^\circ$; $90^\circ:45^\circ:135^\circ:0^\circ$; $45^\circ:135^\circ:0^\circ:90^\circ$; $135^\circ:0^\circ:90^\circ:45^\circ$) such that trials commenced with a different orientation for each of four subgroups of infants. An equal number of infants was allocated to each of these four combinations and the same combination was repeated in the second block, resulting in eight trials per infant. The start position of the trial was also counterbalanced between participants. For example, on horizontal tracking trials, half of the participants began with horizontal movement starting from the left of the screen in Block 1 and right of the screen in Block 2, and the remaining half of the participants began with horizontal movement starting from the right of the screen in Block 1 and left of the screen in Block 2.

Results

Average distance between gaze and center of the object (AvgD) was calculated. Data consisted of x - y coordinates of the point of gaze on the stimulus monitor recorded at 60 Hz. The average distance between the infant's point of gaze and center of the object (AvgD) was calculated with MATLAB using root mean square (in cm) for each trial. Preliminary analysis revealed no significant main effects or interactions for gender of participants or animation start position and so these factors were collapsed for analysis.

Figure 2 shows the AvgD plotted by age and trajectory orientation. This suggests that performance by both age groups is poorer for oblique trajectories, and performance by 6-month olds on oblique trajectories looks comparable to 4-month olds' performance on horizontal and vertical trajectories. An age (4-month olds vs. 6-month olds) \times trajectory orientation (horizontal 0° vs. vertical 90° vs. 45° oblique vs. 135° oblique) \times trajectory order ($0^\circ:90^\circ:45^\circ:135^\circ$ vs. $90^\circ:45^\circ:135^\circ:0^\circ$ vs. $45^\circ:135^\circ:0^\circ:90^\circ$ vs. $135^\circ:0^\circ:90^\circ:45^\circ$) mixed analysis of variance (ANOVA) yielded significant main effects of age, $F(1, 24) = 18.27$, $p < .001$, $\eta_p^2 = .43$, and trajectory orientation, $F(3, 72) = 53.23$, $p < .001$, $\eta_p^2 = .69$ (see Figure 2). Four-month olds had a larger AvgD ($M = 4.02$ cm: 2.9° , $SE = .24$ cm: 0.2°) in comparison to 6-month olds ($M = 2.55$ cm: 1.8° , $SE = .24$ cm: 0.2°). Bonferroni adjusted pairwise comparisons of trajectory orientation showed that the horizontal trajectory ($M = 2.64$ cm: 1.9° , $SE = 0.20$ cm:

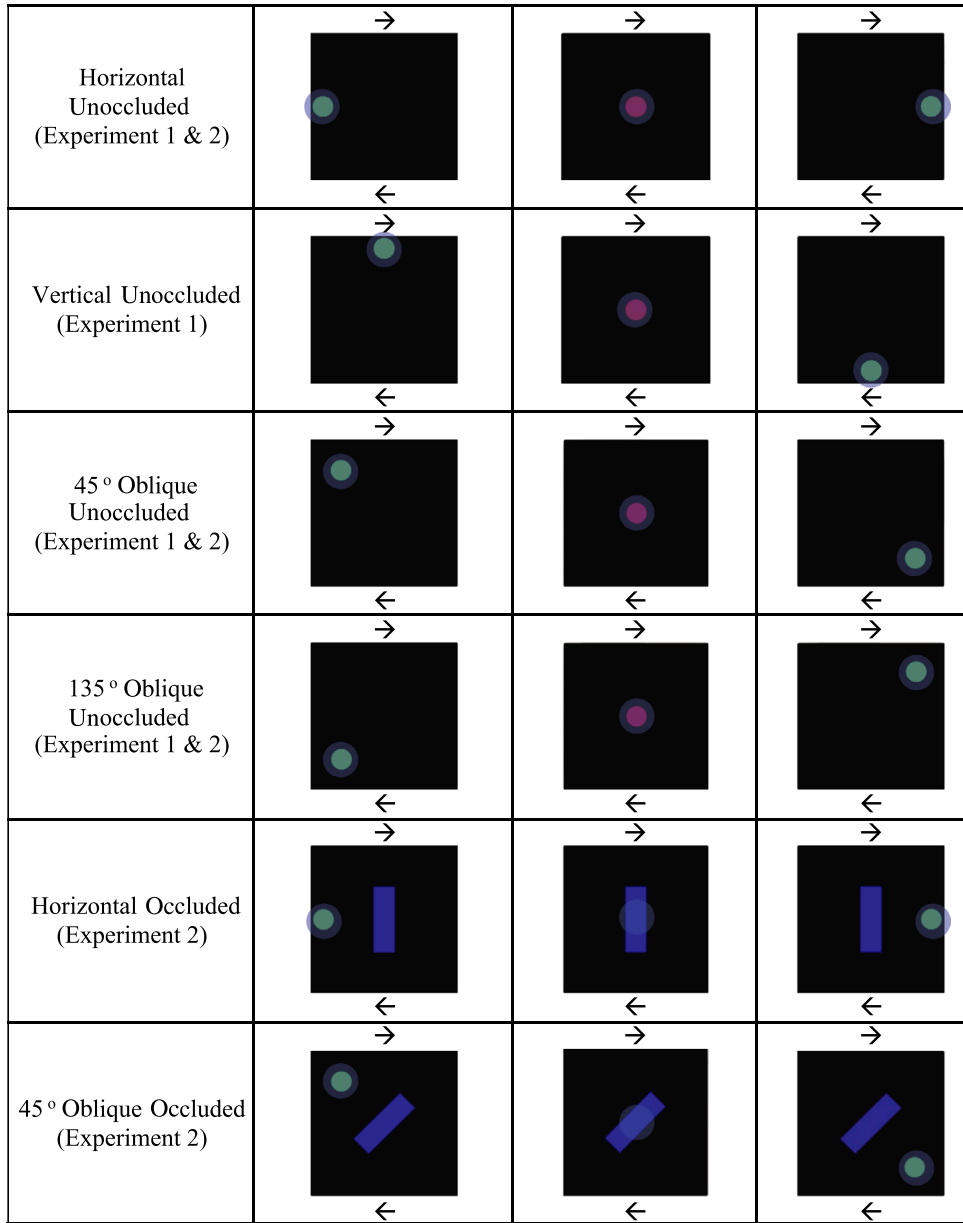


Figure 1. Illustration of the horizontal, vertical, 45° oblique, and 135° oblique unoccluded and occluded visual displays presented to infants in Experiments 1 and 2. The ball color is illustrative and in the actual displays changed every second. Darker ball represents the moving sphere, whereas the lighter (and larger) ball represents region within which fixations were counted toward the accumulated dwell times.

0.1°) had significantly smaller AvgD in comparison to both the 45° oblique trajectory ($M = 4.0$ cm: 2.9°, $SE = .17$ cm: 0.1°), $t(31) = -9.375$, $p < .001$, and the 135° oblique trajectory ($M = 4.05$ cm: 2.9°, $SE = .22$ cm: 0.2°), $t(31) = -6.69$, $p < .001$. Similarly, the vertical trajectory ($M = 2.47$ cm: 1.8°, $SE = .20$ cm: 0.1°) had significantly smaller AvgD in comparison to the 45° oblique trajectory, $t(31) = -10.81$, $p < .001$, and 135° oblique trajectory, $t(31) = -6.38$, $p < .001$. No other comparisons were significant.

Additionally, 6-month olds tracked oblique object movements as accurately as 4-month olds tracked horizontal and vertical object movements: 6-month-old 45° oblique versus 4-month-old horizontal, $t(30) = -0.25$, $p = .80$; 6-month-old 45° oblique versus 4-month-old vertical, $t(30) = 0.13$; $p = .90$, 6-month-old 135° oblique versus 4-month-old horizontal, $t(30) = -0.12$, $p = .90$; 6-month-old 135° oblique versus 4-month-old vertical, $t(30) = 0.22$, $p = .83$.

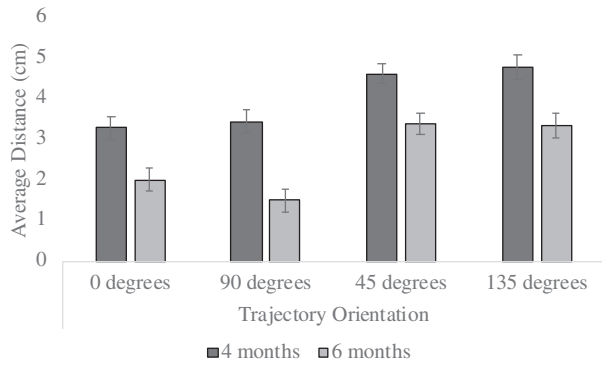


Figure 2. Average distance between gaze and center of the object plotted by age and trajectory orientation for Experiment 1.

There was also a two-way interaction between trajectory orientation and trajectory order, $F(9, 72) = 2.07$, $p = .04$, $\eta_p^2 = .21$, that was qualified by a three-way interaction between trajectory orientation, trajectory order, and age, $F(9, 72) = 2.92$, $p = .005$, $\eta_p^2 = .27$. The two-way interaction between trajectory orientation and trajectory order was significant for both 4-month olds, $F(9, 36) = 2.43$, $p = .03$, $\eta_p^2 = .38$, and 6-month olds, $F(9, 36) = 2.7$, $p = .02$, $\eta_p^2 = .40$. Four-month olds showed a complex relation between trajectory orientation and trajectory order that does not appear to bear on the research question, although the clearest pattern was higher error when the trajectory order began with the 45° trajectory. This was probably a general negative effect of commencing with two oblique trajectories in succession. For 6-month-old, the trajectory orientation effect was not significant when the trajectory order began with the 45° trajectory (Order 3). This is again likely due to a negative effect of commencing with two oblique movements in succession because the trajectory orientation effects were significant for other trajectory orders ($p \leq .011$).

Finally, to test whether infants' performance improved across trials or declined due to habituation, we compared performance on the first and the last test trial. Infants showed a small non-significant decline in performance on this measure, $t(31) = 0.92$, $p = .36$.

Dwell time within a moving area of interest (AoI). Again using MATLAB, we measured time on target by capturing total dwell time (in seconds) for each of the four trajectory orientations (20 s each) within a moving circular AoI centered on the ball. Initial investigation indicated that setting the AoI to the diameter of the ball resulted in rather low dwell times ($M = 3.65$ s, $SE = .32$) because as seen in the AvgD analysis, on average fixations were outside

the area of the ball (4-month-old AvgD = 4.02 cm; 6-month-old AvgD = 2.55 cm). For a fixation to be within the size of the AoI, the distance between gaze and center of the object had to be < 2.25 cm. Consequently, to take account of tracking lag, we set the diameter of the AoI to twice the diameter of the ball. This avoided both a floor effect and a ceiling effect in dwell times ($M = 9.04$ s, $SE = .62$), and thus increased the likelihood of detecting accuracy differences between different trajectories. Preliminary analysis revealed no significant main effect or interaction for gender of participants or animation start position and so these factors were collapsed for analysis.

Figure 3 shows the mean dwell time within the moving AoI plotted by age and trajectory orientation. As with AvgD, performance by both age groups looks poorer for oblique trajectories, but better performance by 6-month olds means that their performance on oblique trajectories looks comparable to 4-month olds' performance on horizontal and vertical trajectories. An age (4-month olds vs. 6-month olds) \times trajectory orientation (horizontal vs. vertical vs. 45° oblique vs. 135° oblique) \times trajectory order (0°:90°:45°:135° vs. 90°:45°:135°:0° vs. 45°:135°:0°:90° vs. 135°:0°:90°:45°) mixed ANOVA yielded significant main effects of age, $F(1, 24) = 20.47$, $p < .001$, $\eta_p^2 = .46$, and trajectory orientation, $F(3, 72) = 53.31$, $p < .001$, $\eta_p^2 = .69$. These were qualified by an interaction between trajectory orientation and age, $F(3, 72) = 3.60$, $p = .02$, $\eta_p^2 = .13$ (see Figure 3). The effect of trajectory orientation was significant for 4-month olds, $F(3, 45) = 12.91$, $p < .001$, $\eta_p^2 = .46$, and 6-month olds, $F(3, 45) = 32.71$, $p < .001$, $\eta_p^2 = .69$. Post-hoc Bonferroni corrected pairwise analysis for 4-month olds

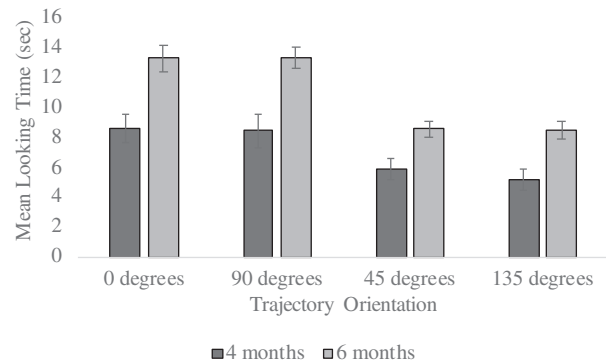


Figure 3. Mean dwell time within the moving area of interest plotted by age and trajectory orientation for Experiment 1. The maximum total dwell time is 20 s summed across the two trials for each orientation.

and 6-month olds revealed that both age groups were better in tracking horizontal and vertical movements than both of the oblique movements ($p \leq .02$). Further comparisons between age groups showed significantly better tracking by 6-month olds than 4-month olds for all trajectory orientations: vertical and horizontal ($p < .001$) and obliques ($p \leq .006$). Thus, the interaction appears to be due to the fact that the superiority in tracking of vertical and horizontal trajectories over oblique trajectories is greater for 6-month olds than it is for 4-month olds. Additionally, on this measure, 6-month olds tracked oblique object movements as accurately as 4-month olds tracked horizontal and vertical object movements: 6-month-old 45° oblique versus 4-month-old horizontal, $t(30) = 0.06$, $p = .96$; 6-month-old 45° oblique versus 4-month-old vertical, $t(30) = -0.09$, $p = .93$; 6-month-old 135° oblique versus 4-month-old horizontal, $t(30) = 0.09$, $p = .93$; 6-month-old 135° oblique versus 4-month-old vertical, $t(30) = -0.06$, $p = .95$.

There was also a significant interaction between trajectory orientation and trajectory order, $F(9, 72) = 2.96$, $p = .005$, $\eta_p^2 = .27$. When the infants began with the 135° trajectory (Order 4), they tracked more accurately on the 135° trajectory than the 45° trajectory that came last in that sequence ($p = .007$). This seems likely due to a specific order effect because comparison of performance on 135° and 45° trajectories presented first yielded no difference ($p = .48$). In contrast, when the animation began with the 45° trajectory (Order 3), infants tracked vertical and horizontal trajectories relatively poorly and showed no significant differences between tracking each orientation ($p \geq .079$). As in the case of AvgD, this is likely due to a negative effect of commencing with two oblique movements in succession.

As with the AvgD measure, we compared performance on the first and the last test trial. Infants showed a significant decline in performance on this measure, $t(31) = 4.75$, $p < .001$, which is likely due to habituation across trials.

Discussion

Both AvgD and dwell time measures converged to reveal the same pattern of performance, from which two very clear results emerged. First, 6-month olds were more accurate at tracking the moving image, for all trajectory orientations. Second, both age groups tracked horizontal and vertical trajectories more accurately than oblique trajectories. The interactions between trajectory

orientation and trajectory order did not qualify the overall effects of trajectory, other than to indicate that when infants encountered two oblique trajectories as first and second displays, poorer performance on these appeared to carry over to produce a negative effect on performance on subsequent vertical and horizontal trajectories.

Unexpectedly, we did not find that vertical tracking was less accurate than horizontal tracking, although for 4-month olds there was a trend in this direction for all but one trajectory order. It seems likely that the lack of a clear horizontal advantage arose because we did not use sinusoidal object motion, circumstances under which the horizontal tracking advantage has been detected in infancy (Grönqvist et al., 2006).

The finding that 4-month olds tracked horizontal and vertical trajectories better than oblique trajectories provides a plausible explanation of the fact that this age group perceive persistence of objects moving vertically or horizontally through occlusion, but not for objects moving obliquely (Bremner et al., 2017). However, at first sight, the even stronger trajectory orientation effect for 6-month-olds, apparent in both measures, does not appear to explain why that age group perceives object persistence for all trajectories (Bremner et al., 2017). However, it is important to note that on both measures 6-month olds performed as well with oblique trajectories as 4-month olds did with horizontal and vertical trajectories. This raises the possibility that a minimum level of tracking is required to support perception of object persistence across occlusion, whereas 4-month olds only achieve this level with vertical and horizontal trajectories, 6-month olds achieve it for all trajectories.

Experiment 2

Although these results present a plausible explanation of 4-month-old infants' inability to perceive persistence of an object moving on an oblique trajectory, a stronger link could be made if we could demonstrate the same effects on tracking in a moving object occlusion event of the sort used to investigate perception of object persistence. Thus, in Experiment 2, we directly compared orientation effects on tracking accuracy with displays with and without an occluder in the object's path. Because in Experiment 1 we did not obtain a difference in tracking accuracy between horizontal and vertical trajectories, we presented only horizontal and oblique trajectory displays to limit the number of trials

infants were exposed to. On the face of it, a direct comparison between trials with and without an occluder is potentially made difficult by the fact that the object is absent for part of the trajectory, but it is possible that infants will continue to track across the gap in perception. Additionally, by choosing an occluder width used by Bremner et al. (2017), we ensured that the object was totally out of sight for a very short time.

Method

Participants

Sixteen 4-month-old infants ($M = 129.1$ days, range = 114–142 days; 6 girls) and sixteen 6-month-old infants ($M = 186.1$ days, range = 175–196 days; 9 girls) took part in the experiment. A further two 4-month olds and eight 6-month olds did not complete testing due to fussiness ($n = 9$) or failure to calibrate ($n = 1$). Infants were recruited during 2019 in the same fashion and from the same population as in Experiment 1.

Apparatus and Stimuli

As in Experiment 1, Adobe Animate software was used to create visual displays. Unoccluded visual displays were identical to a subset of those in Experiment 1, and consisted of an image of a 4.5 cm sphere (3.2°) on a black background that translated back and forth on a horizontal or diagonal (45° oblique or 135° oblique) trajectory. The length of the trajectory, rate of motion, and translation time were identical to Experiment 1. In the case of the occluded visual displays, a stationary centrally placed blue occluder with a long dimension 14.5 cm (10.3°) and short dimension 4.7 cm (3.4°) hid the sphere temporarily (it was hidden completely for 667 msec.) as it translated back and forth behind the occluder. The visual angle of the occluder was similar to that reported in Bremner et al. (2017). For each of the occluded trajectory visual displays (horizontal, 45° oblique, and 135° oblique), the occluder was centrally placed so that the short dimension was aligned to the path of movement of the sphere (see Figure 1).

Procedure

Other than the displays presented, the procedure for this experiment was the same as in Experiment 1. Infants were presented with eight tracking trials in total with an attention getter prior to the start of

each trial. The visual displays presented in these trials differed in terms of trajectory orientation (horizontal and one of the two oblique orientations) and occluder type (occluded, unoccluded trials). Half of the participants were presented with the horizontal and 45° oblique trajectories both occluded and unoccluded, whereas the other half were presented with the horizontal and 135° oblique trajectories occluded and unoccluded. There were two counterbalanced blocks of occluded and unoccluded trials. Each block consisted of alternating trials between horizontal and one of the two oblique trajectories counterbalanced by the start position (e.g., left vs. right for horizontal) of each trajectory resulting in four trials in each block. All participants began with the horizontal trajectory. For an example of one order, a subgroup of infants saw a block of occluded trials that began with horizontal (movement from left to right), 45° oblique (movement from bottom left to top right), horizontal (movement from right to left), and 45° oblique (movement from top right to bottom left) trajectories, and then saw a second block of unoccluded trials with the same trajectory orientation and trajectory start order. This resulted to eight trials in total. An equal number of infants was allocated to each of the resulting four combinations.

Results

AvgD

As in Experiment 1, average distance between point of gaze and the center of the object was calculated. Because there were no differences between point of gaze and the center of the object for participants presented with 45° and 135° trajectories, in the occluded, $t(30) = -0.32$, $p = .75$ and unoccluded, $t(30) = 0.50$, $p = .62$, conditions, we collapsed data across these orientations and compared diagonal with horizontal trajectories.

Figure 4 shows the AvgD plotted by age and trajectory orientation. This suggests that accuracy was again greater for older infants, but was lower for diagonal trajectories. It also appears that accuracy was slightly greater for occluded trials than unoccluded trials. An age (4-month olds vs. 6-month olds) \times trajectory orientation (horizontal vs. diagonal) \times display type (occluded vs. unoccluded trials) \times display order (occluded trials first vs. unoccluded trials first) mixed ANOVA yielded significant main effects of age, $F(1, 28) = 5.06$, $p = .03$, $\eta_p^2 = .15$, trajectory orientation, $F(1, 28) = 538.01$, $p < .001$, $\eta_p^2 = .95$, and display type, $F(1,$

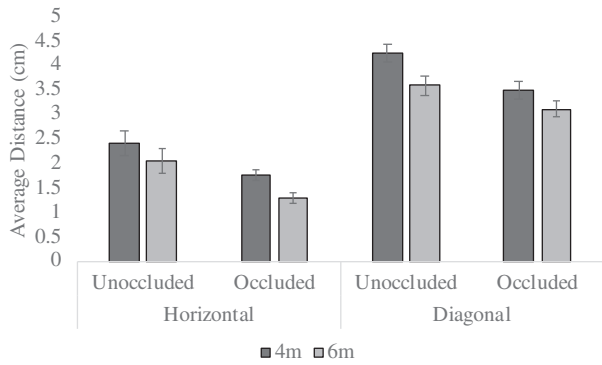


Figure 4. Average distance between gaze and center of the object plotted by age, display type, and trajectory orientation for Experiment 2.

28) = 37.97, $p < .001$, $\eta_p^2 = .58$. Four-month olds had a larger AvgD ($M = 2.99$ cm: 2.1° , $SE = .15$ cm: 0.1°) in comparison to 6-month olds ($M = 2.52$ cm: 1.8° , $SE = .15$ cm: 0.1°), diagonal trajectories had a larger AvgD ($M = 3.62$ cm: 2.6° , $SE = .10$ cm: 0.1°) in comparison to horizontal trajectories ($M = 1.88$ cm: 1.3° , $SE = .12$ cm: 0.1°), and unoccluded trials ($M = 3.07$ cm: 2.2° , $SE = .14$ cm: 0.1°) had a larger AvgD in comparison to occluded trials ($M = 2.43$ cm: 1.7° , $SE = .09$ cm: 0.1°).

There was also a two-way interaction between display type and display order, $F(1, 28) = 13.55$, $p = .001$, $\eta_p^2 = .33$, that was qualified by a three-way interaction between display type, display order, and age, $F(1, 28) = 9.58$, $p = .004$, $\eta_p^2 = .26$. This interaction is located in the 4-month olds' data, where there was a significant interaction between display type and display order, $F(1, 14) = 40.94$, $p < .001$, $\eta_p^2 = .75$, in comparison to the 6-month olds' data, for which the display type by display order interaction was not significant, $F(1, 14) = 0.13$, $p = .74$, $\eta_p^2 = .01$. The interaction in the 4-month-olds' data was due to significantly larger AvgD on unoccluded trials that followed occluded trials, than when they came first ($p = .004$), compared to no order difference for occluded trials ($p = .34$). Possibly unoccluded trials were less engaging (hence less accurate tracking on these trials overall), an effect that was enhanced following block of occlusion trials. When unoccluded trials came first, there was no difference in 4-month olds' accuracy between unoccluded and occluded trials ($p = .20$).

Finally, we compared performance on the first and the last test trials. Given the possibility that superior performance on occluded trials was due to their more engaging nature, we included trial type in this analysis. A trial (first vs. last) by display

type (occluded vs. unoccluded) repeated measures ANOVA yielded a main effect of trial, $F(1, 31) = 373.98$, $p < .001$, $\eta_p^2 = .92$, and no significant interaction between trial and display type, $F(1, 31) = 0.40$, $p = .53$.

Dwell Time

As in Experiment 1, using MATLAB, we measured time on target by capturing total dwell time (in seconds) for each of the two trajectory orientations and display types (20 s each: horizontal and either 45° or 135° occluded animations, and horizontal and either 45° or 135° unoccluded animations) within a moving circular AoI centered on the ball. Again, initial investigation indicated that setting the AoI to the diameter of the ball resulted in rather low dwell times ($M = 3.89$ s, $SE = .42$ s) because fixations were largely outside the AoI due to tracking lag. Consequently, to take account of tracking lag, we again set the diameter of the AoI to twice the diameter of the ball, which avoided a floor effect in dwell times ($M = 9.47$ s, $SE = .65$ s), and thus increased the likelihood of detecting accuracy differences between different trajectories. Because there were no differences between participants presented with 45° trajectory and 135° trajectory in the occluded, $t(30) = -1.57$, $p = .13$, and unoccluded animations, $t(30) = -0.39$, $p = .70$, we collapsed data across these orientations and compared diagonal with horizontal trajectories. Preliminary analysis revealed no significant main effect or interaction for gender or horizontal start position and so these factors were collapsed for analysis.

Figure 5 shows the mean dwell time within the moving AoI plotted by age and trajectory orientation. This suggests that again on this measure older

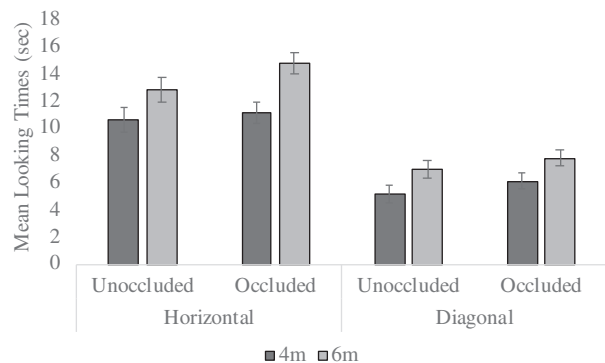


Figure 5. Mean dwell time within the moving area of interest plotted by age, display type, and trajectory orientation for Experiment 2. The maximum total dwell time is 20 s summed across the two trials for each orientation/display type.

infants were more accurate, accuracy was lower for diagonal trajectories, and performance was slightly better for occluded displays. An age (4-month olds vs. 6-month olds) \times trajectory orientation (horizontal vs. diagonal) \times display type (occluded vs. unoccluded) \times display order (occluded trials first vs. unoccluded trials first) mixed ANOVA yielded significant main effects of age, $F(1, 28) = 6.42, p = .02, \eta_p^2 = .19$, trajectory orientation, $F(1, 28) = 253.92, p < .001, \eta_p^2 = .90$, and display type, $F(1, 28) = 15.0, p = .001, \eta_p^2 = .35$. Six-month olds had longer dwell times ($M = 10.62$ s, $SE = .65$ s) than 4-month olds ($M = 8.31$ s, $SE = .65$ s), there were longer dwell times for the horizontal trajectory ($M = 12.38$ s, $SE = .57$ s) than the diagonal trajectory ($M = 6.55$ s, $SE = .4$ s), and longer dwell times for occluded trials ($M = 10.02$ s, $SE = .41$ s) than unoccluded trials ($M = 8.92$ s, $SE = .53$ s).

As with the AvgD analysis, there was also a two-way interaction between display type and display order, $F(1, 28) = 24.92, p < .001, \eta_p^2 = .47$, that was qualified by a three-way interaction between display type, display order, and age, $F(1, 28) = 9.37, p = .005, \eta_p^2 = .251$. Again, this interaction is located in the 4-month-olds' data, where there was a significant interaction between display type and display order, $F(1, 14) = 38.45, p < .001, \eta_p^2 = .73$, in comparison to the 6-month olds' data, for which the display type by display order interaction was not significant, $F(1, 14) = 1.61, p = .23, \eta_p^2 = .10$. The interaction in the 4-month olds' data were due to significantly smaller dwell times in the AoI on unoccluded trials that followed occluded trials, than when they came first ($p = .045$), compared to no order difference for occluded trials ($p = .15$). In terms of accuracy, this is a similar pattern to that observed on the AvgD measure and is open to the same interpretation. When unoccluded trials came first, there was no difference in 4-month-olds' accuracy between unoccluded and occluded trials ($p = .52$).

As with the AvgD measure, we compared performance on the first and the last test trials, again including trial type in the analysis. A trial (first vs. last) by display type (occluded vs. unoccluded) repeated measures ANOVA yielded a main effect of trial, $F(1, 31) = 316.92, p < .001, \eta_p^2 = .91$, and no significant interaction between trial and display type, $F(1, 31) = 0.018, p = .89$.

Discussion

The important finding emerging from both measures in Experiment 2 is that oblique tracking was

again less accurate when the object passed behind an occluder, that is, under display conditions very similar to those presented in object persistence work. Again, 6-month olds were more accurate than 4-month olds, with or without an occluder. Interestingly, infants tracked more accurately when the occluder was present than when it was absent. One might have expected temporary occlusion or simply the presence of the static occluder to disrupt tracking. However, the object was totally out of sight for a very short time (667 ms) and it is quite likely that the events involving occlusion attracted more attention through presenting more information. If it was the occlusion event rather than the occluder that attracted greater attention, this could explain greater tracking accuracy in this condition. However, accuracy fell off equally in occluded and unoccluded trials, so if greater accuracy on occluded trials was due to greater attention, there was no evidence that attention was maintained more across trials for the occluded display.

General Discussion

Experiment 1 indicates that both 4- and 6-month olds are less accurate in tracking oblique trajectories than vertical and horizontal trajectories, and Experiment 2 confirms that this oblique deficit also applies when the object is temporarily occluded in the middle of its path. Although the oblique deficit applies at both ages, superior performance across orientations by 6-month olds may mean that they have reached a tracking threshold for all trajectory orientations that is sufficient to support perception of object persistence in moving object occlusion tasks. Such an account of the relation between tracking and object persistence is in keeping with the explanation that Bremner et al. (2017) presented to account for differences in findings across studies. Bremner et al. (2007) found that 4-month olds detected perception of continuity of a shallow (32°) oblique trajectory provided the occluding contours were orthogonal to the trajectory. In contrast, Bremner et al. (2017) found that 4-month olds did not detect continuity of an object moving on a 45° oblique trajectory even if the occluding contours were orthogonal to the trajectory. They suggested that the difficulty of coordinating vertical and horizontal intraocular muscles is liable to increase with increasing obliquity, and reconciled their findings in terms of a model in which trajectory continuity is perceived only when processing load remains below a particular level (cf. Johnson, 1997).

Processing horizontal and vertical trajectories and processing disappearance at an oblique occluding contour do not together exceed the processing level for detection of object persistence by 4-month olds. Processing a 45° oblique trajectory, however, apparently does exceed this level under tested conditions. Processing a shallow (32°) trajectory does not appear to exceed the level, but does if combined with the processing load for disappearance at an oblique occluding edge. It seems likely that tracking accuracy contributes directly to processing load in the sense that increased accuracy reduces the load in perceiving an object's trajectory and in extrapolating that trajectory behind an occluder. Thus, the increased tracking accuracy shown by 6-month olds across all trajectories likely contributes directly to their ability to perceive object persistence in the case of oblique as well as horizontal and vertical object movements. If this is the case, it may also be the case that improved tracking that results from presentation of sinusoidal object motion rather than the saw tooth motion used in object persistence work might result in better perception of object persistence in 4-month olds and even younger infants.

Limitations

As indicated in the introduction, our aim was to investigate tracking accuracy under conditions similar to those existing in work on object persistence, so we did not present object movements that were necessarily optimal for most accurate tracking. In particular, presentation of sinusoidal motion might have led to more accurate tracking. Although we believe that our effects relating to trajectory orientation are robust, our results should not be taken as definitive estimates of best tracking by the age groups tested.

Although our finding that infants tracked more accurately in the presence of an occluder may well be due to this display attracting more attention than a simple moving object display, this result was not predicted, and our interpretation is speculative.

Our power calculations were based on predicted effects of trajectory orientation and age and their interactions. Thus, on the face of it, our study may have been under-powered to detect unpredicted interactions involving trajectory order. Nevertheless, interactions between trajectory and trajectory order emerged with large effect sizes consistently across measures. Additionally, the theoretically significant main effects of trajectory and age and their interactions emerged clearly despite interactions involving trajectory order.

Conclusion

We believe that the conclusions that can be drawn from these two experiments may have important implications for research that uses moving object tasks to assess infants' object perception and knowledge. A general methodological conclusion is that infants' performance on tasks designed to measure high-level perception or cognition should be designed with constraints on lower-level tracking in mind. Here we have demonstrated that infants' tracking of objects moving on oblique trajectories is poorer than for vertical or horizontal trajectories. However, we should also draw on other findings from the object tracking literature in designing investigations that involve moving object events. To an extent, this has happened. For instance, work using moving object occlusion displays to investigate 2- to 6-month-old infants' perception of object persistence (Bremner et al., 2005, 2007, 2017; Johnson et al., 2003) has been informed by work on object tracking (Mareschal et al., 1997) in selecting appropriate object speeds. However, different object speeds are likely to be optimal at different ages, and the choice is liable to be crucial in the first two months (Aslin & Shea, 1990). Also, we know that infant tracking is more accurate for objects moving sinusoidally rather than on "triangular" saw tooth trajectories (von Hofsten & Rosander, 1997), but to our knowledge studies of object persistence use displays in which the object moves at constant velocity from starting points or between reversals, conditions that may not be optimal for object tracking. The lesson that we have learned is that there is a need for close attention to the literature on the development of smooth tracking when setting the parameters in tasks involving moving objects.

Finally, in our view, the apparent link between tracking accuracy and perception of object persistence provides further support for a model in which perception of object persistence is initially dependent on lower level perceptual capacities. It has already been argued that perception of the persistence of an object moving through occlusion is initially dependent on the presence of multiple cues to occlusion (Bremner et al., 2015). However, it seems likely that perception of object persistence is limited to situations in which object movement parameters match the infant's limited tracking ability. This is more than a methodological issue, because the implication is that infants' everyday experience will comprise a range of objects and object speeds, some of which may not be sufficiently optimal to support perception of the persistence of the object when it goes out

of sight. Thus, rather than perceiving object persistence across the board, infants' perception of persistence may be initially quite patchy. So in addition to development of object knowledge being dependent on accumulated experience of events, it is also liable to be dependent on the infant's increasing ability to perceive events veridically.

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