Orientation effects in the development of linear object tracking in early infancy

Diana S.Y. Tham, Alison Rees, Gavin Bremner

Lancaster University

Alan Slater

University of Exeter

Scott P Johnson

UCLA

Author note

This research was funded by Leverhulme Trust Research Grant RPG-2014-376 awarded to the third and fourth authors. The authors are grateful to Peter Tovee for assistance in data coding. The authors acknowledge the assistance of staff of University Hospitals of Morecambe Bay NHS Trust in recruitment, and are grateful to parents and infants who took part in the work. Address enquiries to the third author: j.g.bremner@lancaster.ac.uk

Abstract

Infants' 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 infants do not perceive persistence for objects moving obliquely. To investigate whether this constraint results from young infants' poorer oblique oculomotor tracking, in two experiments we recorded eye movements of 16 4-month-old and 16 6-month-old infants tracking horizontal, vertical, and oblique trajectories. Six-month-olds tracked more accurately, and both age groups tracked horizontal and vertical trajectories more accurately than oblique trajectories. However, 6-month-olds tracked oblique trajectories as accurately as 4-month-olds tracked horizontal and vertical trajectories. Similar results were also obtained when the object passed behind an occluder mid-trajectory. Thus, 4-month-olds tracking of oblique trajectories may be insufficient to support object persistence, whereas six-month-olds may have reached a tracking threshold for all trajectory orientations sufficient to support perception of object persistence.

Keywords: linear tracking, orientation effects, object persistence

Orientation effects in the development of linear object tracking in early infancy

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 localise 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 localise 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 to 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, 1989). 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.

Thus, 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 of age (Johnson, Bremner, Slater, Mason, Foster, & Cheshire, 2003). The evidence for this follows habituation to an event in which an object cycles back and forth, passing behind an occluder in the middle part of its trajectory. Infants presented with either continuous or discontinuous object trajectories in the absence of the occluder look longer at the discontinuous trajectory, implying that they perceived the habituation display as composed of a continuous movement. However, 4-month-olds only perceive object persistence when the gap in perception is short spatially (Bremner, Johnson, Slater, Mason, Foster, & Spring, 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, Johnson, Slater, Mason, Cheshire, & Spring, 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, Gredebäck, & von Hofsten, 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. Further, 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, Gredebäck, & von Hofsten, 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 time on target and the average distance between gaze and the center of the target seemed appropriate, the former 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, and the latter because it is one of the primary measures used in other work on object tracking. We obtained both of these measures with an eye tracker. In addition, rather than optimise the conditions for tracking accuracy, we aimed to present a task in which the object movements mimicked those presented in the object persistence work. Thus, 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, 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 Caucasian-White infants of mainly middle class parents recruited 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°/s), comparable to the 9.4°/sec rate of motion in object persistence work (Bremner et al., 2017). In order to maximise 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 seconds and the ball translated twice for each animation. A 60cm x 33.5cm monitor was used for the presentation of stimuli. A Tobii x60 eye-tracker 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, 8 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 sec. There were two blocks of trials. Each block consisted of a combination of horizontal (0°), vertical (90°), 45° oblique, and 135° oblique trajectories. A Latin square ordering resulted in four different trajectory order (0°:90°:45°:135°; 90°:45°:135°:0°; 45°:135°:0°:90°; 135°:0°:90°:45°), 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. 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). Data consisted of x-y coordinates of the point of gaze on the stimulus monitor recorded at 60Hz. The average distance between point of gaze and center of the object was calculated using root mean square (in cm) for each trial. The average distance between point of gaze and center of the object (AvgD) was calculated with MATLAB. Figure 2 shows AvgD plotted by age and trajectory orientation. This suggests that performance by both age groups is poorer for oblique trajectories, but that 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.

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. An age (4-month-olds vs. 6-month-olds) x trajectory orientation (horizontal vs. vertical vs. 45° oblique vs. 135° oblique) x 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) = 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* = 0.24 cm: 0.2°) in comparison to 6-month-olds (*M* = 2.55 cm: 1.8°, *SE* = 0.24 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: 0.1°) had significantly smaller AvgD in comparison to both the 45° oblique trajectory (*M* = 4.0 cm: 2.9°, *SE* = 0.17 cm :0.1°), t (31) = -9.375, $p <$ .001, and the 135° oblique trajectory (*M* = 4.05 cm: 2.9°, *SE* = 0.22 cm: 0.2°), t (31) = -6.69, $p < .001$. Similarly, the vertical trajectory (*M* = 2.47 cm: 1.8°, *SE* = 0.20 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 vs. 4-month-old horizontal, $t(30) = -.25$, $p = .80$; 6-month-old 45 ° oblique vs. 4-month-old vertical, $t(30) = .13$; $p = .90$, 6-month-old 135° oblique vs. 4-month-old horizontal, $t(30) = -.12$, $p = .90$; six-month-old 135° oblique vs. 4-month-old vertical, $t(30) = .22$, $p = .83$.

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, $\eta_p^2 = .27$ (see Figure 3). 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 45^0 orientation. This was probably a general negative effect of commencing with two oblique trajectories in succession. For 6-month-olds, the trajectory orientation effect was not significant when the trajectory order began with 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 ($p \leq .011$).

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 seconds each) within a moving circular area of interest (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 sec., SE = 0.32) because as seen in the AvgD analysis, on average fixations were outside the area of the ball (4-month-old AvgD = 4.02cm; 6-month-old AvgD = 2.55cm). For a fixation to be within the size of the area of interest (AoI), the distance between gaze and centre of the object had to be less than 2.25cm. Consequently, to take into account 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 sec., $SE = 0.62$), and thus increased the likelihood of detecting accuracy differences between different trajectories.

Figure 4 shows 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. 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. An age (4-month-olds vs. 6-month-olds) x trajectory orientation (horizontal vs. vertical vs. 45° oblique vs. 135° oblique) x 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 4). 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 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 ($p \leq .001$) 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 vs. 4-month-old horizontal, $t(30) = .06$, $p = .96$; 6-month-old 45°

oblique vs. 4-month-old vertical, $t(30) = -.09$, $p = .93$; 6-month-old 135° oblique vs. 4-month-old horizontal, $t(30) = .09$, $p = .93$; six-month-old 135° oblique vs. 4-month-old vertical, $t(30) = -.06$, $p = .95$.

There was also a significant interaction between trajectory orientation and trajectory order, F (9, 72) = 2.96, $p = .005$, $\eta_p^2 = .27$ (see Figure 5). When the infants began with the 135° trajectory (order 4), infants 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.

Discussion

Both measures converged to reveal the same pattern of performance, from which two very clear results emerged. Firstly, 6-month-olds were more accurate at tracking the moving image, for all trajectory orientations. Secondly, 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 and 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. Although, 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, 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).

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 was identical to Experiment 1. In the case of the occluded visual displays, a stationary centrally placed blue occluder with a long dimension 14.5cm (10.3°) and short dimension 4.7cm (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 is 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 8 visual displays in total with an attention getter prior to the start of each visual display. The visual displays 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 both the horizontal and 45° oblique trajectories whereas the other half were presented with both the horizontal and 135° oblique trajectories. 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 (for example, left versus right for horizontal) of each trajectory resulting in 4 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), oblique 45°oblique (movement from bottom left to top right), horizontal (movement from right to left), and 45°oblique trajectories, and then saw a second block of unoccluded trials with the same trajectory orientation and trajectory start order. This resulted to 8 trials in total. An equal number of infants were allocated to each of the resulting four combinations.

Results

Average distance between gaze and center of the object (AvgD). As in Experiment 1, average distance between point of gaze and the center of the object was calculated. As 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. An age (4-month-olds vs. 6-month-olds) x trajectory orientation (horizontal vs. diagonal) x display type (occluded vs. unoccluded trials) x display order (occluded trials first vs. unoccluded trials first) mixed ANOVA yielded significant main effects of age, F (1, 28) = 5.06, p = .03, η_p^2 = .15, trajectory orientation, F (1, 28) = 538.01, p < .001, η_p^2 = .95, and display type, F (1, 28) = 37.97, p < .001, η_p^2 = .58. Four-month-olds had a larger AvgD (M = 2.99cm: 2.1°, SE = 0.15cm: 0.1°) in comparison to 6-month-olds (M = 2.52cm: 1.8°, SE = 0.15cm: 0.1°), diagonal trajectories had a larger AvgD (M = 3.62cm: 2.6°, SE = 0.10cm: 0.1°) in comparison to horizontal trajectories (M = 1.88cm:

1.3°, *SE* = 0.12cm: 0.1°), and unoccluded trials (*M* = 3.07cm: 2.2°, *SE* = 0.14cm: 0.1°) had a larger AvgD in comparison to occluded trials (*M* = 2.43cm: 1.7°, *SE* = 0.09cm: 0.1°).

There was also a two-way interaction between display type and display order, F (1, 28) = 13.55, p =.001, η_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, η_p^2 = .26 (see Figure 6). This interaction is located in the four-month-old data, where there was a significant interaction between display type and display order, F (1, 14) = 40.94, $p < .001$, η_p^2 = .75, in comparison to the 6-month-old data, for which the display type by display order interaction was not significant, F (1,14) = .13, p = .74, η_p^2 = .01. The interaction in the 4-month-old 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).

Dwell time within a moving area of interest (AoI). 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 seconds each: horizontal and either 45° or 135° occluded animations, and horizontal and either 45° or 135° unoccluded animations) within a moving circular area of interest (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* = 3.89s, *SE* = 0.42s) because fixations were largely outside the AoI due to tracking lag. Consequently, to take into account 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* = 9.47s, *SE* = 0.65s), and thus increased the likelihood of detecting accuracy differences between different trajectories. As 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. An age (4-month-olds vs. 6-month-olds) x trajectory orientation (horizontal vs. diagonal) x display type (occluded vs unoccluded) x display order (occluded trials first vs unoccluded trials first) mixed ANOVA yielded significant main effects of age, F (1, 28) = 6.42, p = .02, η_p^2 = .19, trajectory orientation, F (1, 28) = 253.92, p < .001, η_p^2 = .90, and display type, F (1, 28) = 15.0, p = .001, η_p^2 = .35. Six-month-olds had longer dwell times (M = 10.62s, SE = 0.65s) than 4-month-olds (M = 8.31s, SE = 0.65s), there were longer dwell times for the horizontal trajectory (M = 12.38s, SE = 0.57s) than the diagonal trajectory (M = 6.55s, SE = 0.4s), and longer dwell times for occluded trials (M = 10.02s, SE = 0.41s) than unoccluded trials (M = 8.92s, SE = 0.53s).

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, η_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, η_p^2 = .251 (see Figure 7).). Again, this interaction is located in the four-month-old data, where there was a significant interaction between display type and display order, F (1, 14) = 38.45, p < .001, η_p^2 = .73, in comparison to the 6-month-old data, for which the display type by display order interaction was not significant, F (1,14) = 1.61, p = .23, η_p^2 = .10. The interaction in the 4-month-old data was 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).

Discussion

The important finding demerging 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 msec) 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.

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 is 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.

Beyond what this work indicates regarding the relationship between trajectory orientation, tracking accuracy, and perception of object persistence, we believe that the general conclusions that can be drawn from these two experiments may have important wider 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 and Shea, 1990). Also, we know that infant tracking is more accurate for objects moving sinusoidally rather than on 'triangular' saw tooth trajectories (von Hofsten and Rosander), 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 consist of a range of 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.

References

Aslin, R.N. (1993). Perception of visual direction in human infants. In C.E. Granrud (Ed.) *Visual perception and cognition in infancy.* New Jersey: Laurence Erlbaum Associates. pp 91-120.

Aslin, R.N., & Salapatek, P. (1975). Saccadic localization of peripheral targets by the yery young human infant. *Perception and Psychophysics, 17,* 293-302. doi: 10.3758/BF03203214

Aslin, R.N., & Shea, S.L. (1990). Velocity thresholds in human infants: Implications for the perception of motion. *Developmental Psychology, 26,* 589-598. doi: 10.1037/0012-1649.26.4.589

Bertenthal, B. I., Longo, M. R., & Kenny, S. (2007). Phenomenal permanence and the development of predictive tracking in infancy. *Child Development, 78*, 350-363. doi: 10.1111/j.1467-8624.2007.01002.x

Bremner, J.G., Johnson, S.P., Slater, A.M., Mason, U., Cheshire, A., & Spring, J. (2007). Conditions for young infants' failure to perceive trajectory continuity. *Developmental Science, 10,* 613-624. doi: 10.1111/j.1467-7687.2007.00616.x

Bremner, J.G., Johnson, S.P., Slater, A.M., Mason, U., Foster, K., Cheshire, A., & Spring, J. (2005). Conditions for Young Infants' Perception of Object Trajectories. *Child Development, 76*, 1029-1043. doi: 10.1111/j.1467-7687.2007.00616.x

Bremner, J.G., Slater, A.M., & Johnston, S.P. (2015). Perception of object persistence: the origins of object permanence in infancy. *Child Development Perspectives, 9,* 7-13. doi: 10.1111/cdep.12098

Bremner, J.G., Slater, A.M., Mason, U., Spring, J., & Johnson, S.P. (2017). Limits of object persistence: Young infants perceive continuity of vertical and horizontal trajectories, but not 45-degree oblique trajectories. *Infancy, 22,* 303-322. doi: 10.1111/infa.12170

Gredebäck, G., & von Hofsten, C. (2004). Infants' evolving representations of object motion during occlusion: A longitudinal study of 6- to 12-month-old infants. *Infancy*, *6*, 165-184. doi: 10.1207/s15327078in0602_2

Gredebäck, G., von Hofsten. C., & Boudreau, J. P. (2002). Infants' visual tracking of continuous circular motion under conditions of occlusion and non-occlusion. *Infant Behavior and Development, 25*, 161-182. doi: 10.1016/S0163-6383(02)00119-4

Grönqvist, H., Gredebäck, G., & von Hofsten, C. (2006). Developmental asymmetries between horizontal and vertical tracking. *Vision Research, 46,* 1754-1761. doi: 10.1016/j.visres.2005.11.007

Johnson, S.P., Bremner, J.G., Slater, A.M., Mason, U.C., Foster, K., & Cheshire, A. (2003). Infants' perception of object trajectories. *Child Development*, *74*, 94-108. doi: 10.1111/1467-8624.00523

Mareschal, D., Harris, P., & Plunkett, K. (1997). Effects of linear and angular velocity on 2-, 4-, and 6-month-olds' visual pursuit behaviors. *Infant Behavior & Development*, *20*, 435-448. doi: 10.1016/S0163-6383(97)90034-5

Rottach, K.G., Zivotofsky, A.Z., Das, V.E., Averbuch-Heller, L., Discenna, A.O., Poonyathalang, A., & Leigh, R.J. (1996). Comparison of horizontal, vertical and diagonal smooth pursuit eye movements in normal human subjects. *Vision Research, 36*, 2189-2195. doi: 10.1016/0042-6989(95)00302-9

Schiller, P. H. (1998). The neural control of visually guided eye movements. In: J. E. Richards (Ed.), Cognitive neuroscience of attention. A developmental perspective (pp. 3–50). Mahwah, NJ: Erlbaum.

von Hofsten, C., & Rosander, K. (1996). The development of gaze control and predictive tracking in young infants. *Vision Research, 36,* 81-96. doi: 10.1016/0042-6989(95)00054-4 von Hofsten, C., & Rosander, K. (1997). Development of smooth pursuit tracking in young infants. *Vision Research, 37,* 1799-1810. doi: 10.1016/S0042-6989(96)00332-X

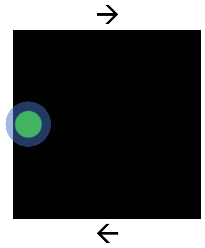
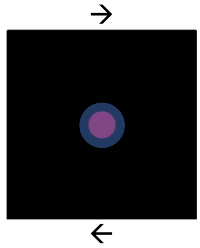
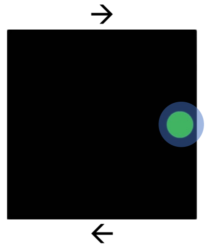
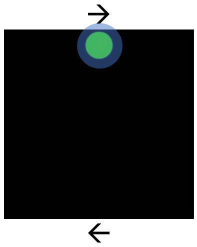
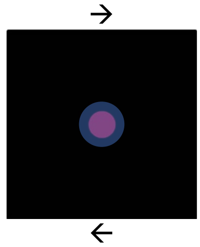
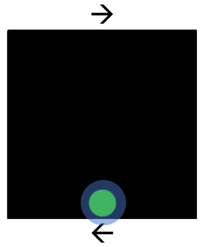
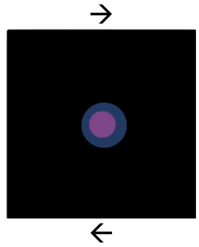
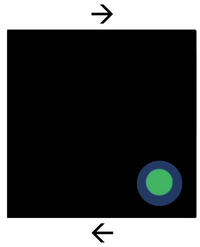
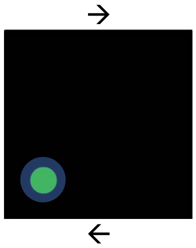
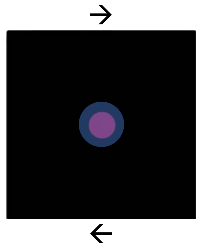
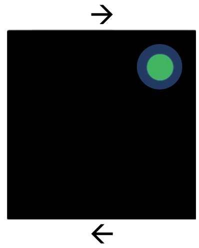
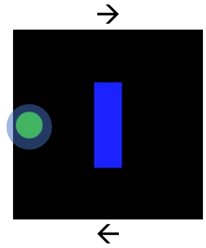
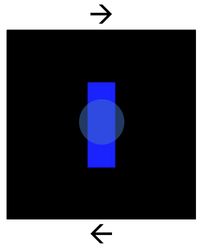
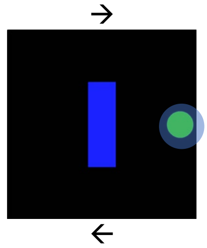
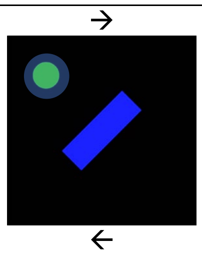
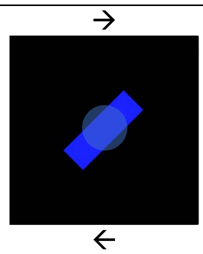
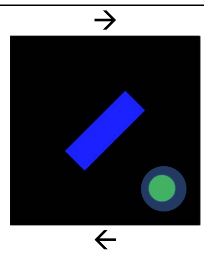
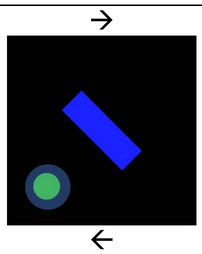
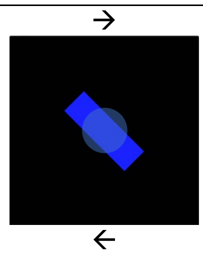
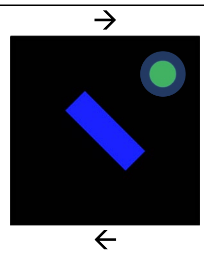
Horizontal unoccluded (Experiment 1 & 2)			
Vertical unoccluded (Experiment 1)			
45 ° oblique unoccluded (Experiment 1 & 2)			
135 ° oblique unoccluded (Experiment 1 & 2)			
Horizontal occluded (Experiment 2)			
45 ° oblique occluded (Experiment 2)			
135 ° oblique occluded (Experiment 2)			

Figure 1. Illustration of the horizontal, vertical, 45º oblique, and 135º oblique unoccluded and occluded visual displays presented to infants in Experiment 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 towards the accumulated dwell times.

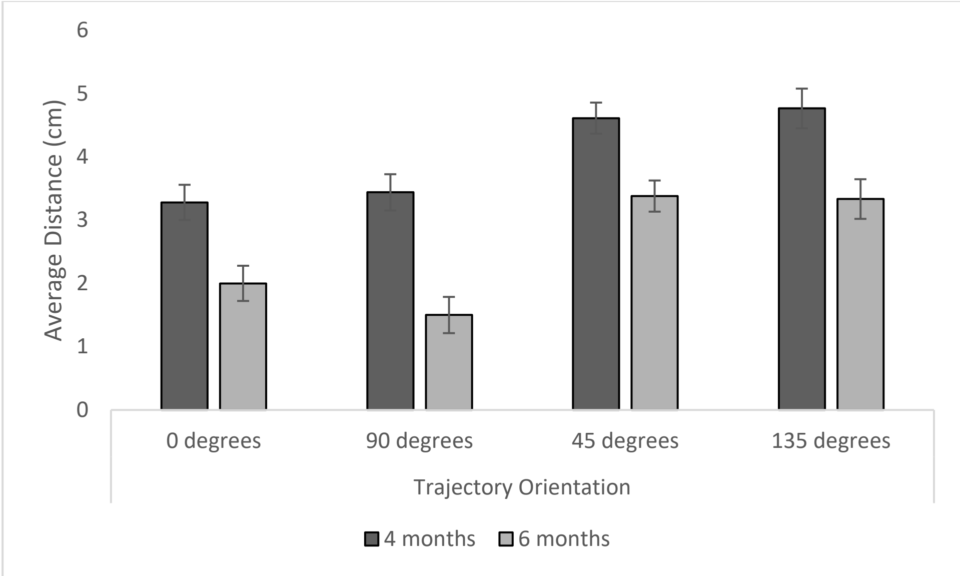


Figure 2. Average distance between gaze and center of the object (AvgD) plotted by age and trajectory orientation.

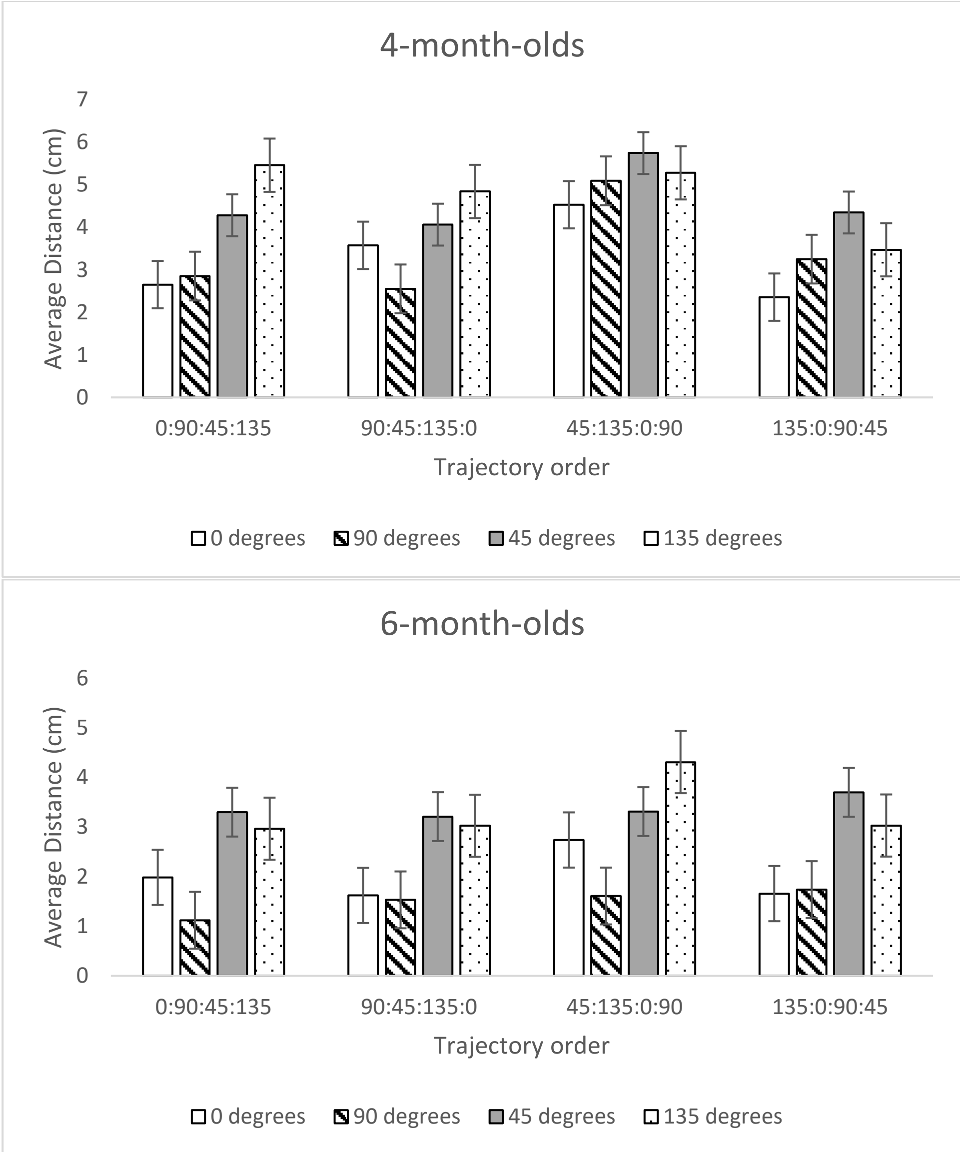


Figure 3. Interaction between animation order, trajectory orientation, and age for average distance between gaze and center o the object (AvgD).

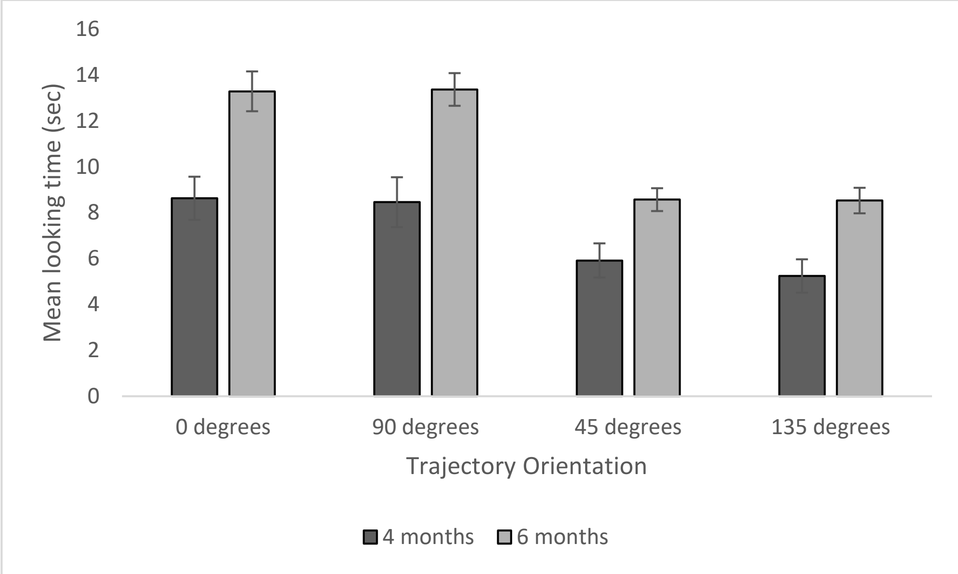


Figure 4. Mean dwell time within the moving area of interest (AoI) plotted by age and trajectory orientation.

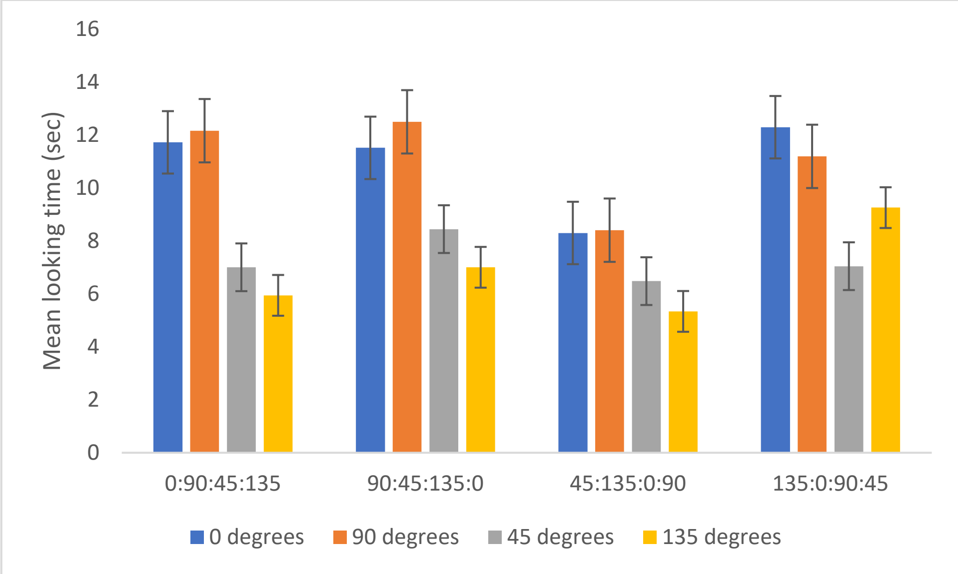
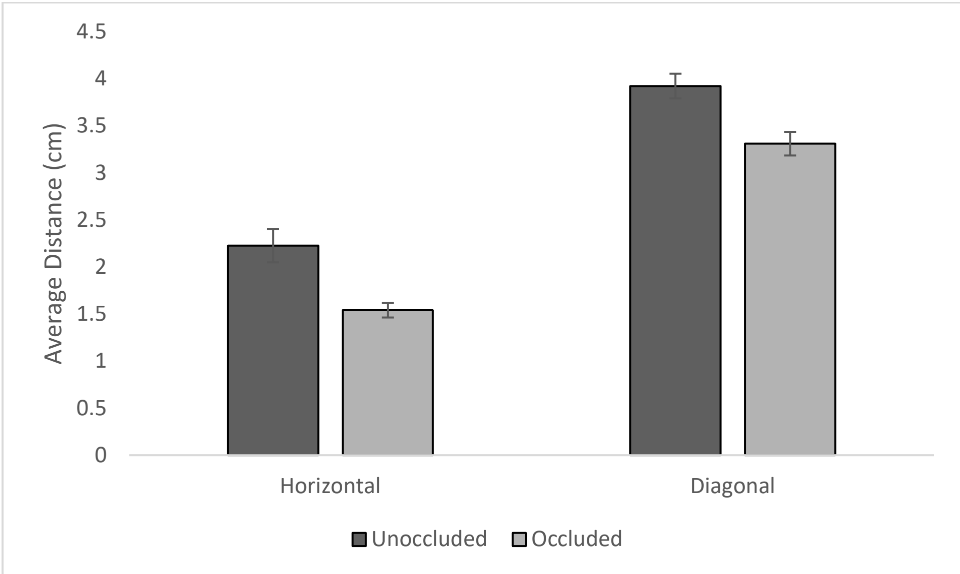
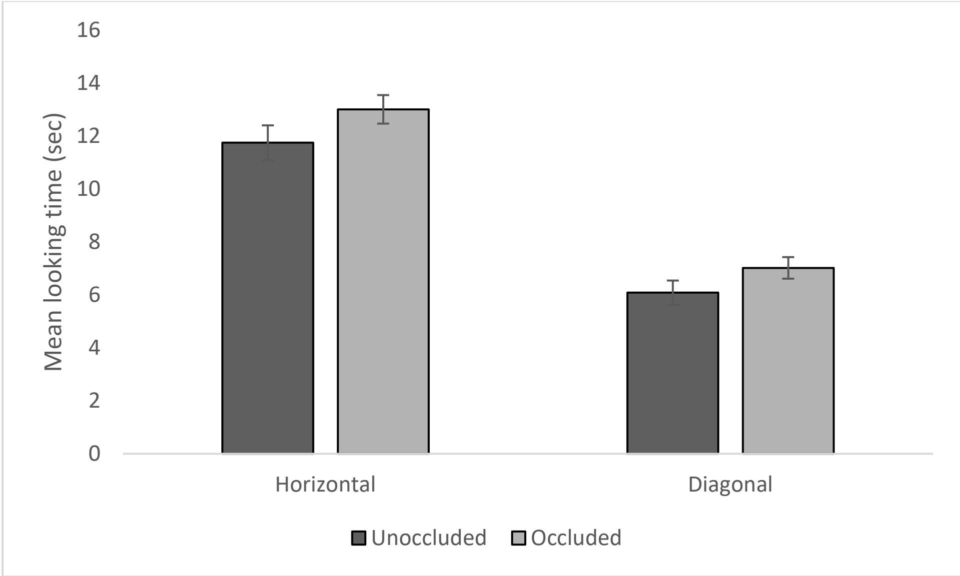


Figure 5. Interaction between trajectory orientation and trajectory order of dwell time within the moving area of interest (AoI).




16
14
12
10
8
6
4
2
0
Mean looking time (sec)
Horizontal
Diagonal
Unoccluded
Occluded

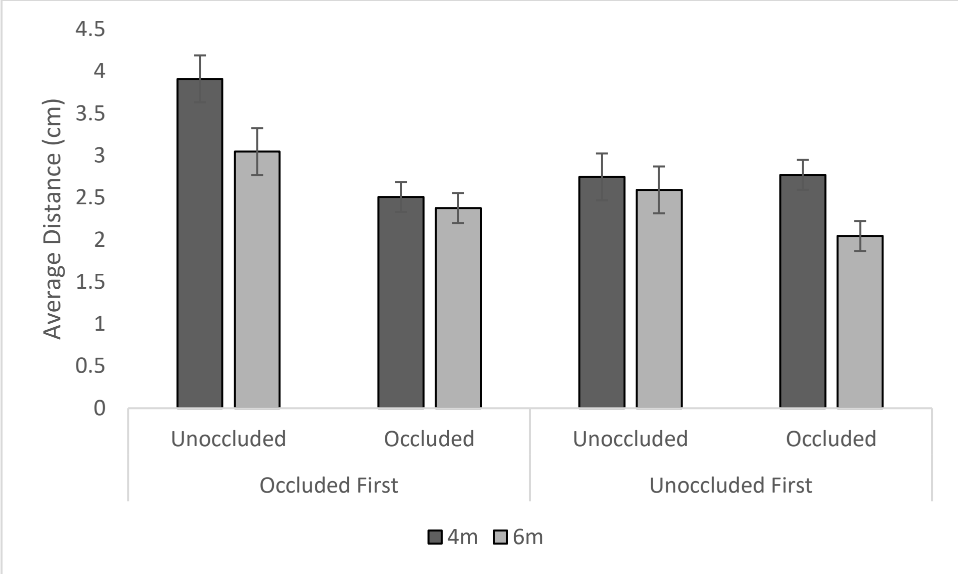


Figure 6. Average distance between gaze and center of the object (AvgD) plotted by occluder type, occluder order, and age.

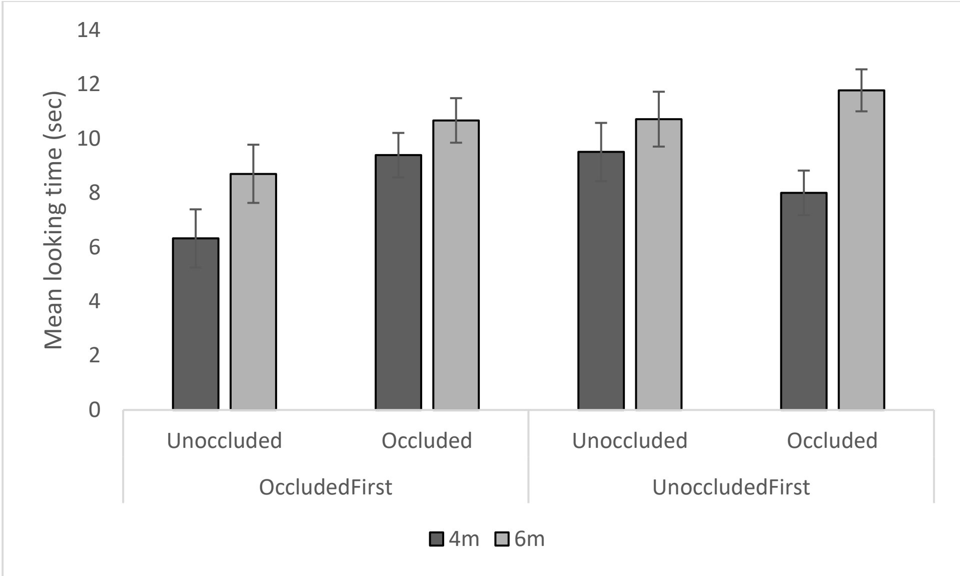


Figure 7. Interaction between occluder type, occluder order, and age of of dwell time within the moving area of interest (AoI).