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Limits of object persistence: Young infants perceive continuity of vertical and horizontal trajectories, but not 45-degree oblique trajectories

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Abstract

Previous research indicated that 4-month-old infants perceive continuity of objects moving on horizontal trajectories but appear to have difficulty processing occlusion events involving oblique trajectories. However, because perception of continuity of vertical trajectories has not been tested, it is uncertain whether this indicates a specific deficit for oblique trajectories or a specific advantage for horizontal trajectories. We evaluated the contribution of trajectory orientation and the form of occlusion in three experiments with 144 4-month-olds. Infants perceived continuity of horizontal and vertical trajectories under all conditions presented. However, they did not perceive continuity of an oblique (45˚) trajectory under any condition. Thus 4-month-olds appear unable to process continuity of a 45˚ trajectory. In a fourth experiment with 48 6- and 8-month-old infants, we demonstrated that by 6 months infants' difficulty with oblique trajectories is overcome. We suggest that young infants' difficulty with markedly oblique trajectories likely relates to immature eye movement control.

Limits of object persistence: Young infants perceive continuity of vertical and horizontal trajectories, but not 45-degree oblique trajectories

Perception of the continuity of objects' trajectories as they pass behind environmental features that temporarily hide them from view is a fundamental aspect of adults' perception of a world of enduring objects. Questions regarding the developmental origins of this ability have attracted considerable interest and controversy among investigators of infant ability.

There is now a long history of work that measures infants' responses to event sequences in which an object moves back and forth, passing behind an occluder for part of its path. Much of the early work interpreted infants' responses in terms of their knowledge of object permanence. For instance, Bower, Broughton, and Moore (1971) interpreted 2-month-olds' visual anticipation of re-emergence of the temporarily invisible object as evidence that the infants understood its continued existence while occluded (object permanence). However, questions arose about the reliability of earlier methods and, more recently, various investigators have used violation of expectation methods to investigate young infants' ability to reason about the path of a temporarily hidden object. For instance, infants' longer looking at an event in which an object appears to move through the position of a hidden obstruction is taken as evidence for understanding object permanence, the impenetrable nature of objects, and reasoning about the possibility or impossibility of events on the basis of this knowledge. Such claims are made about infants of 6 months (Baillargeon, 1986) or even 2.5 months of age (Spelke, Breinlinger, Macomber, & Jacobson, 1992).

However, some evidence calls in question the ability of young infants to reason about hidden objects' trajectories and about path obstruction. For instance, Spelke, Katz, Purcell, Ehrlich, and Breinlinger (1994) found that infants were incapable of inferring the invisible final resting position of an object from the visible segment of its trajectory. Also, even 2-

year-olds fail to search correctly for objects in tasks in which the object's location can be predicted from the visible part of its trajectory and knowledge of path obstruction (Hood, Carey, & Prasada, 2000). Additionally, use of predictive tracking as a measure of object knowledge is not without problems. Young infants' object tracking is highly sensitive to rate of object movement (Mareschal, Harris, & Plunkett, 1997; Muller & Aslin, 1978), and accuracy of predictive tracking increases with age (Gredebäck & von Hofsten, 2004; Johnson, Amso, & Slemmer, 2003; Rosander & von Hofsten, 2004). Although the tendency has been to interpret this improvement in terms of increased ability to represent the occluded object, it is possible that improvements in anticipatory tracking are linked to development of oculomotor control rather than object perception or knowledge (but see Johnson et al., 2003a for evidence from 4-month-olds against this possibility).

Given these concerns, the confidence with which we can reach conclusions regarding infants' trajectory perception would be increased if we could obtain confirmatory evidence from a different measure. Johnson, Bremner, Slater, Mason, Foster, and Cheshire (2003) habituated 2-, 4-, and 6-month-olds to an event in which an object moved back and forth, passing behind an occluder for the middle section of its path, and then presented test trials with the occluder removed which either involved the object moving on a continuous trajectory or consisted of the parts of the object's trajectory that had been visible during habituation (see Figure 1). When the occluder was 17.7 cm wide (10.1˚ visual angle), 4-month-olds looked longer at the continuous test display, whereas 6-month-olds looked longer at the discontinuous test display. In other words, 4-month-olds appeared to perceive the habituation event as involving a discontinuous trajectory (thus treating the continuous test display as novel), whereas 6-month-olds appeared to perceive it as involving a continuous trajectory. However, when the occluder was only 7.0 cm wide (4.0˚), 4-month-olds (but not 2-month-olds) perceived the habituation event as a continuous trajectory. A further experiment revealed an orderly relationship between occluder width and direction of preference on test trials.

Following this, Bremner, Johnson, Slater, Mason, Foster, Cheshire, and Spring (2005) manipulated time and distance out of sight separately by changing object size, object speed, and by speeding up and slowing down the object while it was behind the occluder. They found evidence that both time and distance out of sight were important variables; when either of these was short, 4-month-olds perceived the trajectory as continuous. Also, it has been demonstrated that the addition of auditory information for the object's trajectory supports perception of continuity across larger gaps in time and space (Bremner, Slater, Johnson, Mason, & Spring, 2012).

In a third study, Bremner, Johnson, Slater, Mason, Cheshire, and Spring (2007) demonstrated that 4-month-olds did not perceive trajectory continuity if the object's trajectory changed from a high horizontal to a low horizontal trajectory, or from a falling oblique to a rising oblique trajectory while it was out of sight. Additionally, the latter effect occurred even when a visible surface was provided that the object could have bounced on. Finally, it emerged that infants had difficulty processing oblique linear trajectories, 32 degrees from horizontal.

The results of these studies suggest that young infants' ability to perceive continuity of an object is subject to basic perceptual processing constraints, making it likely that the appropriate interpretation of infants' responses should be framed in terms of perceptual processing ability rather than in terms of object knowledge or reasoning about events. A specific assumption is that coherent deletion and accretion at occluding edges is perceived as the object disappearing behind the occluder and hence persisting while out of sight (Kahneman, Triesman, & Gibbs, 1992; Michotte, Thines, & Crabbe, 1964/1991). It is evident that deletion and accretion are sufficient to cue occlusion in adults, because they perceive object continuity even when there is no visible occluding surface (Kahneman et al., 1992; Kawachi & Gyoba, 2006; Michotte et al., 1964/1991). However, it appears that deletion and accretion are not sufficient to support perception of object continuity through occlusion in young infants, because 4-month-olds need the additional cues of background occlusion and at least a virtual occluding edge to perceive an occlusion event and hence object continuity (Bremner, Slater, Johnson, Mason, & Spring, 2012). Furthermore, deletion and accretion events must be spatially congruent with the occluding edges (Bremner, Slater, Mason, Spring, & Johnson, 2016).

In summary, accumulated evidence points to constraints on young infants' perception of continuity across occlusion relating both to the nature of the object's trajectory and the need for multiple cues to occlusion. This calls for an account of the development of object persistence, in which perception of persistence emerges around 4 months in constrained form. According to this account, object persistence is a perceptual phenomenon that emerges in infancy and forms the basis for a later emerging general conceptual principle of object permanence (Bremner, Slater, & Johnson, 2014). This is in sharp contrast to claims that infants possess innate knowledge of object permanence and reason about events (Baillargeon, 1986; Spelke et al., 1992). Accepting both accounts would provide a scenario in which infants understand the general principle of permanence but nevertheless encounter a world in which permanence is frequently violated.

Given this theoretical orientation, the overarching aim of the present series of experiments is to further extend our investigation of the perceptual factors that constrain young infants' perception of object continuity and how these may change with age. Our starting point in this case is one particular constraint on young infants' perception of object continuity, the finding that 4-month-olds only perceive the continuity of a shallow oblique trajectory (32˚) as it passes behind an occluder if the occluding edges are orthogonal to the object's path (Bremner et al., 2007). This seems a particularly important constraint compared with, say, infants' perception of trajectory discontinuity when the height or angle of the trajectory changes when the object is occluded (Bremner et al., 2007). After all, a change in trajectory during occlusion could cue the involvement of different objects and hence a discontinuity in the event.

Bremner et al. (2007) interpreted the oblique trajectory effect as an indication that infants had problems processing particular occlusion events rather than oblique trajectories as such, suggesting that the negative result when the occluding edges were not orthogonal relative to the to the object's path might be due to the difficulty in aligning the two visible components of trajectory either side of the occluder, rather like a dynamic version of the Poggendorf illusion. If this is the only factor leading to processing difficulty, infants should have similar problems processing a horizontal trajectory when the occluding edges are not orthogonal (i.e. not vertical). Thus in our first experiment we investigate perception of continuity of a horizontal trajectory when the occluder has edges at 45 degrees to the path of motion, and compare this to another potentially complex occlusion event in which the occluder's edges are serrated. In the second experiment, we return to the case of oblique trajectories with orthogonal and non-orthogonal occluding edges to clarify the earlier finding (Bremner et al., 2007). Finally, to date, infants' perception of trajectory continuity has only been investigated for objects moving on horizontal and oblique trajectories. Thus in the third experiment, to extend the generality of our findings, we investigate infants' ability to process vertical trajectories when the occluding edges are orthogonal and non-orthogonal. And in the final experiment, in the light of the results of experiment 2, we tested 6- and 8-month-old infants to see whether 4-month-old infants' limitations with oblique trajectories were overcome with age.

Experiment 1

In Experiment 3 of Bremner et al. (2007), 4-month-olds were habituated to a 2D event in which a ball cycled back and forth on a linear trajectory angled 32 degrees to the horizontal, disappearing behind a narrow occluder with vertical occluding edges placed in the center of its path. Following this, they were presented with test displays with the occluder absent in which the object either moved continuously or discontinuously, deleting and accreting in the same way as during habituation. They showed no looking preference for either test display, suggesting that they had no percept that the event represented continuous or discontinuous motion. Infants in Experiment 4 of Bremner et al. (2007) were habituated to the same oblique motion but the occluder was rotated so that its occluding edges were orthogonal to the object's path of motion, and the infants subsequently showed a significant novelty preference for the discontinuous test display. This finding was interpreted as evidence that, as in the case of horizontal trajectories with this occluder width, infants perceived continuity of trajectory in the habituation display.

These contrasting results suggest that it is the nature of the deletion and accretion events rather than the fact that the trajectory is oblique that creates processing problems for young infants. Bremner et al. (2007) suggested that processing occlusion at a non-orthogonal edge might be computationally more complex than the case of occlusion at an orthogonal edge, leading to difficulties in perceiving continuity of object motion or in aligning the components of the trajectory on each side of the occluder. However, it is possible that the null result was due to the combination of the oblique trajectory and the form of the deletion and accretion events. In order to clarify the factor(s) underlying the result of Experiment 3 in Bremner et al. (2007), our first step was to investigate 4-month-olds' perception of an event in which an object moved on a horizontal trajectory, passing behind a narrow occluder with occluding edges angled 45 degrees relative to the object's path or motion (see Figure 2a). If the processing problem encountered in Bremner et al. (2007) arose purely from the nature of the occlusion event, infants should not perceive trajectory continuity in this case either, whereas if the problem arose only from the cumulative load of processing the occlusion event and an oblique trajectory, we would expect perception of trajectory continuity. As another manipulation aimed at testing the conditions for perception of continuity we included a second condition in which the habituation display consisted of an object cycling back and forth on a horizontal trajectory passing behind an occluder with serrated occluding edges (see figure 2b). This provided a test of whether trajectory continuity was only perceived when deletion and accretion occurred at linear boundaries. In this case, although the overall orientation of the occluding edges was orthogonal to the path of movement, locally, the occluding edge orientation varied considerably, providing complex deletion and accretion events.

Method

Participants. Forty-eight 4-month-old infants (*M* = 126.04 days; range 112-140 days; 24 girls and 24 boys) took part in the experiment. A further 11 infants did not complete testing due to fussiness. Twelve infants were assigned to each of the two experimental and two control conditions in such a way as to ensure that the mean age and gender balance were comparable across conditions. Throughout the series of experiments, infants took part in only one experiment. In all experiments, participants were recruited by personal contact with parents in the maternity unit when the baby was born, followed up by telephone contact near test age to those parents who volunteered to take part. Infants with reported health problems including visual and hearing deficits and those born two weeks or more before due date were omitted from the sample. The majority were from Caucasian, middle class families.

Apparatus & Stimuli. A Macintosh computer and a Samsung 100 cm color monitor were used to present stimuli and collect looking time data. An observer viewed the infant on a second monitor, and infants were recorded onto videotape for later independent coding of looking times by a second observer. Both observers were unaware of the hypothesis under investigation. Using HABIT software (Cohen, Atkinson, & Chaput, 2000) the computer presented displays, recorded looking time judgments, calculated the habituation criterion for each infant, and changed displays after criteria were met. The observer's judgments were input with a key press on the computer keyboard.

In habituation and test displays in all experiments, objects were presented against a black background with a 20 x 20 grid of white dots measuring 48 x 48 cm (27˚ x 27˚ visual angle) serving as texture elements. Habituation and test displays used in Experiment 1 are illustrated in Figure 2. The habituation displays consisted of a stationary centrally placed blue occluder and a 6.7 cm (3.8˚) green ball undergoing continuous lateral translation back and forth at a rate of 16.5 cm/s (9.4˚/s), the center of its trajectory concealed by the occluder (see Figure 2). In the case of the oblique occluder display, the occluder had long dimension 21.5 cm (12.3˚) and short dimension 7 cm (4˚) and was oriented so that occluding edges were at 45˚ to the horizontal. The ball was visible on either side of the occluder in its entirety for 1319 ms and was completely occluded for 83 ms. Transition from full visibility to full occlusion or the reverse took 549 ms. In the case of the serrated occluder display, the occluder was oriented so that the occluding serrated edges were vertical; the short dimension ranged between 12 cm. (6.9˚) serration tip to tip and 7 cm. (4˚) serration trough to trough. The ball was visible in its entirety for 1501 ms and was completely occluded for 67 ms. Transition from full visibility to full occlusion or the reverse took 466 ms. The animation was run as a continuous loop for the duration of the trial. In choosing these parameters, the aim was to present occluders that had the same width across which total occlusion occurred, and this resulted in a longer total occlusion time for the oblique occluder because the object moved diagonally relative to its short dimension.

In test displays the occluder was removed and the ball translated back and forth in the same way as in the habituation display. In the continuous trajectory test display, the ball was always visible. In the discontinuous trajectory display, the ball went out of and back into view by progressive deletion and accretion in the same way as it had during habituation, that is, along oblique linear boundaries in the oblique occluder condition, and along vertical serrated boundaries in the serrated occluder condition, but without a visible (i.e., color- or luminance-defined) occluding edge (Figure 2).

Procedure. Each infant was seated 100 cm from the display and tested individually in a darkened room. For infants in the experimental conditions, the habituation display (horizontal trajectory with either the oblique or the serrated occluder) was presented until looking time declined across four consecutive trials, from the second trial on, adding up to less than half the total looking time during the first four trials. Timing of each trial began when the infant fixated the screen after display onset. The observer pressed a key as long as the infant fixated the screen, and released when the infant looked away. A trial was terminated when the observer released the key for two seconds or 60 s had elapsed. Between trials, a beeping target was shown to attract attention back to the screen. Following habituation trials, infants were presented with the two test trials in alternation, three times each, for a total of six trials. Infants in the control conditions received only the continuous and discontinuous test trials, without prior habituation trials, to assess any intrinsic preference. On test trials, half the infants in each condition were presented with the continuous trajectory first, and the rest viewed the discontinuous trajectory first. The second observer coded looking times from videotape for purposes of assessing reliability of looking time judgments. Interobserver correlations were high across the three experiments in this report (*M* Pearson $r = .99$).

Results

Figure 3 displays the mean looking times at the two test displays in the experimental and control groups for the oblique and serrated occluder displays. Infants in both experimental groups looked longer at the discontinuous test display, whereas infants in the control groups looked approximately equally at the two displays. Because looking time data tend to be positively skewed, violating an assumption of ANOVA, data in this and subsequent experiments were log transformed prior to analysis (data plotted in figures represent raw scores). A 2 (display: oblique vs. serrated occluder) x 2 (condition: experimental vs. control) x 2 (test trial order) x 2 (test trial type: continuous vs. discontinuous) x 3 (test trial block) mixed ANOVA yielded a significant effect of test trial type, F (1,40) = 22.65, $p < .001$, $\eta_p^2 = .36$. This was qualified by a significant interaction between test trial type and condition, F (1,40) = 31.25, $p < .001$, $\eta_p^2 = .44$. These are the important effects with respect to the experimental question, reflecting longer looking at the discontinuous test displays in the experimental conditions but no consistent difference in looking in the control conditions. Thus the initial conclusion is that infants perceived trajectory continuity in the habituation displays of both experimental conditions.

There was also a significant interaction between test trial type and test trial order, F (1,40) = 8.4, $p = .006$, $\eta_p^2 = .17$, and both were further qualified by a significant interaction between test trial type, condition, display, and test trial order, F (1,40) = 5.43, $p = .025$, ηp2 = .12. To clarify the secondary effects involving condition, further analyses were carried out on experimental and control conditions separately.

In the experimental conditions there was a significant effect of test trial type, F (1,20) = 42.8, $p = .001$, $\eta_p^2 = .68$, qualified by a significant interaction between display, test trial order, and test trial type, F (1,20) = 5.2, $p = .033$, $\eta_p^2 = .21$. This interaction was explored by analyzing performance on the oblique and serrated display conditions separately. In the oblique display condition, infants looked significantly longer at the discontinuous test display, F (1,10) = 20.9, $p = .001$, $\eta_p^2 = .67$, and there were no other significant main effects or interactions. In the serrated display condition, infants also looked significantly longer at the discontinuous test display, F (1,10) = 21.9, p = .001, η_p^2 = .69, but this effect was qualified by a significant interaction between test trial order and test trial type, F (1,10) = 7.15, p = .023, η_p^2 = .42, such that the effect of test trial type was significant when test trials commenced with the discontinuous test trial, F (1,5) = 24.12, p = .004, η_p^2 = .83, but was not significant when test trials commenced with the continuous test trial, F (1,5) = 2.29, p = 19, η_p^2 = .31. This is consistent with the novelty effect of the discontinuous test trial being attenuated by prior presentation of the less novel continuous test trial.

In the control conditions, the effect of test trial type was not significant, F (1,20) = .46, p = .51, η_p^2 = .02, but there was a significant main effect of test trial block, F (2,19) = 7.3, p = .004, η_p^2 = .43, and a significant interaction between test trial order and test trial type, F (1,20) = 7.56, p = .012, η_p^2 = .27, both of which were qualified by a significant interaction between test trial order, test trial type, and test trial block, F (2,19) = 3.77, p = .042, η_p^2 = .28. These effects are primarily due to reductions in looking across trial blocks and do not bear on the research questions. Thus they are not decomposed further here, though a full analysis is available from the first author on request, as are the analyses of other secondary effects obtained in later experiments.

Discussion

The significant preference for the discontinuous test display in the experimental conditions is consistent with infants having perceived trajectory continuity in the habituation display, though the qualification of this effect by test trial order in the serrated occluder display suggests a somewhat weaker effect in this case. This provides, at best, weak evidence that the form of the occlusion event affects perception of continuity of a horizontal trajectory. Possibly the serrated occluder provides a more complex occlusion event that induces a higher processing load, but this is a weak effect. Also, there is no evidence that occlusion at a diagonal edge presented a processing constraint in this experiment.

Why then did Bremner et al. (2007) obtain poorer performance when the trajectory was oblique and the occluding edges were vertical? Possibly processing an oblique trajectory and occlusion at a non-orthogonal boundary provide additive loads. In other words, there may be an interaction between trajectory orientation and the form of the occlusion event. However, remember that Bremner et al. (2007) used a shallow 32˚ oblique trajectory. Thus, to test the generality of their result and to allow comparison with the occlusion conditions on the oblique occluder display of Experiment 1, in Experiment 2 we replicated the conditions of Bremner et al. (2007) using a 45˚ oblique trajectory.

Experiment 2

Method

Participants. Forty-eight 4-month-old infants (*M* = 129.6 days; range 107-150 days; 20 girls and 28 boys) took part in the experiment. A further 9 did not complete testing due to fussiness. Twelve infants were assigned to each of the two experimental and two control conditions in such a way as to ensure that the mean age and the gender balance were comparable across conditions.

Stimuli. Figure 4 illustrates the habituation displays used in experiment 2. Habituation displays consisted of a stationary centrally placed blue occluder with the same dimensions as the oblique occluder in Experiment 1, and the same green ball this time undergoing continuous translation back and forth on a 45˚ oblique trajectory at the same rate as in Experiment 1, the center of its trajectory concealed by the occluder (see Figure 3). In the case of the vertical occluder display the ball's visibility, occlusion, and transition times were the same as in the oblique occluder display in Experiment 1. In the case of the oblique occluder display, the occluder was oriented so that its occluding edges were at 45˚ to the vertical and thus orthogonal to the ball's trajectory. The ball was visible in its entirety for

1634 ms and was completely occluded for 67 ms. The transition from full visibility to full occlusion or the reverse took 400 ms.

In test displays the box was removed and the ball translated back and forth in the same way as in the habituation display. In the continuous trajectory test display, the ball was always visible. In the discontinuous trajectory display, the ball went out of and back into view by progressive deletion and accretion at vertical or oblique linear boundaries.

Procedure. Infants in the two experimental groups were first habituated to the oblique trajectory event with either the vertical edge or oblique (orthogonal) edge occluder, and then were presented with the two test displays in alternation, for six trials. Infants in the two control groups were presented only with the corresponding set of test trials. Habituation and test trials were carried out according to the same criteria and procedures as in Experiment 1.

Results

Figure 5 displays the mean looking times at the two test displays in the experimental and control groups for the vertical and oblique occluder displays. Infants in both experimental groups looked more at the continuous test display, whereas infants in the control groups looked approximately equally at the two displays. A 2 (display: vertical vs. oblique occluder) x 2 (condition: experimental vs. control) x 2 (test trial order) x 2 (test trial type: continuous vs. discontinuous) x 3 (test trial block) mixed ANOVA yielded a significant effect of test trial type, $F\ (1,40) = 4.13$, $p = .049$, $\eta_p^2 = .09$. This was qualified by a significant interaction between test trial type and condition, $F\ (1,40) = 4.4$, $p = .042$, $\eta_p^2 = .1$. Infants in the experimental groups looked significantly longer at the continuous test display, $F\ (1,23) = 5.8$, $p = .02$, $\eta_p^2 = .2$, whereas those in the control groups looked about equally at the two displays, $F\ (1,23) = .01$, $p = .94$, $\eta_p^2 < .001$. These are the important effects with respect to the research question suggesting that infants perceived a discontinuous trajectory in the habituation displays.

There was also a significant effect of test trial block F (2,39) = 8.04, p = .001, η_p^2 = .29, qualified by a significant interaction between display, condition, test trial order, and test trial block, F (2,39) = 5.05, p = .01, η_p^2 = .21. Thus further analyses were carried out to clarify these effects.

In the experimental conditions separate analyses of the vertical occluder and oblique occluder displays did not yield significant effects of test trial type in either case: vertical occluder, F (1,10) = 2.61, p = .137, η_p^2 = .21, oblique occluder, F (1,10) = 2.54, p = .14, η_p^2 = .2. Separate analyses of the two test trial order groups indicated that when test trials commenced with the discontinuous test display there was a significant effect of test trial block, F (2,9) = 11.01, p = .004, η_p^2 = .71, qualified by a significant interaction between display and test trial block, F (2,9) = 6.03, p = .022, η_p^2 = .57 and a significant interaction between test trial and test trial block, F (2,9) = 4.28, p = .049, η_p^2 = .49. These interactions are hard to interpret but do not appear to bear on the research questions, being largely due to differential declines in looking across test trials.

In the control conditions, there was no significant effect of test trial type, F (1,20) = .006, p = .94, η_p^2 = .001. However, there was a significant effect of test trial block, F (2,19) = 7.06, p = .005, η_p^2 = .43, qualified by significant interactions between display, test trial order, and test trial block, F (2,19) = 8.62, p = .002, η_p^2 = .48, and between display, test trial type, and test trial block, F (2,19) = 4.14, p = .032, η_p^2 = .3. These effects do not bear on the research questions, being due to a differential reduction in looking across trials

Discussion

Unlike the results obtained by Bremner et al. (2007) the orientation of the occluder had no effect on performance. In the case of a 45° trajectory, overall there was a significant preference for the continuous test display, suggesting that the infants perceived the trajectory as discontinuous. However, there were a number of interactions with display and test trial type, and the effect of test trial type was not reliable in the case of each display analyzed separately. Thus a conservative interpretation is that there was a null preference on test trials, consistent with infants forming no percept regarding whether the trajectory was continuous or discontinuous. Note, however, that although the preference for the continuous test display was nonsignificant when split by occluder type, the trend was towards perception of discontinuity in both cases and the effect sizes were > .2, suggestive of medium to large directional effects in each case.

The results of Experiment 2 suggest that the primary determinant of processing difficulty is the orientation of the trajectory. How, then, do we reconcile this outcome with the result obtained by Bremner et al. (2007), in which presence of orthogonal occluding edges led to perception of continuity of an oblique trajectory? It seems very possible that in the case of their shallow oblique trajectory, processing load was reduced, such that it interacted with the manner of occlusion. However, in the case of a 45° trajectory, it may be the case that the processing load presented by the object trajectory is sufficient to lead to at least a null result irrespective of the nature of the occlusion event.

On the basis of these results, it is tempting to conclude that young infants have particular difficulty processing oblique trajectories. However, an alternative is that they are only capable of processing trajectories that are relatively close to the horizontal. To our knowledge, there has been no work on perception of continuity of vertical trajectories. Thus, to clarify the nature of constraints on young infants' trajectory processing, in Experiment 3 we presented displays in which the object moved on a vertical trajectory, hidden in its center portion by an occluder with orthogonal or oblique occluding edges.

Experiment 3

Method

Participants. Forty-eight 4-month-old infants (M = 127.4 days; range 110-142 days;

16 girls and 32 boys) took part in the experiment. A further 14 did not complete testing due to fussiness. Twelve infants were assigned to each of the two experimental and two control conditions in such a way as to ensure that the mean age and the gender balance were comparable across conditions.

Stimuli. Figure 6 illustrates the habituation displays used in Experiment 3. Habituation displays consisted of a stationary centrally placed blue occluder with the same dimension as in Experiment 2 and the same green ball this time undergoing continuous vertical translation up and down at a rate of 16.5 cm/s (9.4˚/s), the center of its trajectory concealed by the occluder (see Figure 4). In the case of the horizontal occluder display the occluding edges were horizontal and the ball's visibility, occlusion, and transition times were the same as in the oblique occluder display in Experiment 2. In the case of the oblique occluder display, the occluding edges were at 45˚ to the vertical and the ball's visibility, occlusion, and transition times were the same as in the vertical occluder display in Experiment 2.

In test displays the box was removed and the ball translated back and forth in the same way as in the habituation display. In the continuous trajectory test display, the ball was always visible. In the discontinuous trajectory display, the ball went out of and back into view by progressive deletion and accretion at a horizontal or oblique linear boundary.

Procedure. Infants in the two experimental groups were first habituated to the vertical trajectory event with either the horizontal or oblique occluder, and then were presented with the two test displays in alternation, for six test trials. Infants in the two control groups were presented only with the corresponding set of test trials. Habituation and test trials were carried out according to the same criteria and procedures as in Experiments 1 and 2.

Results

Figure 7 displays the mean looking times at the two test displays in the experimental and control groups for the horizontal and oblique occluder displays. Infants in both experimental groups looked markedly longer at the discontinuous test display, whereas infants in the control groups looked approximately equally at the two displays. A 2 (display: horizontal vs. oblique occluder) x 2 (condition: experimental vs. control) x 2 (test trial order) x 2 (test trial type: continuous vs. discontinuous) x 3 (test trial block) mixed ANOVA yielded a significant effect of test trial type, $F\ (1,40) = 35.18$, $p < .001$, $\eta_p^2 = .47$. There was also a significant effect of condition, $F\ (1,40) = 11.07$, $p = .002$, $\eta_p^2 = .22$, and these effects were qualified by a significant interaction between test trial type and condition, $F\ (1,40) = 23.25$, $p = .001$, $\eta_p^2 = .37$. In the experimental conditions, there was a significant looking preference for the discontinuous test display, $F\ (1,20) = 62.04$, $p = .001$, $\eta_p^2 = .76$, whereas in the control conditions, there was no effect of test display, $F\ (1,20) = .58$, $p = .46$, $\eta_p^2 = .03$. Thus the conclusion is that infants perceived a continuous trajectory in the habituation displays in both experimental conditions.

The test trial effect was also qualified by a significant interaction between test trial type and test trial order, $F\ (1,40) = 6.2$, $p = .017$, $\eta_p^2 = .13$. Finally, there was a main effect of test trial block, $F\ (2,39) = 7.98$, $p = .001$, $\eta_p^2 = .29$, qualified by a significant interaction between condition and test trial block, $F\ (2,39) = 3.99$, $p = .026$, $\eta_p^2 = .17$. These effects relate to differential reductions in looking across test trials and do not bear on the research questions.

Discussion

The results of Experiment 3 indicate clearly that young infants are capable of detecting the continuity of vertical trajectories, even when the occluding edges are oblique. Thus it appears evident that oblique trajectories present particular processing difficulties for this age group. This leads naturally to the question of whether this difficulty is short lived or persists into later infancy. Thus, in Experiment 4 we tested 6- and 8-month-olds on the oblique trajectory vertical occluder display used in Experiment 2.

Experiment 4

Method

Participants. Twenty-four 6-month-old infants (*M* = 190.4 days; range 173-204 days; 11 girls and 13 boys) and twenty-four 8-month-old infants (*M* = 246.5 days; range 231-263 days; 11 girls and 13 boys) took part in the experiment. A further two 6-month-olds did not complete testing due to fussiness. In each age group, twelve infants were assigned to experimental and control conditions in such a way as to ensure that the mean age and the gender balance were comparable across conditions.

Stimuli. These were identical to those used in the vertical occluder condition of Experiment 2 (Figure 4).

Procedure. Infants in the 6- and 8-month-old experimental groups were first habituated to the oblique trajectory vertical occluder event, and then were presented with the two test displays in alternation, for six test trials. Infants in the control groups were presented only with the set of test trials. Habituation and test trials were carried out according to the same criteria and procedures as in Experiments 1 to 3.

Results

Figure 8 displays the mean looking times at the two test displays by 6- and 8-month-olds in the experimental and control groups. At both ages, infants in the experimental groups looked markedly longer at the discontinuous test display, whereas infants in the control groups looked approximately equally at the two displays. A 2 (age: 6-month-old vs. 8-month-old) x 2 (condition: experimental vs. control) x 2 (test trial order) x 2 (test trial type: continuous vs. discontinuous) x 3 (test trial block) mixed ANOVA yielded a significant effect of age, $F(1,40) = 5.95$, $p = .019$, $\eta_p^2 = .37$, due to longer looking overall by the 6-month-olds.

There was also a significant effect of test trial type, F (1,40) =23.21, $p < .001$, $\eta_p^2 = .37$, and a significant effect of condition, F (1,40) = 9.3, $p = .004$, $\eta_p^2 = .19$. These effects were qualified by a significant interaction between test trial type and condition, F (1,40) = 13.14, $p = .001$, $\eta_p^2 = .25$. Infants in the experimental groups looked significantly longer at the discontinuous test display, F (1,23) = 24.2, $p < .001$, $\eta_p^2 = .51$, whereas infants in the control groups looked about equally at the two test displays, F (1,23) = .92, $p = .35$, $\eta_p^2 = .04$.

There was also a significant interaction between test trial type and test trial order, F = (1,40) = 12.39, $p = .001$, $\eta_p^2 = .24$, and a significant effect of test trial block, F (2,39) = 27.33, $p =< .001$, $\eta_p^2 = .58$, qualified by a significant interaction between test trial type and test trial block, F (2,39) = 5.43, $p = .008$, $\eta_p^2 =.22$. These effects are due to differential reductions in looking across test trials and do not bear on the research questions.

Discussion

The clear finding of Experiment 4 is that, unlike 4-month-olds, 6- and 8-month-olds perceive continuity of an oblique trajectory. In contrast to the lack of a preference for one test display over the other shown by 4-month-olds with the oblique trajectory vertical occluder display in Experiment 2, both 6- and 8-month-olds showed a significant preference for the discontinuous test display, evidence that they had perceived the habituation trajectory as continuous. And the fact that there was no age effect in Experiment 4 indicates that the improvement in perception of oblique trajectories likely occurred some time between 4 and 6 months of age.

General Discussion

The results of the first three experiments suggest that it is the orientation of the object's trajectory rather than the nature of the occlusion event that provides the primary processing load for 4-month-olds. In the case of a horizontal trajectory, disappearance at oblique or serrated occluding contours did not interfere with perception of trajectory continuity, and a horizontal trajectory was perceived as continuous when disappearance occurred at orthogonal or oblique occluding contours. In contrast, in the case of a 45˚ oblique trajectory, 4-month-olds did not perceive trajectory continuity, looking rather more at the continuous test display. Experiment 4, however, demonstrated clearly that by 6 months of age infants perceive continuity in the same oblique trajectories.

The results of Experiments 1 to 3 indicate that 4-month-olds' difficulties lie with oblique trajectories rather than with the manner in which occlusion occurs. In Experiment 2 we obtained the same negative result for the oblique trajectory whether the occluding contours were orthogonal or oblique relative to the trajectory, whereas in earlier work (Bremner et al., 2007) 4-month-olds detected perception of continuity of an oblique trajectory provided the occluding contours were orthogonal to the trajectory. As already indicated, however, Bremner et al. (2007) used a shallow oblique trajectory. Below we present an account in terms of mutual influence between vertical and horizontal tracking systems that provides a possible neurophysiological basis for increasing error with increasing obliquity. Thus it may be possible to reconcile these apparently conflicting findings in terms of a model in which trajectory continuity is no longer perceived once a processing load threshold is reached (cf. Johnson, 1997). Processing horizontal and vertical trajectories, and processing disappearance at an oblique occluding contour do not together exceed this threshold. Processing a 45˚ oblique trajectory does exceed this threshold. Processing a shallow (32˚) trajectory does not exceed the threshold, but does if combined with disappearance at an oblique occluding edge. Although this is something of a post hoc account, a similar example exists in recent research on the effects of shape and color change in a moving object on young infants' perception of trajectory continuity (Bremner, Slater, Johnson, Mason, & Spring, 2013). Infants perceived continuity despite a change in object shape, whereas a change in object color led to a null preference between test trials, and a change in both color and shape led infants to perceive the trajectory as discontinuous. Thus it appears that a change in shape does not in itself provide sufficient information to abolish perception of continuity, whereas a change in color does cross this threshold, and there is an additive effect of shape and color change sufficient to lead to perception of discontinuity.

One question that needs to be answered is why our manipulations led only to a null preference on test trials with 4-month-olds, suggesting no distinct percept regarding whether the trajectory is continuous or discontinuous. In particular, one might have imagined that additive effects of a 45° trajectory and occluding contours angled relative to the trajectory would have led to perception of trajectory discontinuity. Note, however, that the effect sizes in both conditions were large enough to suggest a medium to large directional effect, and possibly with larger *N*s a modest preference for the continuous display would have reached significance; indeed across the two conditions of Experiment 2, the effect was significant. However, other positive factors are likely to have provided information for continuity. Time and distance out of sight was short, and the object's trajectory was constant. It appears that trajectory discontinuity is only perceived under more extreme processing loads in which the trajectory changes while the object is out of sight (Bremner et al., 2007), when time and distance out of sight is long (Johnson et al., 2003b), or when there are strong cues to a change in object identity such as when the object changes both shape and color (Bremner et al., 2013).

Interestingly, infants perceived continuity of vertical trajectories, so it appears to be specifically oblique trajectories that are problematic for 4-month-olds. But why should continuity be hard to perceive in oblique trajectories? A possible answer to this question lies in the neurophysiological mechanisms of visual tracking. Oblique eye movements, whether they consist of smooth tracking movements or saccades across the occluded part of the trajectory, require coordination of input to extraocular muscles controlling vertical and horizontal components of movement (Schiller, 1998). This problem is made more complex by the fact that vertical and horizontal components of eye movements differ in terms of acceleration and time to completion. Evidence for differences of these sorts can be found in research on saccades in rhesus monkeys (Freedman, 2008) and smooth pursuit movements in adult humans (Rottach, Zivotofsky, Das, Averbuch-Heller, Discenna, Poonyathalang, & Leigh, 1996), and Rottach et al. (1996) concluded that horizontal and vertical pursuit are controlled by separate systems with identifiably different neural substrates.

Evidence of this sort indicates the complexity of controlling oblique eye movements, both while following a visible object on an oblique trajectory and when completing a saccade or saccades to the point of re-emergence when the object is behind the occluder, and considerable research effort has been directed to identifying the process through which horizontal and vertical components are coupled (see, for example, Grossman & Robinson, 1988). It is plausible that 4-month-olds' inability to perceive continuity in oblique trajectories arises from incomplete development of this coupling, with the result that it is harder both to track an object on an oblique trajectory and to perceive alignment of trajectory components either side of the occluder. 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. It is worth noting, however, that Grönqvist et al. (2006) attribute errors in circular tracking to mutual influence between horizontal and vertical tracking systems, and it is plausible that similar errors would affect oblique tracking, particularly in the case of a 45 degree trajectory in which the influence of vertical and horizontal components may be maximized. However, if this is the basis of infants' difficulty, our results in Experiment 4 suggest that this limitation is overcome by the age of 6 months.

There is also some direct evidence that is in keeping with oblique movements presenting difficulties for young infants. Johnson, Slemmer, and Amso (2004) investigated eye movements in the classic object unity task (Kellman & Spelke, 1983). Although their primary aim was to identify differences in tracking between 3-month-olds perceiving object unity and those not doing so, it is notable that diagonal tracks along visible parts of the diagonal rod and across occluder were much less frequent than horizontal and vertical movements. It is possible that an investigation of the nature of diagonal eye movements in comparison with vertical and horizontal movements will both provide an explanation of our results and valuable information regarding the development of visual tracking in early infancy.

Finally, what can we conclude from the present results regarding development of object permanence? On the one hand, perception of object continuity across occlusion has in the past been taken as an indicator of object permanence (Bower et al, 1971; Spelke et al., 1992). If this conclusion is valid, it would seem that any form of object permanence existing at 4 months is highly conditional, which runs counter to the common assumption that object permanence is a general principle. Our previous work has indicated a range of perceptual constraints on 4-month-olds' detection of continuity, and the present work indicates that there is a further constraint relating to the orientation of the trajectory. An alternative is that our work taps into perception of continuity and just that: it has no implications for development of object permanence, which may or may not be present in the early months. However, this argument lacks parsimony, and elsewhere (Bremner, Slater, & Johnson, 2014), we argued for a third alternative, namely that developments in the early months of life, detected in object unity and trajectory continuity tasks, concern the development of object persistence across occlusion, a perceptual precursor of the cognitive principle of object permanence. Young infants perceive object persistence under limited conditions and, unlike adults, need multiple cues to detect persistence. In the present work, we see that one constraint concerning objects moving on oblique trajectories is surmounted by 6 months of age. Our view is that perception of object persistence must become sufficiently robust to apply across a wide range of occlusion events before it can form a basis for a general principle of object permanence.

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Figure captions

Figure 1: Schematic depiction of events shown to infants in Johnson et al. 2003b to gauge perception of trajectory continuity. A: Habituation event. A ball moves behind an occluding screen and re-emerges, then returns on a repetitive cyclic trajectory. B: Discontinuous trajectory test event. The ball moves to the place occupied previously by the occluder and goes out of sight in the same manner. C: Continuous trajectory test event. The ball moves back and forth as before but remains visible during the entire trajectory. The rationale is that if infants perceived trajectory continuity during habituation they should show a novelty preference for the discontinuous test trial.

Figure 2: The oblique and serrated occluder habituation and test displays used in Experiment 1.

Figure 3: Mean looking times to the two test displays in oblique and serrated occluder experimental and control conditions in Experiment 1. Error bars in this and subsequent data figures display standard errors.

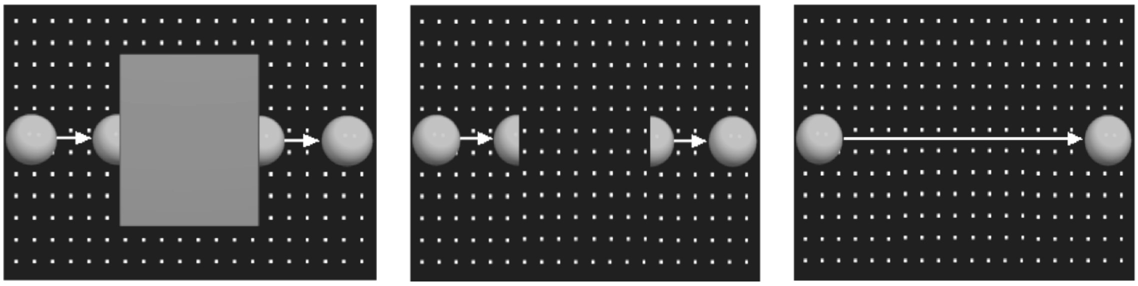
Figure 4: The habituation displays for vertical and oblique (orthogonal) occluder conditions of Experiment 2.

Figure 5: Mean looking times to the two test displays for vertical and orthogonal occluder experimental and control conditions in Experiment 2.

Figure 6: The habituation displays for horizontal (orthogonal) and oblique occluder conditions of Experiment 3.

Figure 7: Mean looking times to the two test displays for horizontal (orthogonal) and oblique occluder experimental and control conditions of Experiment 3.

Figure 8: Mean looking times to the two test displays by 6- and 8-month-olds in the experimental and control conditions of Experiment 4.



A B C

Figure 1

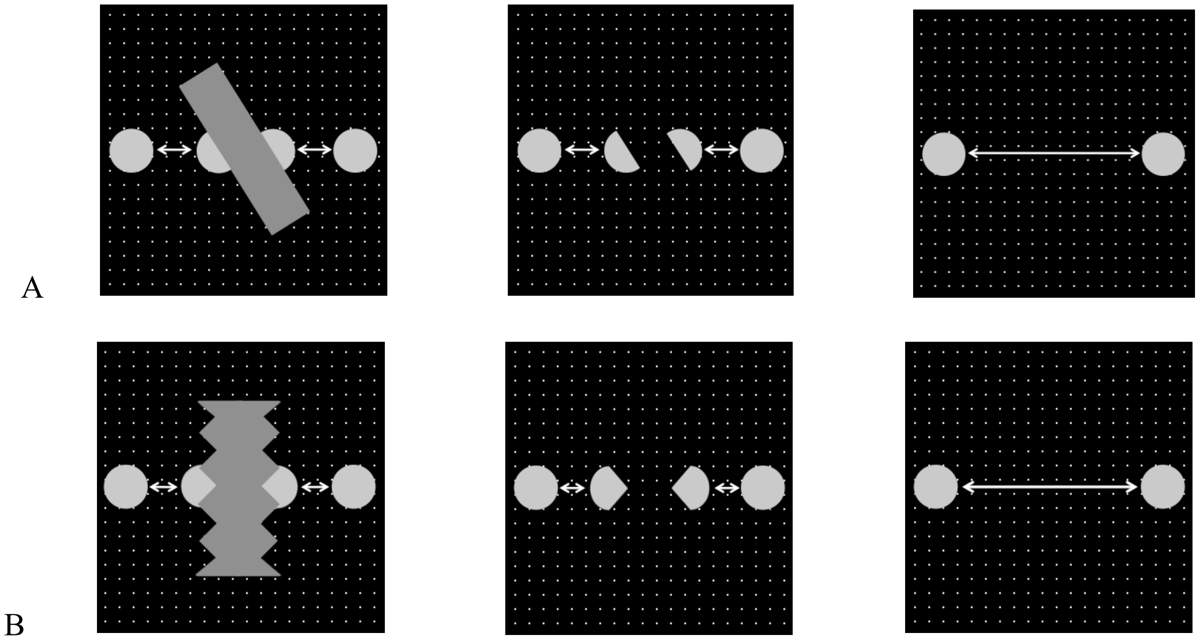
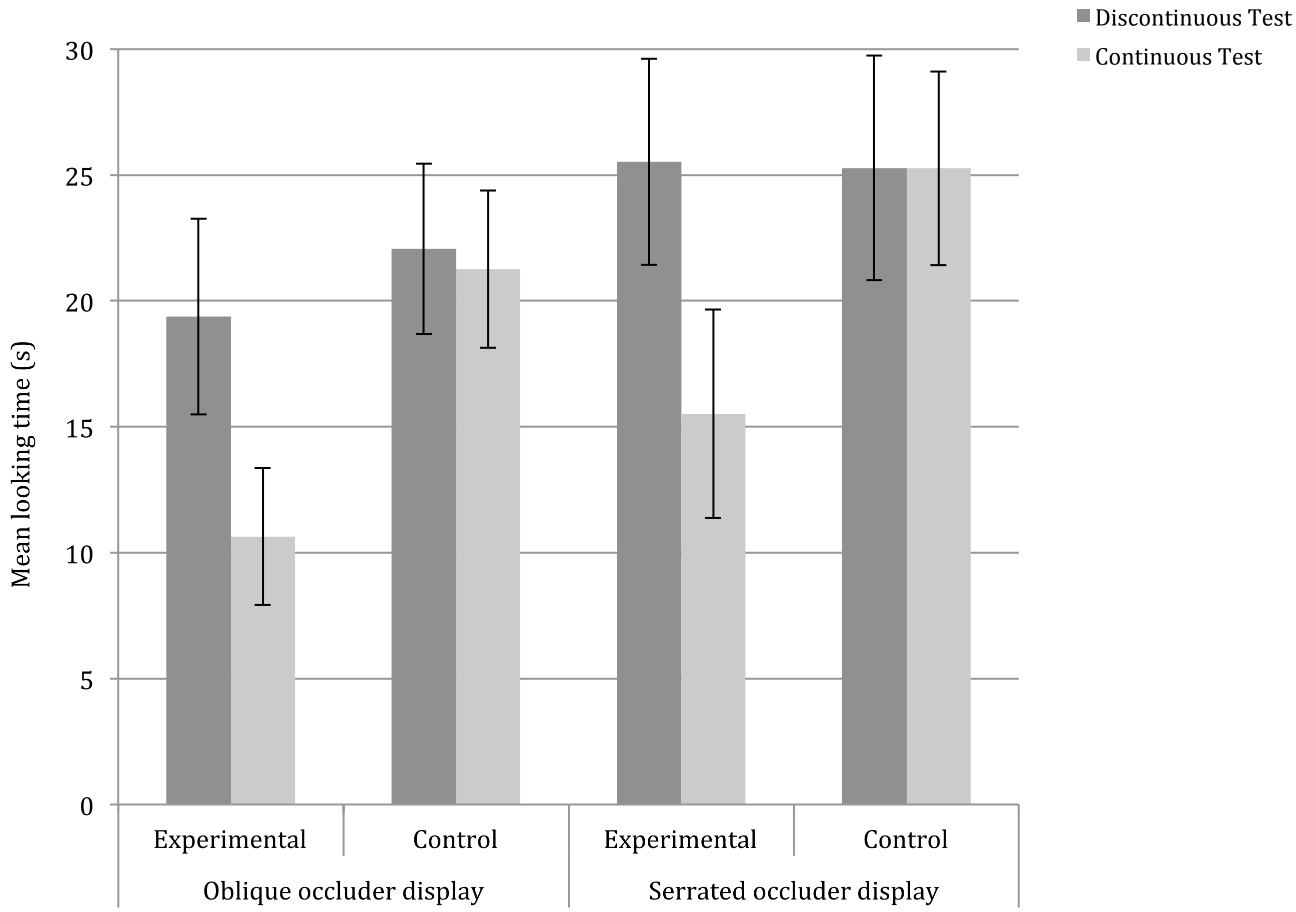


Figure 2


Discontinuous Test
Continuous Test
Mean looking time (s)
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10
5
0
Experimental
Control
Experimental
Control
Oblique occluder display
Serrated occluder display

Figure 3

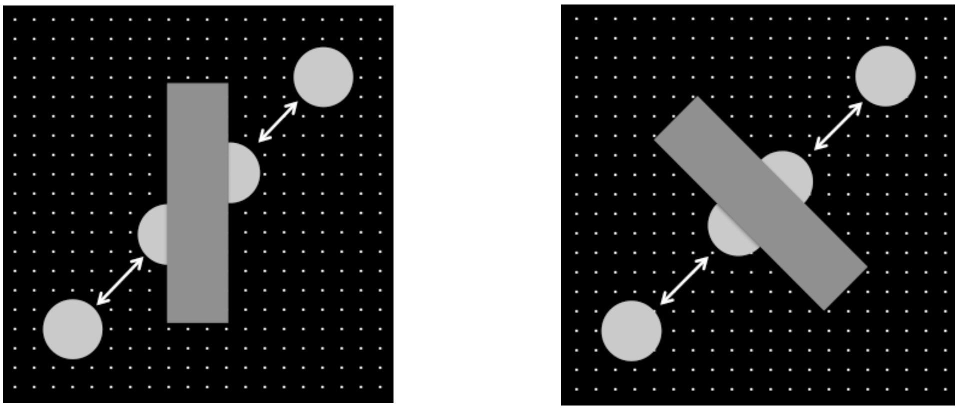
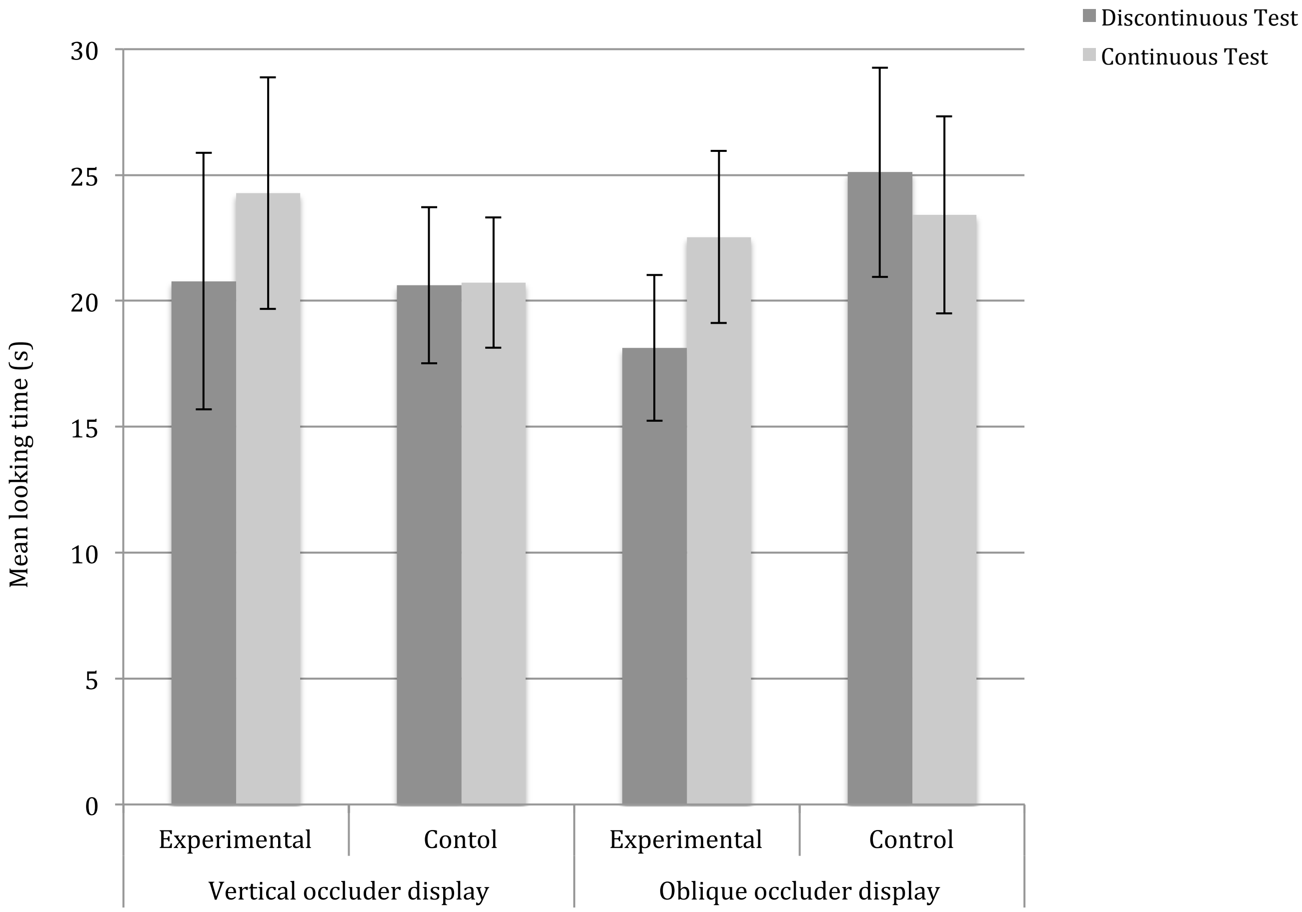


Figure 4


Discontinuous Test
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Mean looking time (s)
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Control
Vertical occluder display
Oblique occluder display

Figure 5

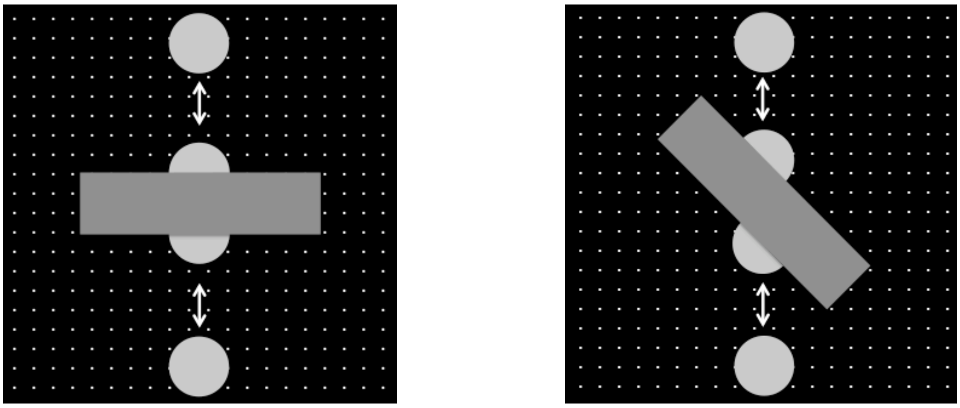
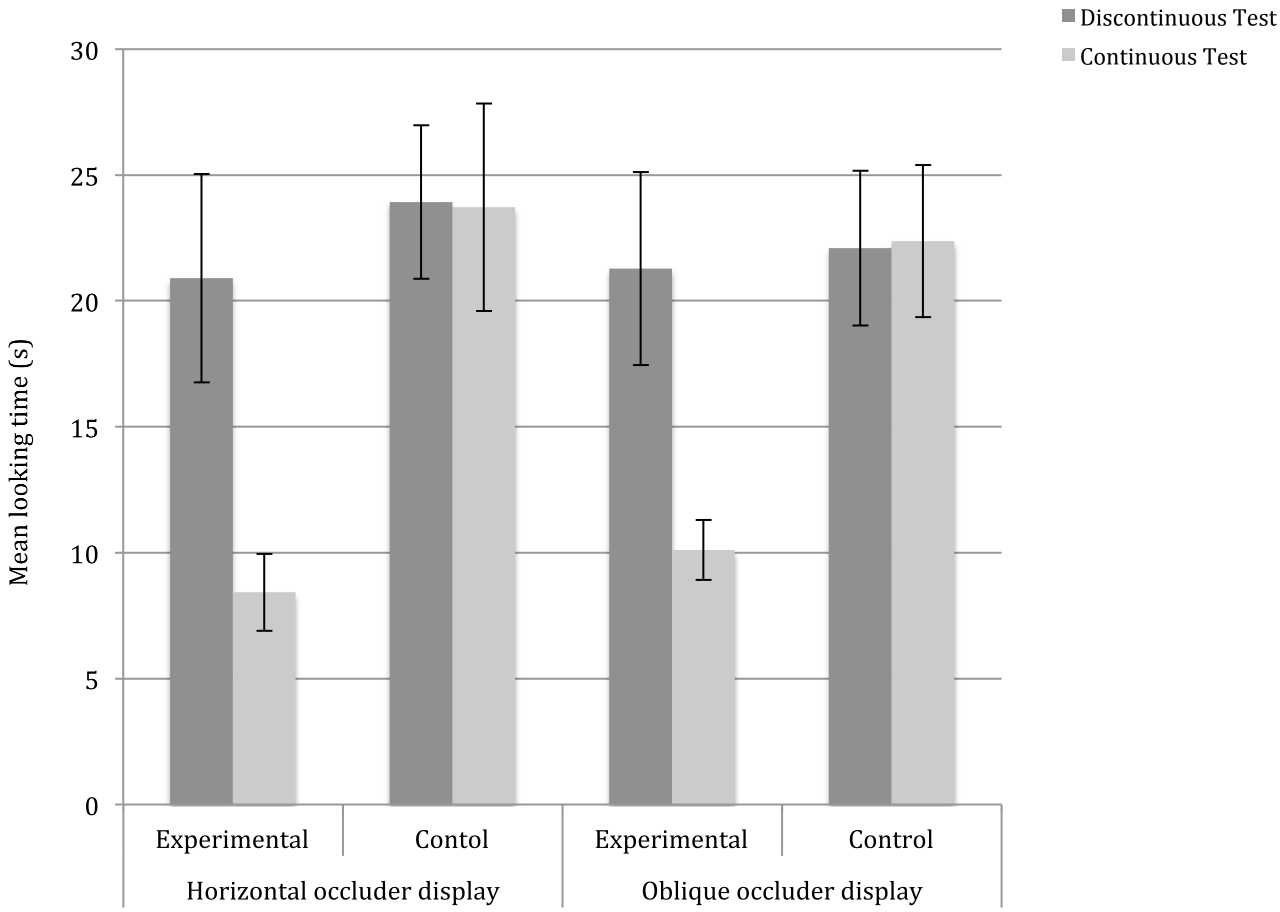


Figure 6


Discontinuous Test
Continuous Test
Mean looking time (s)
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Experimental
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Experimental
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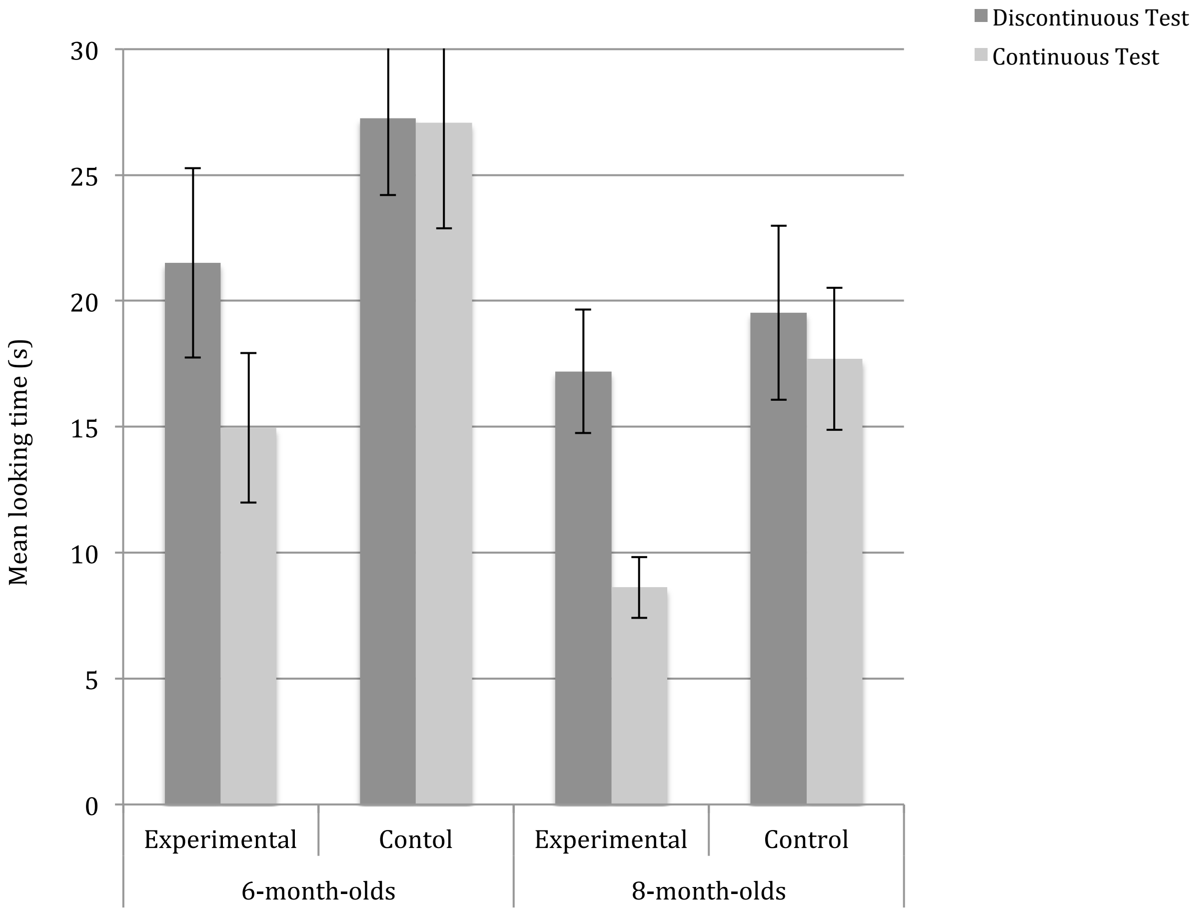
Horizontal occluder display
Oblique occluder display

Figure 7


Discontinuous Test
Continuous Test
30
25
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15
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Mean looking time (s)
Experimental
Contol
Experimental
Control
6-month-olds
8-month-olds

Figure 8