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PAPER

Conditions for young infants′ failure to perceive trajectory continuity

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Abstract

When viewing an event in which an object moves behind an occluder on part of its trajectory, 4-month-old infants perceive the trajectory as continuous only when time or distance out of sight is short. Little is known, however, about the conditions under which young infants perceive trajectories to be discontinuous. In the present studies we focus first on infants' perception of trajectories that change during a period of occlusion. Four-month-olds perceive discontinuity in trajectories that change in height or orientation while behind an occluder, and this is true even when a change in direction could be due to an invisible bouncing collision with a surface. Further experiments reveal that infants do not perceive diagonal linear trajectories as continuous across an occlusion unless the occluding and revealing edges are orthogonal to the path of movement. Implications for theories of perceptual and cognitive development are discussed.

Introduction

One of the fundamentals of human perception is the ability to detect the persistence of objects and surfaces in our surroundings despite periodic gaps in perception. These gaps occur in two ways. First, as *we* move through the world, far objects pass out of sight behind closer objects and back into sight again. Second, as *objects* move through the world, we see them disappear and then reappear from behind closer objects. In both these cases, whether disappearance is partial or total, we perceive the occluded object to persist over the period of occlusion.

Given how basic this ability is to everyday adult perception, it is unsurprising that its developmental origins have been a central focus of research in developmental psychology. For the past 35 years or so a considerable volume of research has investigated the degree to which infants of various ages possess the ability to fill in these gaps in perception. And one of the most commonly used research tools has involved measuring infants' responses to an event in which an object moves back and forth, disappearing and emerging from behind an occluder on part of its path. Early work of this sort tended to be framed in terms of infants' knowledge of object permanence. For instance, Bower, Broughton and Moore (1971) used their finding that 2-month-olds anticipated the re-emergence of an object from behind a screen as evidence for object permanence (i.e. that infants understand the object's continued existence while occluded). In addition, they found evidence of tracking 'disruption' when anomalies were introduced in the trajectory, such as premature re-emergence of the object. However, other workers have interpreted the findings of tracking tasks at lower levels in terms of object identity (Moore, Borton & Darby, 1978) or prediction of event sequences (Goldberg, 1976). It also seemed hard to replicate Bower's results (Meicler & Gratch, 1980; Muller & Aslin, 1978), probably because measures of tracking disruption turned out to be highly dependent on object movement rate, irrespective of whether or not the object passed out of sight (Muller & Aslin, 1978). More recently, Mareschal, Harris and Plunkett (1997) obtained evidence confirming the view that tracking disruption is influenced by low-level factors such as object speed and time out of sight. Despite this, recent research indicates growing accuracy of anticipatory tracking with age (Gredebäck & von Hofsten, 2004; Rosander &

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von Hofsten, 2004), and the tendency has been to interpret this as indication of increasing ability to represent the occluded object. However, as Goldberg pointed out, it is logically possible that infants are capable of anticipatory tracking without representing or perceiving the persistence of the object while it is occluded. Thus, although anticipatory tracking may suggest underlying representation of the object tracked through occlusion, it cannot be relied on as a sufficient index of this. Consequently, we believe it is more parsimonious to use measures of anticipatory tracking to investigate trajectory perception within a theoretical framework that makes no prior assumptions regarding infants' ability to perceive or represent the persistence of the temporarily occluded object (Johnson, Amso & Slemmer, 2003).

Other measures have been used in attempts to investigate infants' processing of moving object occlusion events. For instance, Baillargeon (1986) habituated infants to an event in which a toy truck ran down a track, disappeared behind a screen and re-emerged again. On test trials the screen was lifted and a block was placed on or behind the track before the screen was lowered again. Following this, the truck ran down the track as before, emerging from behind the screen in both cases. Six- and 8-month-old infants looked longer at the event after seeing the block placed on the track, and this was interpreted as evidence that they reasoned that the re-emergence was impossible given the placement of the block. Spelke, Breinlinger, Macomber and Jacobson (1992) used a similar technique to investigate the same ability in even younger infants, reporting evidence that even 2.5-month-olds detected a violation of solidity when one object appeared to have moved through another. Other evidence, however, calls into question the ability of young infants to extrapolate motion paths in order to register violations of object solidity and impenetrability in occlusion events. First, Spelke, Katz, Purcell, Ehrlich and Breinlinger (1994) found no evidence that infants were capable of predicting the final resting position of an object on the basis of its trajectory while in sight. Second, children as old as 2 years (Hood, Carey & Prasada, 2000) or 2.5 years (Berthier, DeBlois, Poirier, Novak & Clifton, 2000) fail to search correctly for objects whose location can be predicted from a previously viewed trajectory and knowledge of path obstruction. Thus the ability of young infants to reason about path of motion and object solidity is far from clear.

This does not mean that using moving object occlusion tasks to investigate infant ability is untenable. It just means that we may make better progress than previous work by adapting our methodology and theoretical orientation so as to tackle lower level questions about infants' perception of occlusion events. Rather than framing explanations in terms of object permanence, it may be more profitable to ask questions about the infant's ability to perceive continuity in events involving temporary occlusion of objects. Taking this stance, it may be possible to account for early abilities at a perceptual level. And the exciting developmental possibility is that knowledge of the physical world is constructed from these early perceptual abilities.

The results of recent work taking this stance confirm the importance of time and distance out of sight in infants' perception of moving object occlusion events. Johnson, Bremner, Slater, Mason, Foster and Cheshire (2003b) 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 complete test display, whereas 6-month-olds

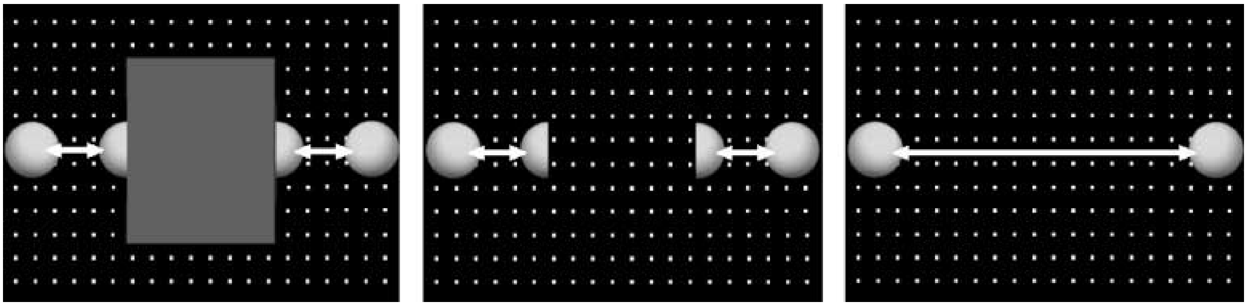

Figure 1 *Schematic depiction of events shown to infants in Johnson* et al. *(2003b) and Bremner* et al. *(2005) to gauge perception of trajectory continuity. Left panel: Habituation event. A ball moves behind an occluding screen and re-emerges, then returns on a repetitive cyclic trajectory. Middle panel: Discontinuous trajectory test event. The ball moves to the place previously occupied by the occluder, going out of sight and reappearing in the same manner as during habituation. Right panel: Continuous trajectory test event. The ball moves back and forth as before but remains visible during the entire trajectory.*

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. The occluder width effect with 4-month-olds was further examined by replicating the wide occluder finding and adding tasks using intermediate occluder widths. The outcome was an orderly relationship between occluder width and direction of preference on test trials.

The investigation by Johnson *et al.* (2003b) provided no information regarding the relative contribution of time and distance out of sight, since these covaried when occluder width was manipulated. However, 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 time or distance out of sight was short, 4-month-olds perceived the trajectory as continuous. This was true even when the acceleration or deceleration behind the occluder violated smoothness of motion. This finding is in keeping with Spelke, Kestenbaum, Simons and Wein's (1995) conclusion that smoothness of motion is not an important factor in establishing object identity, but in apparent disagreement with more recent work by Wilcox and Schweinle (2003) showing that young infants take violations of smoothness as indication that two objects (and hence two separate trajectories) are involved. It is possible that the different findings here emerge because Wilcox and Schweinle used a very extreme 'acceleration' such that re-emergence was virtually instantaneous. Maybe if similar extremes of acceleration were applied in the task employed by Bremner *et al.* (2005), infants would perceive the trajectory as discontinuous.

The findings of Johnson *et al.* (2003b) and Bremner *et al.* (2005) confirm the importance of low-level perceptual factors such as time or distance out of sight in infants' perception of moving object occlusion events. Their results are in keeping with a developmental account in which there is a progressive increase in the ability to fill in gaps in perception, and there is a clear parallel here with the work on object unity, which shows that 2-month-olds only perceive object unity if the occluder is narrow, whereas 4-month-olds fill in wider perceptual gaps (Johnson, 2004). Knowledge of object permanence may follow from these perceptual capacities, which in themselves undergo considerable development during the first 6 months.

Studies to date have limited their attention to infants' perception of linear horizontal trajectories, but there are good reasons to extend investigation beyond this simple case. Although in everyday life there are many cases in which objects move on constant horizontal trajectories, there are also cases in which objects change direction, and for adults a change in trajectory while an object is out of sight would not necessarily signal a different object on reappearance and hence discontinuity of the trajectory. Judgment of continuity over an invisible change in trajectory is probably most likely when the change can be interpreted as due to a collision with a surface, and least likely in cases involving multiple changes that cannot be explained due to collisions with surfaces. Thus it is of interest to investigate young infants' perception of trajectories that change in different ways. If infants' trajectory perception is influenced by knowledge of physical reality, we might expect them to respond differentially to trajectory changes that vary in plausibility with respect to everyday physical reality. Alternatively, infants' perception of trajectory continuity may be based on quite simple perceptual variables that have little to do with expectations about normal reality. Recent work on infants' perception of object trajectories (Johnson *et al.*, 2003b; Bremner *et al.*, 2005) has revealed temporal and spatial constraints on perception that are probably best explained by an information processing account in which initial low-level constraints on perception of trajectory continuity are gradually overcome during the first year. According to such an account, if increasing time and distance out of sight abolishes trajectory continuity, we might expect any change in the orientation or a displacement of the visible trajectory between disappearance and reappearance to lead to perception of discontinuity, whether or not the change has a plausible physical explanation.

Experiment 1

Our strategy in the first experiment was to compare infants' perception of three different moving object occlusion events. In the first, the object moved on a horizontal path until disappearing behind an occluder, and emerged on a horizontal path that was either lower or higher than the initial path (Figure 2a). In the second, the object moved on a falling diagonal trajectory until occlusion, and emerged from the occluder on a rising diagonal trajectory (Figure 2b). In the third, the trajectory was identical to the second, but a surface was added such that if the object had bounced on it while behind the occluder, it would have emerged on the rising diagonal path (Figure 2c). In each case, we used one occluder width that, when the trajectory was horizontal and unchanging, had yielded a preference

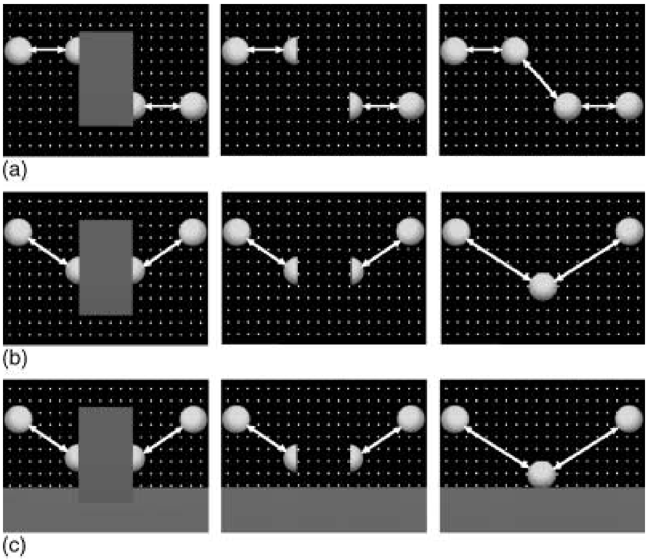

Figure 2 *The displays presented in Experiment 1. Left panel: Habituation Event; Middle panel: Discontinuous Test Event; Right panel: Continuous Test Event. High-low Display Figure 2a; Falling-Rising Display Figure 2b; Falling-Rising with Surface Display Figure 2c.*

for the discontinuous test display (Johnson *et al*., 2003b), indicating perception of trajectory continuity.

It appears to us that the knowledge-based and perceptual accounts outlined above make differential predictions regarding the likely outcome of these manipulations of trajectory. If infants' perception of trajectory is influenced by plausibility, we would predict that the three events described above should yield different likelihoods of a continuity judgment. The first, although maintaining a horizontal trajectory, requires the assumption of two changes in direction while occluded (first, from horizontal to diagonal and then from diagonal back to horizontal on a different level, either abruptly or gradually), whereas the other two only require the assumption of one change in direction. Thus, this event should be least likely to lead to a continuity judgment. Additionally, by providing a clear physical basis for the change in trajectory, the third event should be most likely to lead to a continuity judgment. In contrast, according to the perceptual account, each of these changes in trajectory has an equal likelihood of leading to perception of discontinuity. Trajectory change is just one other factor that, along with time and distance out of sight, is liable to alter infants' perception of trajectory continuity. Event A contains a change in height of trajectory (and height of occlusion and emergence) but maintains constancy of trajectory, whereas Events B and C maintain height of occlusion and emergence, but orientation of the trajectory differs pre- and post-occlusion. Thus we might expect the effects of these two manipulations to be more or less equivalent. And because this account does not invoke physical knowledge, it makes no differential prediction regarding perception of Events B and C.

In this study and those that follow, we used the same method as in previous work. That is, infants were habituated to one of the events outlined above, and then tested for preference between two successively presented test displays with the occluder absent: a continuous display in which the object moves continuously, changing trajectory in the space hitherto occupied by the occluder, and a discontinuous display presenting only the parts of the trajectory visible during habituation.

Method

Participants

Sixty 4-month-old infants (*M* age 126.1 days, SD = 8.3, 32 girls and 28 boys) took part in this study. A further 15 infants did not complete the study due to fussiness (14 infants) or failure to habituate (one infant). Infants in all four experiments in this report were recruited by visits to parents in the hospital shortly after birth and follow-up phone calls. All infants were full-term and had no known developmental difficulties.

Apparatus and stimuli

A Macintosh computer and a 76 cm colour 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. The computer presented displays, recorded looking time judgments, calculated the habituation criterion for each infant, and changed displays after the criterion was met. The observer's judgments were input with a keypress on the computer keyboard.

The habituation display consisted of a stationary 21.5 × 12.1 cm (12.3 × 6.9°) blue box and a 6.7 cm (3.8°) green ball undergoing continuous movement from one side of the display to the other, the centre of its trajectory occluded by the box. The animation was run as a continuous loop for the duration of the trial. In test displays, the box was removed and the ball moved back and forth 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 just as in the habituation stimulus, but without a visible (i.e. colour- or luminance-defined) occluding edge. Objects were presented against a black background with a 12 ×

20 grid of white dots measuring 48.8 × 33.0 cm (27.4 × 18.7°) serving as texture elements. One-third of the infants were assigned at random to a *High-Low Group* in which during habituation trials the object moved on a high horizontal trajectory to the left of the occluder and on a low horizontal trajectory to the right of the occluder (or vice versa; Figure 2a). The ball was visible in its entirety on either side of the box for 1400 ms, and was completely occluded for 367 ms. The transition from full visibility to full occlusion or the reverse took 367 ms. The continuous test showed the object moving horizontally and changing to an accelerated diagonal trajectory and back to a lower/higher horizontal trajectory in the space previously occupied by the occluder, whereas in the discontinuous test trial only the parts of the trajectory that had been seen during habituation were visible. One-third of infants were assigned at random to a *Falling-Rising Group* for which habituation trials consisted of the object moving on a falling oblique (32° clockwise from horizontal) trajectory to the left of the occluder and on a rising diagonal trajectory at a symmetrical orientation to the right of the occluder (Figure 2b). As in the High-Low display, the ball was visible in its entirety on either side of the box for 1400 ms, and was completely occluded for 367 ms, and the transition from full visibility to full occlusion or the reverse took 367 ms. Continuous test trials showed the object moving continuously, changing direction abruptly at the mid point of the region formerly occupied by the occluder, and discontinuous test trials showed only the parts of the trajectory that had been visible during habituation. The rest of the infants were assigned to a *Falling-Rising with Surface Group* for which the trajectory events were identical to those in the *Falling-Rising Group* but a red horizontal surface extended either side of the occluder with its top edge at a height corresponding to the height at which the ball changed trajectory (Figure 2c).

Design and procedure

Infants in each group were assigned randomly either to an experimental or to a control condition. Infants in the experimental condition were first habituated to the ball-and-box stimulus, and then were presented with the two test displays in alternation, three times each, for a total of six test trials. Infants in the control condition were shown only the six test trials, with no prior habituation, to assess any possible 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.

Each infant was seated 100 cm from the display and tested individually in a darkened room. For infants in the experimental condition, the ball-and-box display 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 2 seconds or 60 s had elapsed. Between trials, a beeping target was shown to attract attention back to the screen. For the control, testing conditions were identical except the infants were not habituated before viewing the test displays. The second observer coded looking times from videotape for purposes of assessing reliability of looking time judgments. Inter-observer correlations were high across the five experiments in this report (*M* Pearson $r = .99$).

Results

Looking time data in many cells were positively skewed, violating assumptions of homogeneity of variance required by ANOVA; therefore scores were log-transformed prior to analysis in all the experiments in this report (data in the figures are based on raw scores). Preliminary analyses including sex revealed no reliable main effects or interactions that bore on the hypotheses under investigation (i.e. no differences in performance as a function of sex), so data were collapsed across this variable in all experiments. Mean habituation time across the sample was 212.6 s (SD = 147.0); the *M* number of trials to habituate was 8.2 (SD = 2.5). There were no reliable differences between experiments in habituation times or trials to habituate, *t*s < 1.9, *ns*.

Table 1 shows looking times at the two test displays. Infants in the control group looked longer overall. In each group, infants in the experimental condition showed a preference for the continuous test display, consistent with perception of the trajectory as discontinuous. In

Table 1 *Mean looking times and standard deviations in experimental and control conditions for each group in Experiment 1*

		Test trial			
		Discontinuous		Continuous	
Group condition		*M*	SD	*M*	SD
High-low	Exp	13.26	11.99	14.66	11.2
	Cont	31.28	17.6	32.93	17.74
Falling-rising	Exp	17.31	14.66	20.78	18.62
	Cont	32.87	17.83	32.24	15.71
Falling-rising + surface	Exp	18.61	13.9	22.6	17.59
	Cont	33.55	11.58	28.06	9.68

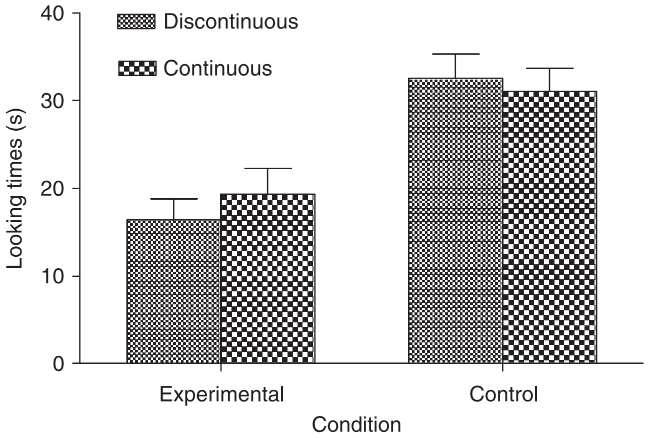

Figure 3 *Mean looking times at Continuous and Discontinuous Test Events in Experimental and Control Conditions of Experiment 1. Error bars represent +1 SE.*

comparison, no consistent pattern of preference was shown in the control groups. A 3 (Group) × 2 (Condition) × 2 (Test Order) × 2 (Test Display) × 3 (Test Block) mixed ANOVA yielded significant main effects of Condition, $F(1, 48) = 16.13$, $p < .0005$, and Test Block, $F(2, 96) = 8.13$, $p < .0005$, which were qualified by a significant Condition × Test Block interaction, $F(2, 96) = 9.15$, $p < .0005$. Infants in the control conditions showed a reduction in looking between block 1 and blocks 2 and 3, LSD $p < .0001$, and looked longer than those in the experimental conditions on the first trial block, $F(1, 48) = 38.75$, $p < .0001$, and the second trial block, $F(1, 48) = 5.68$, $p < .05$, but not the third, $F(1, 48) = 3.49$, $p > .05$. Both longer looking and the decline in looking (habituation) in control conditions are to be expected because these infants had had no prior exposure to moving object displays. The most important effect, however, was a significant interaction between Condition and Test Display, $F(1, 48) = 4.08$, $p < .05$. Infants in the experimental conditions looked longer at the continuous than the discontinuous test display, $F(1, 48) = 4.45$, $p < .05$ (Cohen's $d = .96$), whereas infants in the control conditions showed no preference for one over the other, $F(1, 48) = .56$, $p > .4$ (Figure 3). Additionally, the interaction between Group, Condition, and Test Display was not significant, $F(2, 48) = 1.86$, $p > .05$, indicating that the Condition × Test Display effect was a general one across all groups.

Discussion

Irrespective of the display presented, infants in the experimental conditions showed a preference for the continuous test display, suggesting that they had perceived the habituation display as involving a discontinuous trajectory. This contrasts with the result obtained by Johnson *et al.* (2003b) with the same occluder width and a constant horizontal trajectory, where infants showed a reliable preference for the discontinuous test display. The difference cannot be attributed to longer occlusion times in the present work, because the displays were designed so as to have slightly shorter full occlusion times than the comparable linear trajectory condition from Johnson *et al.* (2003b). In order to achieve this in the case of the high-low displays, we accelerated the ball on the diagonal part of its trajectory. The reader might wonder whether such a manipulation might have contributed to perception of discontinuity in this condition. However, Bremner *et al.* (2005) found that shortening time out of sight by accelerating the ball behind the occluder actually led to perception of trajectory continuity. Thus, it appears that we can be confident that it was the change in trajectory in this display that led to perception of discontinuity of trajectory.

Interestingly, in contrast to the positive effect that Bremner *et al.* (2005) obtained by shortening time out of sight by accelerating the ball while occluded, lengthening time out of sight by slowing the ball behind the occluder did not lead to perception of trajectory discontinuity. They concluded that although it was possible to shift infants towards perception of continuity by reducing time or distance out of sight, it was not so easy to shift them the other way. However, the results of the present experiment indicate that presenting marked changes of angle or height of trajectory has just this effect. Such a finding is in keeping with the presence of a relatively simple perceptual mechanism that registers gross differences in trajectory either side of the occluder as indicative of a discontinuity in trajectory. In reality, however, there are many cases in which trajectories change, sometimes in quite complex ways. This result suggests that 4-month-olds are not sensitive to different forms of trajectory change, and certainly there was no evidence that they judged some changes as more likely to maintain continuity than others. Specifically, the lack of a difference in performance between the three different displays suggests that trajectory components requiring more than one alteration to maintain continuity were not processed as more likely to indicate discontinuity than those requiring just one change, such as in a simple bouncing collision. Also, providing a surface to support a trajectory change through a bounce did nothing to reduce the effect – longer looking at the continuous display was actually most marked in that condition.

Experiment 2

Although we can safely conclude that in the High-Low display (Figure 2a) it was the change in the height of the

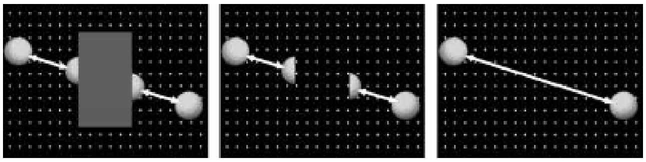

Figure 4 *The displays presented in Experiment 2. Left panel: Habituation Event; Middle panel: Discontinuous Test Event; Right panel: Continuous Test Event.*

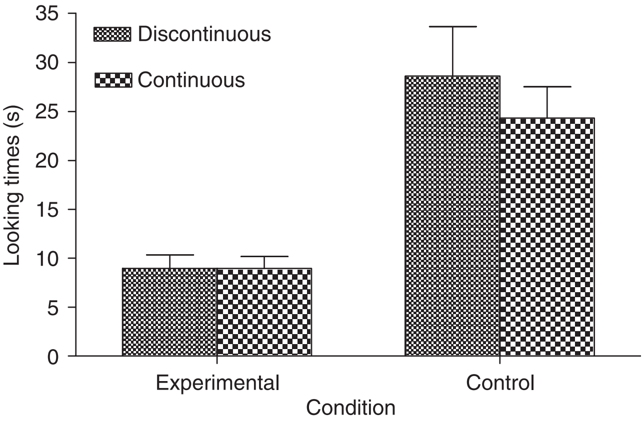

Figure 5 *Mean looking times at Continuous and Discontinuous Test Events in Experimental and Control Conditions of Experiment 2. Error bars represent +1 SE.*

trajectory that eliminated perception of continuity, we cannot so easily conclude that it is the change in trajectory that has this effect in the Falling-Rising displays. Although the effect was general across displays, we have to recognize the possibility that it arose in the latter two displays, not because the trajectory changed but because it was diagonal. In other words, before concluding that perception of discontinuity arose due to the change in trajectory in the Falling-Rising displays, we must demonstrate that we do not get the same effect with an unchanging diagonal trajectory. Thus in Experiment 2, using the same occluder width as before, we investigated infants' response on test trials following habituation to an object moving back and forth on a diagonal trajectory.

Method

Participants

Twenty 4-month-old infants (M age = 125.2 days, SD = 8.7, 11 girls and 9 boys) took part in this study. A further three infants did not complete the study due to fussiness.

Apparatus, stimuli, design and procedure

Unless noted otherwise, all aspects of apparatus, stimuli, experimental design, and procedure were identical to those described for Experiment 1. The displays are illustrated in Figure 4. The habituation display consisted of a stationary 21.5 × 12.1 cm (12.3 × 6.9°) blue box and a 6.7 cm (3.8°) green ball undergoing continuous movement on a diagonal path (18° clockwise from horizontal) from one corner of the display to the other, the centre of its trajectory occluded by the box. As in the displays employed in Experiment 1, the ball was visible in its entirety on either side of the box for 1400 ms, and was completely occluded for 367 ms, and the transition from full visibility to full occlusion or the reverse took 367 ms. In test displays, the box was removed and the ball moved back and forth 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 just as in the habituation stimulus, but without a visible (i.e. colour- or luminance-defined) occluding edge. Half of the infants were randomly assigned to an experimental condition, and the others were assigned to a control condition in which only the test trials were presented.

Results and discussion

Figure 5 shows the looking times at the two test displays for experimental and control conditions. Again, infants in the control condition looked longer overall. However, in neither condition is there any clear indication of a preference for either display. A 2 (Condition) × 2 (Test Trial Order) × 2 (Test Trial) × 3 (Test Block) ANOVA indicated main effects of Condition, $F(1, 16) = 22.76$, $p < .0005$, and Test Block, $F(2, 32) = 10.81$, $p < .0005$, qualified by a significant Condition × Trial Block interaction, $F(2, 32) = 4.63$, $p < .05$. This was due to different patterns in decline in looking between the two conditions, with control infants showing a sharp decline between Blocks 1 and 2, $F(2, 16) = 11.37$, $p < .001$, and experimental group infants showing a decline between Blocks 2 and 3, $F(2, 16) = 3.67$, $p < .05$. There was also a significant Condition × Test Trial Order × Test Trial interaction, $F(1, 16) = 5.45$, $p < .05$. This effect is located purely in the control data, these infants showing a non-significant preference for whichever test display was presented first. This is accountable in terms of habituation over test trials by this group, and the main point to emerge is that there was no overall preference for either test display in either the experimental or the control group.

Although presentation of a linear oblique trajectory did not lead, as with the Falling-Rising displays, to perception of trajectory discontinuity, it resulted in a null response. So it appears that something about an oblique trajectory, in and of itself, provides processing problems

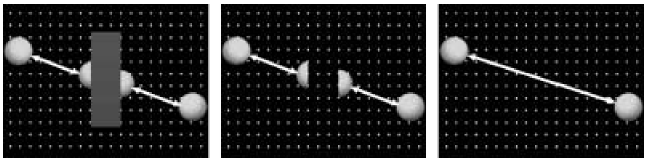

Figure 6 *The displays presented in Experiment 3. Left panel: Habituation Event; Middle panel: Discontinuous Test Event; Right panel: Continuous Test Event.*

for infants such that they form no clear percept of it as continuous or discontinuous. To investigate this effect further, in Experiment 3 we decided to repeat Experiment 2 using a very narrow occluder, to establish if an extremely short time out of sight would lead infants to perceive trajectory continuity, or if their difficulty processing a diagonal trajectory would remain.

Experiment 3

Method

Participants

Twenty 4-month-old infants (*M* age 130.0 days, SD = 9.3, 7 girls and 13 boys) took part in this study. A further seven infants did not complete the study due to fussiness (four infants), failure to habituate (one infant), or because they looked at ceiling on test trials (two infants).

Apparatus, stimuli, design and procedure

Unless noted otherwise, all aspects of apparatus, stimuli, experimental design, and procedure were identical to those described for Experiments 1 and 2. The displays are illustrated in Figure 6. The habituation display consisted of a stationary 21.5 × 7.0 cm (12.3 × 4.0°) blue box and a 6.7 cm (3.8°) green ball undergoing continuous movement on a diagonal path (18° clockwise from horizontal) from one corner of the display to the other, the centre of its trajectory occluded by the box. The ball was visible in its entirety on either side of the box for 1700 ms, and was completely occluded for 67 ms. The transition from full visibility to full occlusion or the reverse took 367 ms. The test displays were identical to those used in Experiment 2, other than that the 'gap' in the discontinuous trajectory corresponded to the narrower occluder width used in the habituation display.

Results and discussion

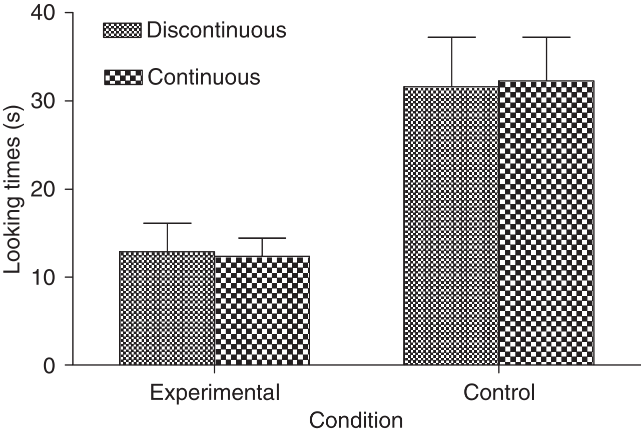

Figure 7 *Mean looking times at Continuous and Discontinuous Test Events in Experimental and Control Conditions of Experiment 3. Error bars represent +1 SE.*

Figure 7 shows the looking times at the two test displays for experimental and control conditions. Again, infants in the control condition looked longer overall than those in the experimental condition. But in neither condition is there any clear indication of a preference for either display. A 2 (Condition) × 2 (Test Trial Order) × 2 (Test Trial) × 3 (Trial Block) ANOVA indicated a main effect of Condition, $F(1, 16) = 17.36$, $p < .001$, with control infants looking longer than those in the experimental condition. There was also a significant interaction between Test Trial Order and Test Trial, $F(1, 16) = 6.81$, $p < .05$, due to infants looking marginally but non-significantly longer on each test trial when it was presented first compared to second. Again, however, there was no evidence that infants in either the experimental or control group showed a preference for either test display.

Even when the occluder was made so narrow that the object was out of sight for only a very short time, there was no evidence that infants perceived an oblique trajectory as continuous across an occlusion. The time and distance out of sight in this display is well within the values that result in perception of continuity in the case of horizontal trajectories, and it is clear that infants have some special difficulty in processing diagonal trajectories. The question is just what it is about these diagonal trajectories that makes for processing difficulty. Is it the fact that the trajectory is diagonal? Alternatively, the problem might relate to the way the object disappears. The vertical component of its movement leads it to move up the occluding edge while disappearing and reappearing, and it is possible that this fact adds complexity to the occlusion event that infants find hard to process. This may link in some way to a static equivalent, the Poggendorf illusion, in which lines that extend behind an occluder at an angle to the occluding edges are perceived as displaced. Possibly we are dealing here with a dynamic

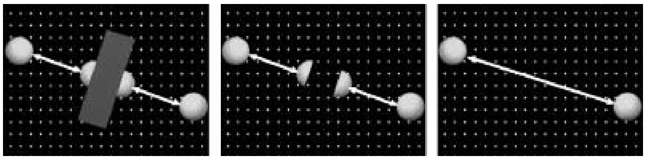

Figure 8 *The displays presented in Experiment 4. Left panel: Habituation Event; Middle panel: Discontinuous Test Event; Right panel: Continuous Test Event.*

Poggendorf illusion such that infants perceive the two trajectory components as parallel but displaced.

To test these possibilities against one another, in Experiment 4 we repeated Experiment 3, using the same occluder width, but re-orienting it so that its occluding edges were orthogonal to the object's direction of motion.

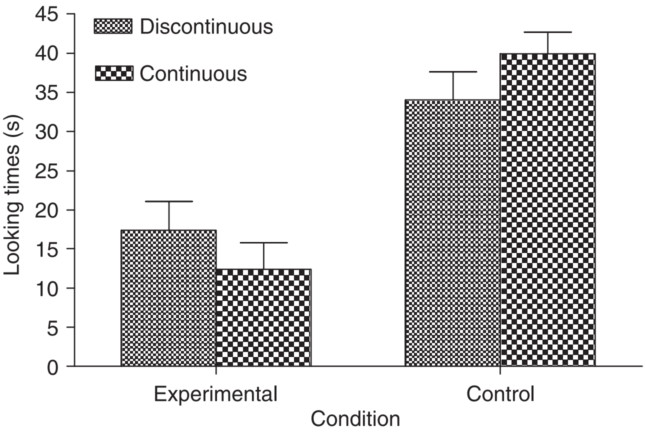

Figure 9 *Mean looking times at Continuous and Discontinuous Test Events in Experimental and Control Conditions of Experiment 4. Error bars represent +1 SE.*

Experiment 4

Method

Participants

Twenty 4-month-old infants (*M* age 125.4 days, SD = 9.1, 11 girls and 9 boys) took part in this study. A further two infants did not complete the study due to fussiness.

Apparatus, stimuli, design and procedure

Unless noted otherwise, all aspects of apparatus, stimuli, experimental design, and procedure were identical to those described for Experiments 1–3. The displays are illustrated in Figure 8. The habituation display consisted of a stationary 21.5 × 7.0 cm (12.3 × 4.0°) oblique blue box and a 6.7 cm (3.8°) green ball undergoing continuous movement on a diagonal path (18° clockwise from horizontal) from one corner of the display to the other, the centre of its trajectory occluded by the box. The box was oriented so that its occluding edges were orthogonal to the object's path of motion. Durations of visibility and occlusion were identical to those in the habituation display employed in Experiment 3. The test displays were identical to those used in Experiment 3, other than that the non-luminance defined occluding edges in the discontinuous test display were orthogonal to the object's path of motion.

Results and discussion

Figure 9 shows the looking times at the two test displays for experimental and control conditions. As usual, infants in the control group look longer at both test displays than those in the experimental group. Also, whereas infants in the control condition look longer at the continuous test display, those in the experimental condition look longer at the discontinuous test display. This pattern was confirmed by a 2 (Condition) × 2 (Test Trial Order) × 2 (Test Trial) × 3 (Trial Block) ANOVA, which revealed a main effect of Condition, $F(1, 16) = 23.54$, $p < .001$, and a significant interaction between Condition and Test Trial, $F(1, 16) = 10.14$, $p < .01$. Infants in the experimental condition looked longer at the discontinuous test display, $F(1, 16) = 5.81$, $p < .05$ ($d = .59$), whereas infants in the control condition did not look significantly longer at either test display, $F(1, 16) = 4.37$, $p > .05$. There was also a significant effect of Trial Block, $F(2, 32) = 12.15$, $p < .001$, due to a general decline in looking across trials. Finally, there was a significant interaction between Test Trial Order and Test Trial, $F(1, 16) = 7.36$, $p < .05$, due to infants in both experimental and control groups looking marginally longer at the discontinuous test display when it was presented first compared to second, $F(1, 16) = 4.39$, $p > .05$.

Reorienting the occluder so that its occluding edges were orthogonal to the object's path of movement led infants to perceive a diagonal trajectory as continuous. This suggests that it is the way in which the object passed out of sight and back into sight rather than the diagonal trajectory *per se* that led to null results in Experiments 2 and 3. It thus appears that we have detected another constraint on young infants' perception of trajectory continuity. This constraint is rather surprising, since by no means all occlusion events in the everyday world take the form of progressive occlusion and disocclusion at linear edges orthogonal to the direction of object motion. Below we discuss this effect in the context of the results of Experiment 1.

General discussion

The results of Experiment 1 indicated that a change in either the height of a horizontal trajectory or the angle of an oblique trajectory disrupted 4-month-olds' perception of trajectory continuity and indeed led to perception of discontinuity. This contrasts with an earlier finding that an acceleration of the object while behind the occluder, far from interfering with infants' perception of trajectory continuity, actually enhances it, and that a deceleration has no effect (Bremner *et al.*, 2005). It seems clear from that work that acceleration has a positive effect by reducing time out of sight, and the general conclusion of that work is that either shortening time or distance out of sight supports perception of trajectory continuity. The interesting thing is that this happens despite a change in the object's trajectory, that is, a change in its speed, while it is out of sight. Thus, in contrast to the effect obtained in Experiment 1, it seems that young infants are either not sensitive to temporal disruptions involving altered timing of emergence or do not perceive them as having implications for perception of trajectory continuity. Interestingly, there is a parallel in the literature on visual cognition in adults using multiple object-tracking tasks (Pylyshyn & Storm, 1988). Participants are successful in such tasks even when targets periodically disappear for short periods behind occluders (Scholl & Pylyshyn, 1999). Also, performance is not affected by speeding up the targets during occlusion until the speed during occlusion reaches 10 times the pre-occlusion rate, causing the target to reappear almost immediately across the spatial gap (Scholl & Nevarez, 2002). Thus, like infants, adults' performance is unaffected by this type of temporal discontinuity.

Another finding in the adult literature is that participants were just as likely to track an object over an occlusion if there was no visible occluder (Scholl & Pylyshyn, 1999). This accords with the argument that coherent deletion and accretion at boundaries is perceived as a real case of occlusion, with the object perceived to disappear as if into an invisible tunnel (Kahneman, Triesman & Gibbs, 1992; Michotte, Thines & Crabbe, 1964/1991). It is our conclusion that the same effect does not arise for young infants. Our argument is as follows. If infants were subject to the tunnel effect, then, relative to the habituation display, the discontinuous test display would be perceived as more familiar than the continuous test display. That is, unlike the continuous test display, it would consist of the same occlusion event as during habituation. The only difference is that the visible occluder is absent, but that is also true of the continuous test display. Thus, if young infants were subject to the tunnel effect we would expect novelty preferences for the continuous test display even under circumstances most favourable to perception of trajectory continuity. However, it is specifically under conditions when time and/or distance out of sight are small that previous work has obtained clear novelty preferences for the discontinuous test display (Johnson *et al.*, 2003b; Bremner *et al.*, 2005). It thus appears likely that the tunnel effect is a product of a more advanced capacity for perception of occlusion.

If altering the timing of re-emergence has only positive effects on trajectory perception, the results of Experiment 1 demonstrate that other changes, such as the height of the trajectory or its angle, do have negative effects on perception of continuity. These changes in the *path* of the object may have their effect because they are simply more salient than the temporal changes brought about by deceleration or acceleration. After all, the result is that the object moves on a grossly different path from that before occlusion. Note, however, that there is a potential circularity here, for it may be argued that such changes are more salient simply because the infant's perceptual system is more precisely tuned to their detection than to detection of changes in timing of emergence.

The fact that the results did not differ between the three displays used in Experiment 1 lends no support to the view that physical plausibility guides infants' perception of trajectories. According to such an account, the high-low trajectory should be least likely to be perceived as continuous because at least two changes in path are needed to 'connect' the visible components across the occlusion, and the falling-rising trajectory with surface should be most likely to be perceived as continuous because a surface is present to provide a physical basis for a simple bouncing collision. In addition, any account based on plausibility or experience of the world has problems explaining these results in the context of earlier findings. In reality, objects do not generally accelerate and decelerate abruptly, yet just such changes did not disrupt perception of continuity (Bremner *et al.*, 2005), nor do they lead to longer looking by control infants when the changes are fully visible in the continuous test display. On the other hand, changes in the path of objects are common in reality, particularly as a result of bouncing collisions with surfaces. And yet, in Experiment 1 such changes led infants to perceive the trajectory as discontinuous.

Our favoured conclusion is that young infants' perception of these events is based on relatively simple parameters. Earlier work indicates that either a short time or short distance out of sight leads to perception of continuity, and this may occur because the processing load is reduced in such cases. The present work suggests that, as in the Bremner *et al.* (2005) experiments, infants are functioning at a quite basic level, in this case to perceive trajectory discontinuity. Here it seems that perception is based on the principle that any clear change in path parameters equals a violation of continuity, such that the two visible trajectory components are treated as disconnected. One interesting question is whether adults in multiple object tracking tasks would tolerate quite abrupt changes in the object's path while occluded, or whether, in parallel with our findings with infants, such changes would lead to disruption.

The results of Experiments 2 and 3 indicate that something about diagonal linear trajectories makes them hard to process in terms of continuity across occlusions. Presumably this contributed to infants' performance in the two falling-rising trajectory conditions of Experiment 1. However, null results were obtained in Experiments 2 and 3, whereas in Experiment 1 infants showed perception of discontinuity, so we retain our conclusion that the change in trajectory in the falling-rising displays was important in leading to the percept of discontinuity. Certainly, however, the results of Experiments 2 and 3 provide evidence of a further constraint on infants' perception of trajectory continuity, suggesting that even under conditions of time and distance out of sight that should have been very favourable, infants did not perceive continuity in diagonal trajectories. And the positive outcome of Experiment 4 suggests that the important factor determining whether these trajectories are perceived as continuous is the manner in which the object passes out of sight behind the occluder and back into sight. Simply orienting the occluder so that the occluding and revealing edges are orthogonal to the path of motion of the object leads infants to perceive the trajectory as continuous. At first sight this suggests a paradox. On the one hand, infants' perception seems to be ruled by relatively simple general principles regarding time and distance out of sight and changes in visible trajectory. On the other hand, only certain apparently very specific cases of occlusion lead to perception of continuity. However, we are probably dealing with a quite distinct perceptual process here, in which case the paradox dissolves. Adults distinguish occlusion from other forms of disappearance (Gibson, Kaplan, Reynolds & Wheeler, 1969), and deletion and accretion according to the normal rules of occlusion are sufficient to support perception of continuity of motion, even when no visible occluder is present (Scholl & Pylyshyn, 1999). Thus what we are tapping into here may be a much more precisely tuned perceptual mechanism for distinguishing lawful occlusions from other forms of disappearance. The importance of being able to make these distinctions quite precisely is that occlusion implies a continuing history of the object along an invisible path, whereas other forms of disappearance specify a discontinuity. From a Gibsonian perspective, whatever the positive or negative effects of altering trajectory parameters, perception that occlusion has taken place (rather than some other form of disappearance) is liable to be the primary precondition for perception of continuity. Even if the object travels on a constant speed horizontal trajectory and is out of sight for a very short time, the prediction is that continuity of trajectory would not be perceived if, instead of disappearing at an occluding edge, the object imploded. However, when normal deletion and accretion occur at occluding edges, other more general factors such as constancy of trajectory, distance, and time out of sight become the determiners of whether the trajectory is perceived as continuous or discontinuous.

What remains a puzzle, however, is why infants should only perceive certain quite specific occlusion events as specifying continuity. Here a parallel with the literature on adult multiple object tracking may break down, because the infant task allows for focal attention, presumably on a single moving object, whereas in the adult task, attention is necessarily spread across many objects. Focal attention may permit much more precise detection of occlusion information and more relevant links may exist with the adult literature on detection of occlusion events referred to above (Gibson *et al.*, 1969). The work reported here has only begun to investigate this matter but, as far as it goes, suggests that the occluding edge must be orthogonal to the path of object motion if trajectory continuity is to be perceived by 4-month-olds. It may be possible to argue that such occlusion events are computationally simpler than other cases, there being no component of motion in the dimension parallel to the occluding edge. And this may either make it hard for infants to process such events as occlusions, or it may create a dynamic Poggendorf-type illusion that leads infants to perceive the two trajectory components as unaligned. But before any clear conclusions can be reached it will be necessary to test young infants with a wide range of conditions that manipulate the contour of the occluding edge and its orientation relative to the object's path.

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