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Infants' Perception of Object Trajectories

Scott P. Johnson, J. Gavin Bremner, Alan Slater, Uschi Mason, Kirsty Foster, and Andrea Cheshire

Filling in the gaps in what humans see is a fundamental perceptual skill, but little is known about the developmental origins of occlusion perception. Three experiments were conducted with infants between 2 and 6 months of age to investigate perception of the continuity of an object trajectory that was briefly occluded. The pattern of results across experiments provided little evidence of veridical responses to trajectory occlusion in the youngest infants, but by 6 months, perceptual completion was more robust. Four-month-olds' responses indicated that they perceived continuity under a short duration of occlusion, but when the object was out of sight for a longer interval, they appeared to perceive the trajectory as discontinuous. These results suggest that perceptual completion of a simple object trajectory (and, by logical necessity, veridical object perception) is not functional at birth but emerges across the first several months after onset of visual experience.

Veridical perception of the objects that surround us is among the most important tasks accomplished by the visual system. The inputs to this process, however, are incomplete, because they consist of fragmented images, reflected from visible object surfaces, and these fragments undergo continual transformation by changes in observer position or object movement. A singular challenge is posed by occlusion, which is ubiquitous in the visual array: Objects frequently go in and out of sight, and most surfaces from any particular vantage point are partly or fully occluded by other, nearer surfaces and may in turn occlude farther surfaces. Filling in the gaps in what we see, therefore, is a fundamental aspect of human perception.

There is now a substantial literature bearing on the development of infants' ability to perceive the unity of partly occluded objects. One early study on which much recent work has been based was reported by Kellman and Spelke (1983). Four-month-old infants were habituated to a rod that moved back and forth behind a box (Figure 1a) and were then tested for a novelty preference on two stimuli in which the box was absent: a complete rod (Figure 1b), representing what an adult would likely expect behind the box, and the two rod parts (Figure 1c), representing the rod surface fragments that were visible during habituation. The infants showed a posthabituation preference for the two rod parts, indicating that, during habituation, they had perceived a complete rod moving behind the box. This work has been extended to show that infants rely on a variety of visual information to segregate surfaces and to perceive object unity (Johnson, 1997). It is interesting that perception of object unity in these displays appears to develop between birth and 2 months. When newborns were tested on an occluded rod display, they showed a preference subsequently for the complete rod (Slater, Johnson, Brown, & Badenoch, 1996). This indicates that during habituation they detected only what was directly visible (the two rod parts), failing to make the perceptual inference necessary to perceive unity and treating the complete rod as novel. However, by 2 months, infants perceive object unity, provided the occluding box is narrow or contains gaps (Johnson & Aslin, 1995).

A parallel can be drawn between this ability to fill in the occluded parts of an object and the ability to perceive the persistence of a moving object when it disappears entirely as it passes behind a screen. The first case involves perceptual filling in of a *spatial* gap (i.e., a gap across a spatial extent), whereas the second case involves filling in of a *spatiotemporal* gap (i.e., a gap across both space and time). Perception of object unity involves interpolating the invisible part of a partially occluded object, and in the case of an object moving behind an occluder and reemerging, the observer must interpolate the path followed by the object during the time it is out of sight. Notably,

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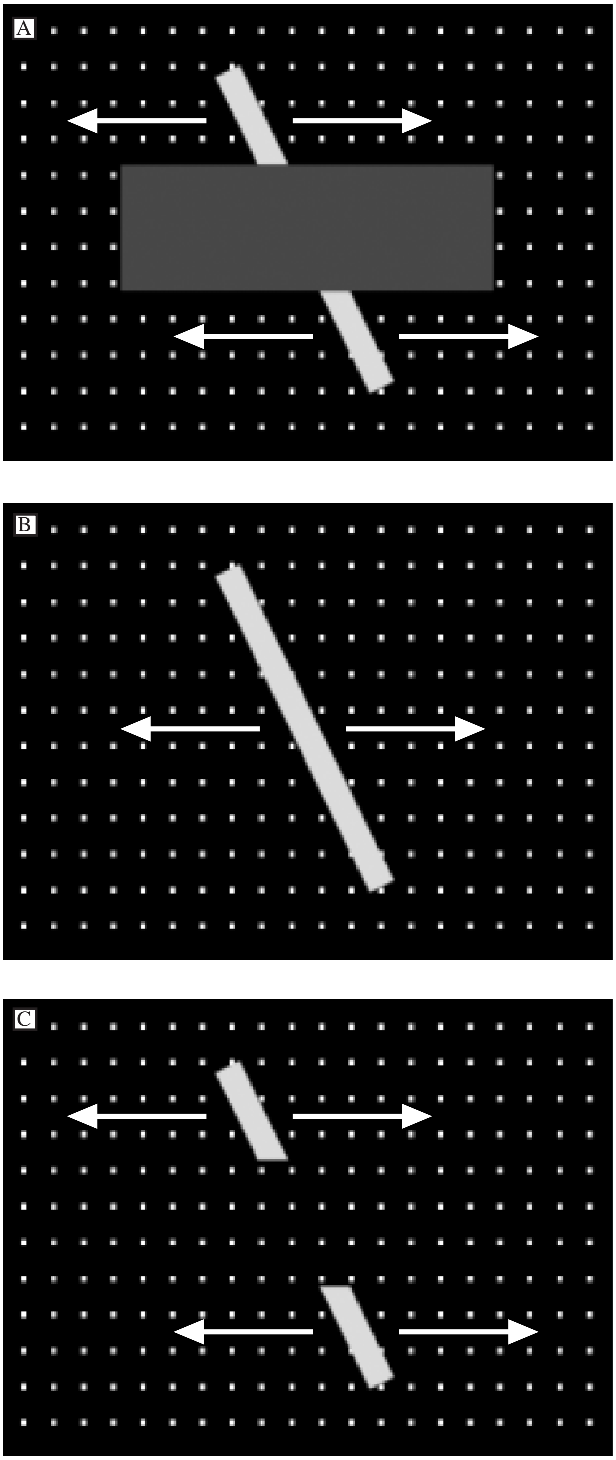

Figure 1. Displays employed in past research to investigate young infants' perception of object unity. A: A partly occluded rod moves relative to a stationary occluder. Infants view this stimulus until habituation of looking occurs. B: Complete rod. C: Broken rod. A posthabituation preference for C relative to B suggests perceptual completion of the rod in A; a preference for B relative to C suggests perception of disjoint objects in A. Both outcomes have obtained, depending on age of the infant and display characteristics.

perceptual filling in of a spatial gap by young infants has been found to rely on both spatial information (e.g., size of the gap imposed by the occluder; Johnson & Aslin, 1995) and spatiotemporal information (e.g., movement of the partly occluded object; Juscyk, Johnson, Spelke, & Kennedy, 1999). In this respect the two kinds of filling in are similar (i.e., both rely on information provided across space and time), but there is a critical difference: In the case of a moving object that becomes occluded for a time, the observer must keep track of its continued existence in the absence of any perceptual support to perceive the continuity of its trajectory. When perceiving object unity, in contrast, information is continually available (in the form of visible rod fragments) for the existence of the missing object part. Perception of trajectory continuity, therefore, might pose a greater challenge to the developing visual system than would perception of object unity.

Occluded trajectory events have been presented to young infants, and the results have been interpreted in terms of infants' knowledge of object identity or their reasoning about physical events. Studies investigating object identity have used measures of either ''tracking disruptions'' or looking times to gauge infants' understanding that an object seen to emerge from behind an occluder is the same as an object that was earlier seen to have become occluded. Studies investigating infant reasoning in response to occlusion events have used either predictive-action (eye movements or reaching) or looking-time measures to gauge infants' understanding that an object seen to have moved behind an occluder will end up at a particular location at a specific time. These studies are examined in turn, along with a consideration of the more general question of infants' perception of object trajectories.

Occlusion Events and Object Identity

Work done on infants' object identity has made much use of tracking tasks in which infants viewed an object that moved behind a screen on part of its path. Measurements were made of tracking disruptions on test trials in which the object either emerged too soon (i.e., the trajectory speed was nonlinear) or emerged in changed form (i.e., the object was replaced behind the occluder). Tracking disruptions were defined as a variation in direction of gaze apart from following the object on a linear path (whether visible or not), a variation such as looking back to the edge of an occluder. In one of the earliest of these studies, Bower, Broughton, and Moore (1971) reported that 2-month-olds showed increased disruption when the object emerged too soon but not when it changed its form, whereas 5-month-olds responded to a change in either variable. Bower et al. interpreted these results in terms of the development of a link between object movement and object features, and integrated this within a developmental account of object permanence. Subsequent researchers using the tracking-disruption measure interpreted findings with older infants in rather different ways, in terms of development of object identity as a precursor to object permanence (Moore, Borton, & Darby, 1978), or more simply still, in terms of infants' prediction of event sequences (Goldberg, 1976). Several investigators, however, failed to replicate Bower et al.'s results (Meicler & Gratch, 1980; Muller & Aslin, 1978). Muller and Aslin (1978) cast doubt on the reliability of tracking disruption as a measure of object identity, showing that object-movement rate (irrespective of whether the object disappeared) and occlusion time were in themselves important determinants of tracking disruption. Following the same line, Mareschal, Harris, and Plunkett (1997) obtained data supporting the conclusion that tracking disruption is a function of low-level perceptual factors relating to object speed, and that the inconsistent detection of tracking disruption between these earlier studies may be due to the different object speeds used. The use of tracking disruption as an index of infants' perception of objects and trajectories, therefore, has led to inconclusive results.

Other studies have employed infant looking times to various postfamiliarization displays to assess which events might appear to violate some expectation of object identity. For example, Xu and Carey (1996) investigated 10- to 12-month-olds' use of featural (i.e., object appearance) versus spatiotemporal information to determine whether one or more than one objects were involved in the tested events. In a task in which one object was seen to emerge and then disappear behind one screen, followed by emergence of an identical object from behind a second screen, infants appeared to expect two objects when the screens were removed (as indicated by longer looking at the unexpected outcome of one object). Xu and Carey concluded that the infants used the fact that no object moved between screens to deduce that at least two were present. In a similar study with a single screen and distinct objects, 10-month-olds showed no evidence of expecting to see two objects when the screens were removed; 12-month-olds provided positive evidence. Xu and Carey therefore proposed that 10-month-olds do not use featural information to individuate objects, relying instead on spatiotemporal information. With a simpler procedure, however, Wilcox and Baillargeon (1998) reported that infants as young as 7.5 months did use featural information to individuate objects. In these "event-monitoring" tasks, infants viewed displays in which two unique objects appeared in succession to the left and right of an occluding screen. The screen was either wide enough to hide both objects side by side, or made more narrow such that only one could be hidden. Infants looked longer at the narrow-screen event, implying an expectation of a single object behind the occluder. This task did not require infants to compare displays with previously seen events, perhaps easing cognitive demands and leading to positive results.

These two studies furnish reasons to speculate on two important issues with respect to infants' processing of trajectory information. First, it may be that looking-time measures will provide a viable means of assessing trajectory perception in infancy. Second, it appears that spatiotemporal information (e.g., occlusion time and screen width) may be a vital factor in leading infants to perceive object trajectories in a veridical fashion.

Predicting the Outcome of Occlusion Events

Much work done on infants' responses to occlusion events has recorded either (a) looking times toward displays that present an object moving behind an occluder, followed by test displays that show the object in one versus another location; or (b) anticipatory reaching or looking toward the place where and when the infant is assumed to expect the object to emerge. For example, Spelke, Breinlinger, Macomber, and Jacobson (1992) presented 2.5-month-olds with events in which a ball was seen to move behind an occluding screen. A small wall was placed behind and orthogonal to the occluder such that it would block the ball's motion and thus determine the ball's final resting position. The occluder was then raised to reveal the ball either adjacent to the wall, or on its far side, relative to the ball's starting point. The infants were reported to look longer at the latter event, suggesting that they detected a violation of the expectation that the ball would not travel through the space occupied by the wall. That is, they expected the ball to rest adjacent to the wall, implying knowledge of object locations in trajectory events under some circumstances. A second set of experiments by Spelke and colleagues, however, raises questions about this interpretation. Spelke, Katz, Purcell, Ehrlich, and Breinlinger (1994) presented infants between 4 and 10 months of age with events in which a ball rolled diagonally under a screen and the screen was lifted to reveal it at its resting place at the end of the trajectory, at either the top or bottom corner of a rectangular apparatus. On test trials, the ball rolled on a new trajectory, and when the screen was lifted it was revealed either at the end of its new trajectory or in the previously seen (but now unlikely) location. Four- and 6-month-olds showed no evidence of expecting the object to be at the end of the new trajectory, looking longer at that outcome than at the ball in its old location. Spelke et al. (1994) concluded that it is only by 8 months that infants begin to expect objects to be found along the line of their movement under these conditions. This experiment was intended to address a different issue from the Spelke et al. (1992) study, which was geared toward infants' physical reasoning rather than simply location processing. Nevertheless, the apparent conflict between outcomes of these experiments raises some doubt about infants' prediction of object location in simple trajectory events.

Questions are raised also by recent reports from Berthier and colleagues in which they measured anticipatory looks and reaches toward the place where a moving, occluded object presumably would be expected to appear. In one set of experiments, infants between 6.5 and 9.5 months were placed in front of a screen-wall apparatus similar to that used by Spelke et al. (1992), and their anticipatory looks and reaches were recorded as a ball moved behind the screen (Berthier et al., 2001). Several notable findings emerged. First, 9.5-month-olds made relatively few predictive eye movements when they were within reach of the apparatus. But when reaching was prevented, and 6.5- and 8.5-month-old infants were presented with either ''wall'' or ''no-wall'' events (i.e., the ball either would not or would be expected to appear on the far side of the screen), more anticipatory looks were observed in the latter condition. These results suggest that the act of reaching interferes with an ability to track objects over occlusion, and that infants take account of the barrier afforded by the wall. However, a subsequent experiment showed that anticipatory looks in 8.5-month-olds were not disrupted when the wall was completely hidden by the screen, implying that the infants were unable to retain information about the violation of the object's trajectory unless some portion of the obstacle remained visible. Further complicating interpretation of the work on anticipatory behaviors is a procedure described by Berthier, DeBlois, Poirier, Novak, and Clifton (2000), in which children between 2 and 3 years of age were seated in front of an apparatus with a series of small doors. Each door could be opened to reveal the potential resting place of a ball on a ramp behind the doors. As in the Spelke et al. (1992) and Berthier et al. (2001) experiments, a wall was placed behind the apparatus to block passage of the ball, but in this case, the position of the wall was changed so as to constrain the door behind which the ball could be found. Not until 3 years of age were the children able to determine reliably where the ball should be located. Based on these reports, then, it is unclear the extent to which infants and young children are able to predict where and when an object should reappear after having become occluded. Tasks that require an overt response, whether oculomotor or manual, appear to elicit a complex array of behaviors that is rather inconsistent across experiments, and as a result, it remains uncertain how and when infants are able to perceive the continuity of an object trajectory that is partly occluded.

The literature reviewed in this section, therefore, alongside the literature on object identity, fails to resolve our question of the development of infants' filling in a spatiotemporal gap. Additionally, many of these reports have used *extrapolation* tasks, whereas a task in which the middle part of object's trajectory is occluded is an *interpolation* task, which provides more perceptual support by presenting information about the object's trajectory before and after occlusion. It seems plausible that infants may be more likely to detect a trajectory discontinuity than they are to expect a particular resting place as a result of a trajectory, or a particular object to appear.

Rationale for the Present Work

Much research using moving object occlusion events has placed more stress on infants' awareness of object features than object trajectories as indicators of identity or location. Techniques such as those developed by Wilcox and Baillargeon (1998) could be extended to investigate how trajectory information per se contributes to identity judgments. However, there has been little investigation of infants' perception of and expectations about object trajectories in their own right. Also, despite the Muller and Aslin (1978) and Mareschal et al. (1997) warnings, surprisingly little attention has been given to identifying optimal occlusion times or movement rates in such tasks. These have varied widely

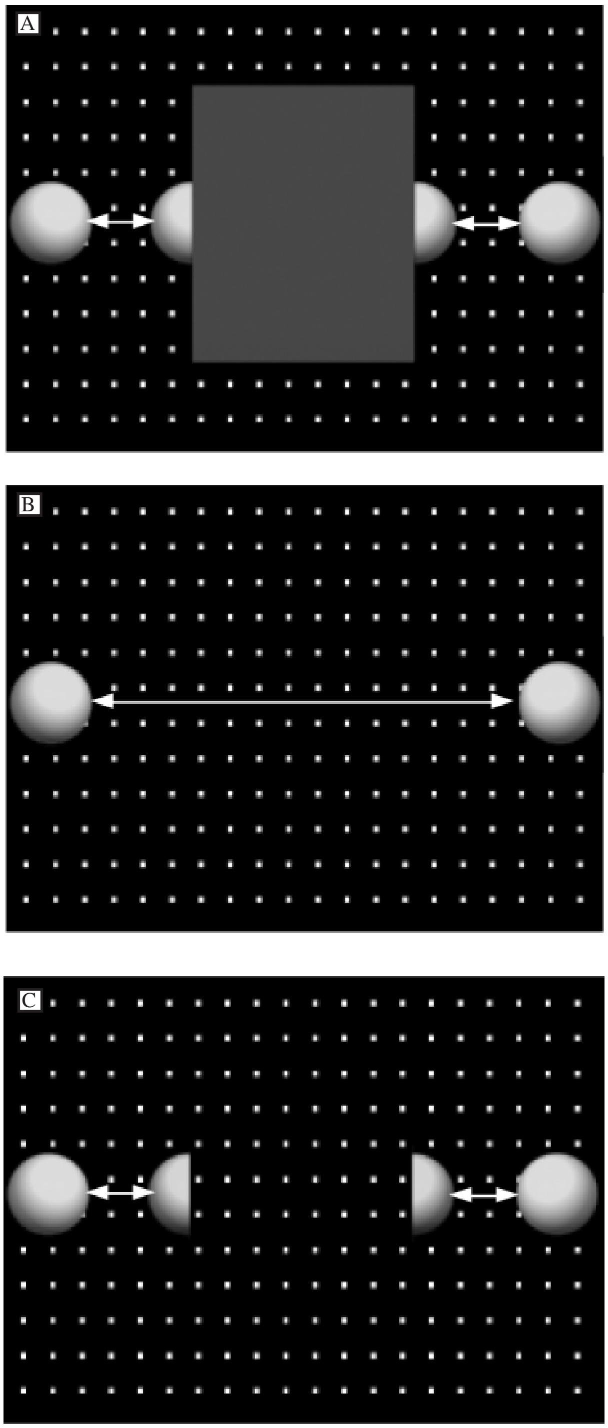

Figure 2. Displays employed in Experiment 1. A: Partly occluded trajectory display. B: Continuous trajectory test display. C: Discontinuous trajectory test display.

between experiments, possibly explaining some of the inconsistencies discussed previously.

Although object-tracking tasks are obvious candidates for interpretation in terms of object identity and permanence, there is currently a heated debate over whether the results of these studies deserve interpretation at this level or can be explained in terms of relatively simple perceptual factors (e.g., Bogartz, Shinskey, & Speaker, 1997; Haith, 1998). On these latter arguments, it is possible that infants' perceptual, rather than cognitive, processing of such events leads to the outcomes reported in those studies. Currently, these challenges lack a strong empirical base. Nevertheless, analysis at this level leads us to conclude that there is a need for systematic investigation of young infants' perception of object movement paths, with no prior assumptions made about the level of cognitive ability that these tasks reveal. Current critics of the object identity interpretation appear to see these tasks as tapping perceptual processes unrelated to object identity and permanence. Although we accept this possibility, it seems likely to us that any such perceptual capacities are vital precursors of object identity and other kinds of object knowledge, such as location.

Consequently, the work we describe in the present report examines development of infants' perception of dynamic object occlusion events, with a focus on how they perceive the trajectory itself. Our question concerns infants' ability to perceive the trajectory as continuous despite partial occlusion, as occurs when the object is fully hidden across a spatiotemporal gap. We used methods that directly parallel the successful work on object unity. After habituation to an event in which an object moved cyclically on a partly occluded linear path, infants were tested on two displays with the occluder absent: one in which they were exposed to a continuous movement of the object across the display (the *continuous* trajectory), and the other in which they saw only the two segments of object movement (the *discontinuous* trajectory; i.e., what they had seen directly during habituation; see Figure 2).

Experiment 1

We began our investigations by observing 4- and 6-month-olds. The age groups were compared directly in the analysis to explore any potential developments in perception of object trajectories in this age range.

Method

Participants. The final sample consisted of 40 full-term infants (19 female), 20 four-month-olds (age: $M = 124.7$ days, $SD = 7.4$), and 20 six-month-olds (age: $M = 188.4$ days, $SD = 7.7$), 10 in each condition. Two additional infants were observed but not included in the analyses because of fussiness. Infants were full term and recruited by hospital visits and follow-up telephone calls. The majority were from Caucasian, middle-class families. Parents were paid a nominal sum for participation.

Apparatus and stimuli. A Macintosh computer and a 76-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. 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 key press on the computer keyboard.

The habituation display consisted of a stationary 21.5×17.7 cm ($12.3 \times 10.1^\circ$ visual angle) blue box and a 6.7-cm (3.8°) green ball undergoing continuous lateral translation back and forth at a rate of 18.2 cm/s (10.4°/s), the center of its trajectory occluded by the box (Figure 2). The ball was visible in its entirety on either side of the box for 1,067 ms and was completely occluded for 667 ms. The transition from full visibility to full occlusion or the reverse took 400 ms. The animation was run as a continuous loop as long as the infant fixated the display, or 60 s had elapsed. In test displays, the box was removed and the ball translated back and forth as in the habituation display. In the continuous trajectory 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., color- 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 ($27.4 \times 18.7^\circ$), serving as texture elements.

Design and procedure. Infants were assigned randomly to either an experimental or 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. Half the infants in each group were presented with the continuous trajectory first, and the other half 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 s 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. Interobserver correlations were high across the three experiments in this report ($M\ r = .99$).

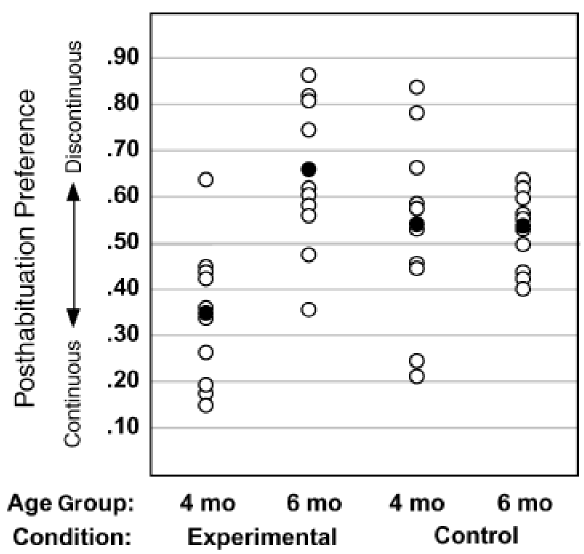

Figure 3. Looking-time preferences from individual infants in Experiment 1, plotted as total looking times toward the discontinuous trajectory divided by total looking toward the discontinuous plus looking toward the continuous trajectory. Infants in the experimental condition were first habituated to the partly occluded trajectory display depicted in Figure 2a. Infants in the control condition viewed the test stimuli with no prior habituation. Four-month-olds in the experimental condition tended to prefer the continuous trajectory, implying perception of the partly occluded trajectory as discontinuous on either side of the occluder. In contrast, 6-month-olds exhibited the opposite preference, implying perception of the trajectory's continuity. Infants in the control condition showed no consistent preference.

Results and Discussion

Figure 3 presents looking-time preferences for individual infants, calculated as looking times toward the discontinuous trajectory divided by total looking at discontinuous plus continuous trajectory displays. The 6-month-olds tended to look longer at the discontinuous trajectory (8 of the 10 infants preferred the discontinuous trajectory; Wilcoxon signed ranks test $z = 2.09$, $p < .05$). In contrast, the 4-month-olds tended to look longer at the continuous trajectory (9 of the 10 infants preferred the continuous trajectory; $z = 2.70$, $p < .01$). Infants in the two control conditions tended to prefer neither test display (zs = 1.17 and 1.48 for 4- and 6-month-olds, respectively, *ns*).

These conclusions were confirmed with parametric analyses of looking times. Looking-time data in some cells were positively skewed, and all data were therefore log-transformed before analysis. Preliminary analyses including participant gender as a factor revealed no effects that bear on the question of interest in any of the three experiments in this report (i.e., no sex differences in performance); data were collapsed across this factor in all parametric analyses. A 2 (age) × 2 (condition: experimental vs. control) × 2 (order: continuous vs. discontinuous trajectory first) × 2 (test display: continuous vs. discontinuous trajectory) × 3 (trial block: first, second, or third) mixed ANOVA revealed a reliable main effect of condition, $F(1, 32) = 22.10$, $p < .001$. This effect was qualified by several higher order interactions: an Age × Condition interaction, $F(1, 32) = 4.29$, $p < .05$; a Condition × Order × Display interaction, $F(1, 32) = 9.48$, $p < .01$; and an Age × Condition × Order × Trial interaction, $F(2, 64) = 4.23$, $p < .05$. There was a tendency to look longer overall by infants in the control conditions, and this tendency was less pronounced in the 4-month-olds. In addition, infants in the control conditions tended to look longer overall at the display presented first, and the decline in looking across trials was more precipitous among 4-month-olds in the control condition, especially those who viewed the discontinuous trajectory first.

Most important, there were significant interactions between age and display, $F(1, 32) = 8.15$, $p < .01$, and between age, condition, and display, $F(1, 32) = 14.97$, $p < .001$, and no other reliable effects. These interactions were interpreted with simple effects tests. Infants in the 6-month-old experimental condition showed a reliable preference for the discontinuous trajectory, $F(1, 32) = 11.75$, $p < .01$ (looking at discontinuous: $M = 13.48$ s, $SD = 8.04$; looking at continuous: $M = 6.69$ s, $SD = 2.82$). In contrast, infants in the 4-month-old experimental condition looked significantly longer at the continuous trajectory, $F(1, 32) = 10.87$, $p < .01$ (looking at discontinuous: $M = 11.88$ s, $SD = 10.24$; looking at continuous: $M = 22.06$ s, $SD = 12.82$). Infants in the 6-month-old control condition showed a slight, nonsignificant preference for the discontinuous trajectory, $F(1, 32) = .66$, *ns* (looking at discontinuous: $M = 30.86$ s, $SD = 16.28$; looking at continuous: $M = 26.48$ s, $SD = 12.70$), as did infants in the 4-month-old control condition $F(1, 32) = 3.34$, *ns* (looking at discontinuous: $M = 27.72$ s, $SD = 11.91$; looking at continuous: $M = 22.44$ s, $SD = 12.31$). A final set of analyses was targeted at the question of whether there were significant differences in test display preferences of the experimental and control groups. The difference was reliable both for 6-month-olds, $t(18) = 2.14$, $p < .05$, and for 4-month-olds, $t(18) = 2.45$, $p < .05$.

The result from the 6-month-olds implies perception of the continuity of the ball's trajectory despite partial occlusion, but the finding from the 4-month-olds was the converse, suggesting that the younger infants did not link the two views of the trajectory across the spatiotemporal gap imposed by the occluder. This latter result seems surprising, if one accepts claims about object continuity and permanence under occlusion in infants at this age (e.g., Baillargeon, 1987). We consider two possibilities for the age discrepancy. First, we examined habituation looking times for evidence of a difference in performance. It could be, for example, that the 4-month-olds were exposed to the ball-and-box display for an insufficient amount of time to permit a veridical percept of the trajectory to emerge. However, there were no significant age differences, either in terms of number of habituation trials ($M = 8.0$, $SD = 2.8$ for 6-month-olds; $M = 7.6$, $SD = 2.3$ for 4-month-olds; $t(18) = .35$, *ns*) nor in terms of total habituation time ($M = 130.84$ s, $SD = 57.82$ for 6-month-olds; $M = 153.74$ s, $SD = 93.15$ for 4-month-olds; $t(18) = .66$, *ns*). A second possibility is that 4-month-old infants have difficulty perceiving the continuity of a partly occluded trajectory but will do so if the task is made easier by reducing the spatiotemporal gap across which continuity would be interpolated. To investigate this possibility, we replicated the methods of Experiment 1 with a narrow occluder. If the 4-month-olds in Experiment 1 failed to perceive trajectory continuity due to spatiotemporal constraints (e.g., if the box was too wide), a reduction in the width of the box might yield a result similar to that of the 6-month-olds, that is, longer looking during test at the discontinuous trajectory display. On the other hand, if 4-month-olds are unable to perceive continuity under any circumstances, a narrow occluder experimental condition should yield the same result obtained in Experiment 1: a significant preference for the continuous trajectory. We also observed a group of 2-month-olds, to explore age differences under conditions in which continuity should be maximally available.

Experiment 2

Method

Participants. The final sample consisted of 40 full-term infants (18 female), 20 two-month-olds (age: $M = 61.6$ days, $SD = 6.1$), and 20 four-month-olds (age: $M = 123.9$ days, $SD = 7.0$), 10 in each condition. An additional 9 infants were observed but not included in the analyses because of fussiness (7) or sleepiness (2). The infants were recruited from the same population, and with the same procedures, as Experiment 1.

Apparatus, stimuli, design, and procedure. The design was identical to that of Experiment 1. Infants were randomly assigned to either the experimental or control group, and to one of the two test display orders. Testing conditions were identical to those in Experiment 1, except the occluder in the habituation stimulus measured 7.0 cm (4.0°) across (see Figure 4). The ball was visible in its entirety on either side of the occluder for 1,667 ms and was completely occluded for only 67 ms. The discontinuous trajectory display contained a gap of equal size (i.e., 7.0 cm) to the box in the habituation display.

Results and Discussion

Figure 5 presents looking-time preferences for individual infants. The 4-month-olds tended to look longer at the discontinuous trajectory (9 of the 10 infants preferred the discontinuous trajectory; $z = 2.70$, $p < .01$). In contrast, the 2-month-olds exhibited no consistent preference (5 of the 10 infants preferred the discontinuous trajectory; $z = .66$, *ns*). Likewise, infants in the two control conditions tended to prefer neither test display (zs = .56 and .56 for 4- and 2-month-olds, respectively, *ns*).

These conclusions were confirmed with parametric analyses of looking times. A 2 (age) × 2 (condition: experimental vs. control) × 2 (order: continuous vs. discontinuous trajectory first) × 2 (test display: continuous vs. discontinuous trajectory) × 3 (trial block: first, second, or third) mixed ANOVA revealed a significant main effect of age, $F(1, 32) = 15.60$, $p < .001$, the result of longer looking overall by the 2-month-olds; condition, $F(1, 32) = 17.05$, $p < .001$, the result of longer looking overall by the control group; test display, $F(1, 32) = 6.33$, $p < .05$, the result of longer looking overall

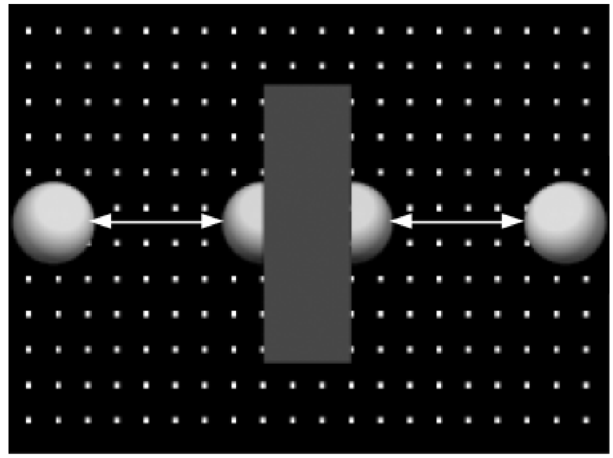

Figure 4. The narrow occluder display from Experiment 2.

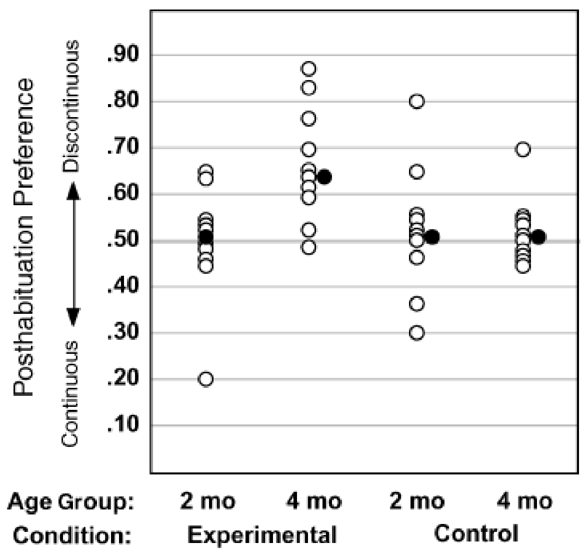

Figure 5. Looking-time preferences from individual infants in Experiment 2. Infants in the experimental condition were first habituated to the narrow occluder display depicted in Figure 4. Four-month-olds in the experimental condition tended to prefer the discontinuous trajectory, implying perception of the partly occluded trajectory as continuous despite partial occlusion. Two-month-olds provided no evidence of continuity perception. Infants in the control group, likewise, showed no consistent preference.

at the discontinuous trajectory; and trial, $F(2, 64) = 12.58$, $p < .001$, the result of an overall decline in looking times across trial blocks.

Most important, there was also a reliable Age × Condition interaction, $F(1, 32) = 9.35$, $p < .01$, and an Age × Condition × Test display interaction, $F(1, 32) = 7.68$, $p < .01$. There were no other reliable effects. Simple effects tests revealed a significant preference for the discontinuous trajectory display by the 4-month-olds, $F(1, 32) = 20.16$, $p < .001$ (looking at discontinuous: $M = 11.75$ s, $SD = 10.32$; looking at continuous: $M = 7.01$ s, $SD = 10.33$), but infants in none of the other groups showed a reliable preference, $F\text{s} < .64$, *ns* (4-month-olds control looking at discontinuous: $M = 32.69$ s, $SD = 11.97$; 4-month-olds control looking at continuous: $M = 31.34$ s, $SD = 13.78$; 2-month-olds experimental looking at discontinuous: $M = 31.90$ s, $SD = 18.88$; 2-month-olds experimental looking at continuous: $M = 30.17$ s, $SD = 17.45$; 2-month-olds control looking at discontinuous: $M = 38.77$ s, $SD = 16.72$; 2-month-olds control looking at continuous: $M = 36.65$ s, $SD = 15.40$). The test display preferences of 4-month-olds in the experimental and control groups were reliably different, $t(18) = 3.34$, $p < .01$, but not those of the 2-month-olds, $t(18) = .57$, *ns*.

These results lead to two conclusions. First, the 4-month-olds appeared to perceive trajectory continuity in the narrow-occluder display in like manner to the 6-month-olds in Experiment 1 with the wide-occluder display. Second, the 2-month-olds provided no evidence of perception of trajectory continuity. We again examined age differences in habituation performance, to probe the possibility that the 2-month-olds may have received insufficient exposure to the occluded trajectory stimulus to permit formation of a veridical percept of its continuity. These analyses revealed that the 2-month-olds looked reliably longer during habituation than did the 4-month-olds, both in terms of habituation trials, $M = 10.0$, $SD = 2.4$ for 2-month-olds, $M = 7.6$, $SD = 2.6$ for 4-month-olds, $t(18) = 2.17$, $p < .05$, and in terms of total habituation time, $M = 356.56$ s, $SD = 160.18$ for 2-month-olds, $M = 144.88$ s, $SD = 132.02$ for 4-month-olds, $t(18) = 3.22$, $p < .01$. It is unlikely, therefore, that the outcome of Experiment 2 can be explained on the insufficient exposure hypothesis. The results of the first two experiments, instead, are consistent with the notion that perception of trajectory continuity in infancy depends on both the age of the infant and the spatiotemporal gap across which continuity must be interpolated. Four months appears to be a pivotal age in the developmental process.

Experiment 3

In the third experiment we explored further the notion that the size of an occluder's physical gap imposed across a linear trajectory determines whether 4-month-olds will perceive the trajectory's continuity. We employed 4-month-olds as participants because our evidence thus far indicated that percepts of continuity, or lack thereof, depend strongly on spatiotemporal factors at this age. A second goal was to replicate the finding of a preference for the continuous trajectory reported in Experiment 1. We used three conditions in which screen width was varied, from 17.7 cm (the same width as the ball-and-box stimulus of Experiment 1) down to two intermediate widths relative to the narrow occluder of Experiment 2.

Method

Participants. The final sample consisted of 60 (32 female) full-term infants (age: $M = 127.1$ days, $SD = 7.3$), 10 in each of six conditions. An additional 5 infants were observed but not included in the analyses because of fussiness. The infants were recruited from the same population, and with the same procedures, as in Experiments 1 and 2.

Apparatus, stimuli, design, and procedure. The design was identical to that of Experiments 1 and 2. Infants were randomly assigned to either the experimental or control group, to 1 of 3 occluder width conditions (12.1 cm, 14.8 cm, or 17.7 cm), and to one of the two test display orders. Testing conditions were similar to those in Experiments 1 and 2, except the occluders in the habituation stimulus measured either 12.1 cm (6.9°), 14.8 cm (8.5°), or 17.7 cm (10.1°) across. In the 12.1-cm condition, the ball was visible in its entirety on either side of the occluder for 1,333 ms and was completely occluded for 400 ms; in the 14.8-cm condition, the ball was visible in its entirety for 1,200 ms and was completely occluded for 533 ms. The display in the 17.7-cm condition was identical to that employed in Experiment 1. The discontinuous trajectory displays contained gaps of equal size (i.e., 12.1, 14.8, or 17.7 cm) to the occluders in the habituation displays.

Results and Discussion

Figure 6 presents looking-time preferences for individual infants. Infants in the 12.1-cm experimental condition tended to look longer at the

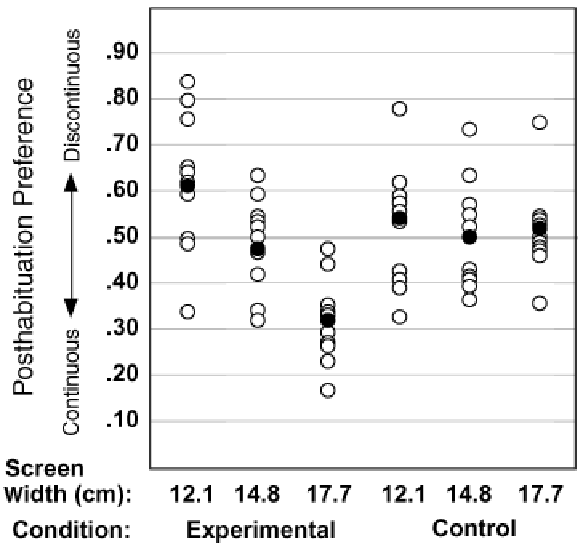

Figure 6. Looking-time preferences from individual infants in Experiment 3. All infants were 4 months of age. Infants in the experimental condition were first habituated to a trajectory display in which the occluder was either 12.1 cm, 14.8 cm, or 17.7 cm wide (the same width as in Experiment 1). Infants in the 12.1-cm experimental condition tended to prefer the discontinuous trajectory, providing some evidence of perception of the partly occluded trajectory as continuous (however, this preference was not reliably greater than the control group). In contrast, infants in the 17.7-cm experimental condition preferred the continuous trajectory, implying perception of the partly occluded trajectory as discontinuous, replicating the effect found first in Experiment 1. Infants in the 14.8-cm experimental condition exhibited an intermediate pattern of performance. Infants in the control group, likewise, showed no consistent preference.

discontinuous trajectory, although the difference fell short of significance with a nonparametric test (7 of the 10 infants preferred the discontinuous trajectory; $z = 1.68$, $p < .10$). Infants in the 14.8-cm experimental condition showed no consistent preference (6 of the 10 infants preferred the discontinuous trajectory; $z = .25$, *ns*), and infants in the 17.7-cm experimental condition preferred the continuous trajectory (all 10 infants showed this pattern; $z = 2.80$, $p < .01$). Infants in the three control conditions exhibited no consistent preference ($zs < .87$, *ns*).

These conclusions were confirmed with parametric analyses of looking times. A 3 (screen width: 12.1, 14.8, or 17.7 cm) × 2 (condition: experimental vs. control) × 2 (order: continuous vs. discontinuous trajectory first) × 2 (test display: continuous vs. discontinuous trajectory) × 3 (trial block: first, second, or third) mixed ANOVA revealed a significant main effect of condition, $F(1, 48) = 40.39$, $p < .001$, which was qualified by a Screen Width × Condition interaction, $F(2, 48) = 9.35$, $p < .01$: There was longer looking overall by infants in the control groups, a difference that was most pronounced in the 17.7-cm screen width condition. There was also a significant main effect of trial, $F(2, 96) = 18.14$, $p < .001$, which was qualified by a Condition × Trial interaction, $F(2, 96) = 13.56$, $p < .001$; an Order × Trial interaction, $F(2, 96) = 3.31$, $p < .05$; and a Screen Width × Condition × Trial interaction, $F(4, 96) = 3.50$, $p < .05$. There was a general decline in looking across trials. The decline in looking was more precipitous among infants in the control conditions, but less of a decline by infants in the 17.7-cm experimental condition. The decline was steeper among infants who viewed the continuous trajectory first. There were also several interactions involving order: Order × Display, $F(1, 48) = 7.64$, $p < .01$; Screen Width × Order × Display, $F(2, 48) = 3.72$, $p < .05$; and Screen Width × Condition × Order, $F(1, 48) = 5.01$, $p < .05$. Infants in general tended to look longer at the test display presented first, an effect that was more pronounced in the 14.8- and 17.7-cm conditions. Looking times tended to be longer for infants in the control conditions that viewed the continuous trajectory first, but this tendency was reversed for infants in the 17.7-cm condition.

Finally, and most important, there was a significant Screen Width × Display interaction, $F(2, 48) = 9.83$, $p < .001$; and a significant Screen Width × Condition × Display interaction, $F(2, 48) = 5.77$, $p < .01$. These interactions were interpreted with simple effects tests. Infants in the 12.1-cm experimental condition looked reliably longer at the discontinuous trajectory, $F(1, 48) = 9.99$, $p < .01$ (looking at discontinuous: $M = 20.25$ s, $SD = 10.66$; looking at continuous: $M = 13.06$ s, $SD = 10.15$). Infants in the 14.8-cm experimental condition showed no reliable preference for either test display, $F(1, 48) < .01$, *ns* (looking at discontinuous: $M = 19.08$ s, $SD = 6.32$; looking at continuous: $M = 21.76$ s, $SD = 14.84$). Infants in the 17.7-cm experimental condition looked longer at the continuous trajectory, $F(1, 48) = 21.40$, $p < .001$ (looking at discontinuous: $M = 5.27$ s, $SD = 3.74$; looking at continuous: $M = 11.06$ s, $SD = 5.81$). Infants in none of the three control conditions showed a consistent test display preference, $Fs < 1.54$, *ns* (12.1-cm control looking at discontinuous: $M = 31.88$ s, $SD = 11.66$; 12.1-cm control looking at continuous: $M = 26.54$ s, $SD = 10.99$; 14.8-cm control looking at discontinuous: $M = 31.96$ s, $SD = 16.30$; 14.8-cm control looking at continuous: $M = 31.95$ s, $SD = 19.27$; 17.7-cm control looking at discontinuous: $M = 40.46$ s, $SD = 14.38$; 17.7-cm control looking at continuous: $M = 37.67$ s, $SD = 14.42$). The test display preferences of infants in the 17.7-cm experimental and control groups were reliably different, $t(18) = 5.06$, $p < .01$, but those of the infants in the 14.8 cm condition were not, $t(18) = .82$, *ns*. The difference in the 12.1-cm condition was likewise nonsignificant, $t(18) = 1.20$, *ns*.

Habituation data were again examined for differences in performance across the three screen width conditions. There were no significant differences across the experimental groups in terms of habituation trials (12.1 cm: $M = 7.6$, $SD = 2.2$; 14.8 cm: $M = 8.1$, $SD = 2.5$; 17.7 cm: $M = 8.3$, $SD = 2.5$; $ts < .7$, *ns*) or in terms of total habituation times (12.1 cm: $M = 133.4$ s, $SD = 92.0$; 14.8 cm: $M = 169.7$ s, $SD = 79.9$; 17.7 cm: $M = 185.7$ s, $SD = 89.8$; $ts < 1.3$, *ns*).

The evidence from Experiment 3 confirms the suggestions from Experiments 1 and 2 that 4-month-olds' perception of the continuity of an object's trajectory is restricted largely by spatiotemporal factors (distance and time out of sight). When the trajectory's center portion was occluded for the longest time (667 ms, in the 17.7-cm condition), the infants appeared to perceive the left and right views of the trajectory as discontinuous, replicating the outcome of Experiment 1 with a second group of 4-month-olds. Performance was intermediate with an intermediate occlusion interval, and there is some evidence that continuity may have been perceived at the shortest interval tested in this experiment (400 ms), but the outcome was more equivocal relative to the narrow-box condition of Experiment 2.

General Discussion

These three experiments present evidence with multiple age groups concerning the emergence of a fundamental perceptual skill in infancy: the ability to register the continuity of a linear trajectory as a moving object becomes progressively occluded and disoccluded. Two-month-olds provided few hints of this ability, whereas 6-month-olds appeared to perceive continuity under the most demanding conditions we employed. Four-month-olds demonstrated an intermediate pattern of performance, apparently perceiving the continuity of a moving object trajectory when it was occluded for a very short duration (67 ms), but appearing to perceive the trajectory as discontinuous when the object was out of sight for a slightly more extended (but still limited) interval (667 ms). Intermediate occlusion times (400 and 533 ms) led to intermediate patterns of performance in a fairly straightforward manner. Taken together, these findings suggest that perception of trajectory continuity emerges several months after birth and becomes more firmly established by 6 months.

There are alternative accounts of the claims just outlined, but we believe the overall pattern of results allows us to rule them out safely. For example, it might be that infants perceive a "subjective" screen in the discontinuous trajectory display, in like manner to the "slit" or "tunnel" effect reported by adults (Michotte, Thinès, & Crabbé, 1991). That is, the ball might be perceived to become occluded and disoccluded even in the absence of a luminance-defined occluder, due to perception of an illusory occluding edge, perhaps indicative of a slit in the background surface. If the infants in the present experiments were subject to the slit effect, we would expect consistent preferences for the continuous trajectory display because the discontinuous trajectory would be experienced as an occlusion stimulus and therefore more similar to the occlusion display seen during habituation. This effect obtained in the 4-month-olds in Experiment 1. Note, however, that the test display preferences reversed in Experiments 2 and 3 when occlusion time was reduced, a manipulation that would not be expected to have any bearing on perception of a subjective screen in the discontinuous trajectory. A second possible alternative account appeals to differences across habituation and test stimuli that might affect post-habituation preferences, such as removal of the occluding box. It might be argued that removing the box effects a bias toward one of the test displays: longer looking toward the discontinuous trajectory because something has been removed, or longer looking at the continuous trajectory because movement has occurred in a location where none was seen before. Again, however, the reversal of test display preferences as a function of occlusion time provides evidence against such interpretations. A third alternative account posits that young infants will often provide posthabituation familiarity preferences rather than novelty preferences (e.g., Bogartz, Shinskey, & Schilling, 2000). This account, too, falls short of explaining the pattern of results across experiments: It is unclear why 4-month-olds would exhibit a familiarity preference after habituation to the narrow occluder and large ball displays (i.e., a preference for the discontinuous trajectory) but exhibit a novelty preference after habituation to the wide occluder display (a preference for the continuous trajectory). Finally, an account based on variations in familiarization time during the initial exposure to the occlusion stimulus fails to explain the data because there was no consistent pattern of differences in habituation trials or habituation times that was consonant with the outcomes from the posthabituation looking times.

The findings of the present experiments are striking in their parallels with results from studies of the development of perception of object unity. Four-month-olds have been found to perceive the unity of two rod parts in partial occlusion displays, such as depicted in Figure 1a, under limited conditions (i.e., when the rod parts are aligned and undergo common translatory motion; Johnson & Aslin, 1996; Kellman & Spelke, 1983). This ability becomes more robust by 6 months, obtaining under a wider set of conditions (e.g., when the object is stationary or rotates in the frontal plane; Craton, 1996; Eizenman & Bertenthal, 1998). Neonates, in contrast, seem to perceive a moving, partly occluded rod as consisting of disjoint surfaces (Slater et al., 1996). The earliest age at which infants have been found to perceive object unity in rod-and-box stimuli is 2 months (Johnson & Aslin, 1995; cf. Kawataba, Gyoba, Inoue, & Ohtsubo, 1999). The effect is fragile at this time, however, and does not obtain when the occluder is wide, although 4-month-olds perceive unity in such a display (Johnson & Aslin, 1996). A key difference between experiments that probe infants' perception of object unity and trajectory continuity is what they reveal about the age at which these perceptual tasks come to be solved. Object unity seems to be perceived several months earlier than does trajectory continuity, and this difference may be due to the additional perceptual challenge posed by tracking the persistence of an object that undergoes a temporary occlusion. Taken together, then, the results from object unity experiments and the present studies suggest that perceptual completion across a spatial gap (object unity) and across a spatiotemporal gap (trajectory continuity) follow a similar developmental course. The timing is shifted in the age of transition toward veridical percepts, however. In the case of object unity, the transitional age appears to be 2 months of age, but in the case of trajectory continuity, the transitional age appears to be 4 months.

How might these findings inform theories of object perception and occlusion, and the development of these skills? Research with adults supports the view that many kinds of perceptual completion are undertaken relatively early in the visual-processing stream (e.g., with low-level mechanisms in cortical areas V1 and V2). Experiments employing visual search tasks, for example, have obtained evidence for preattentive completion of image fragments on the basis of both stereopsis (He & Nakayama, 1992) and monocular cues (Rensink & Enns, 1998). There is evidence as well for a strong role of preattentive early vision in such occlusion phenomena as transparency (Watanabe & Cavanaugh, 1992) and illusory contours (Davis & Driver, 1994). The ubiquity of occlusion in the visual array, therefore, seems to pose the mature visual system little difficulty, and mechanisms to deal with it are functional at the earliest cortical stages of vision (see Nakayama, He, & Shimojo, 1995). Postattentive visual processing, likewise, is immune to occlusion in some respects. Adults' competence at tracking one or more moving objects simultaneously, for example, is unimpaired by short intervals of occlusion at luminance-defined or illusory edges (Michotte et al., 1991; Scholl & Pylyshyn, 1999).

Evidence from very young infants argues against the likelihood that these fundamental visual functions are available in the absence of some period of visual exposure to objects. At present it is unclear precisely how veridical responses to occlusion develop in infancy. The results from studies of object unity and trajectory continuity, however, provide a vital contribution toward discovery of mechanisms of development, in narrowing the time of emergence of these responses to the first several months after birth. Speculation concerning the ontogeny of contour integration and perceptual completion has centered on several factors, including improvements in coherence and synchrony of neural firing (Csibra, Davis, Spratling, & Johnson, 2000), strengthening and pruning of horizontal and vertical connectivities within and between areas of the visual system (Burkhalter, Bernardo, & Charles, 1993; Kovács, 2000), and experience viewing objects as they become occluded and disoccluded (Mareschal & Johnson, 2002; Piaget, 1954). It seems most likely that development of perceptual completion abilities stems from a combination of these factors (Johnson, 2001).

Returning to the issues discussed earlier concerning infants' perception of object identity and their ability to predict the outcomes of occlusion events, our trajectory stimuli presented rudimentary occlusion displays and we obtained evidence that there are restrictions in young infants' ability to perceive these simplistic events veridically. In particular, spatiotemporal information (i.e., time out of sight and distance of spatial interpolation) has a dramatic effect on whether 4-month-olds perceive a trajectory as continuous or discontinuous across occlusion. We obtained no evidence, moreover, of perception of trajectory continuity in the 2-month-olds we tested. There is no evidence of which we are aware that infants perceive occlusion in any form before 2 months after birth, and occlusion is clearly a *sine qua non* of veridical object perception. It seems unlikely that young infants would have more sophisticated levels of knowledge of other object properties under conditions of occlusion, such as identity or permanence, or would be able to predict when and where objects would appear when occluded, if they cannot perceive the continuity of an object on a simple trajectory that is out of sight for less than 1 s.

Our findings are inconsistent, however, with the conjecture that there are no functional object representations at any point in infancy. For example, there is no account based on strictly perceptual means, such as intrinsic preferences for familiarity or limited visual scanning abilities (e.g., Bogartz et al., 1997) that seems adequate to describe the range of responses to trajectory continuity exhibited by the infants we observed. Instead, our data seem to fit better an account advocating a role for the emergence of representational skills over the first few months after birth, with the onset of visual experience. Our findings are inconsistent as well, therefore, with theories advocating a role for functional object representations that are innately available. For example, our results contradict the thesis that perception of object continuity under occlusion must be unlearned because it cannot be achieved by acquiring ''contrastive evidence'': conditions under which occluded objects continue to exist versus conditions under which they do not (Baillargeon, 1995). On the contrastive evidence hypothesis, physical knowledge of objects is necessarily unlearned if it is attained outside this particular mechanism, and there are no observable cases in the real world in which solid objects go out of existence; therefore contrastive evidence is not available concerning continuity. Other, similar accounts likewise posit a minor role for postnatal experience in shaping object knowledge (e.g., Spelke, 1990).

Our data indicate that fundamental developments occur in knowledge of object continuity. Our data also clarify the range of mechanisms that may underlie young infants' success at continuity tasks in their suggestion that development of perceptual filling in is rooted in means that do not require contrastive evidence but do require some exposure to visual input. The following account would appear to be more consistent with the present findings, and the bulk of the extant literature: The first step in the development of veridical object perception may be to parse the optic array into its visible constituents based on information about motion, luminance differences, edge orientation, and other cues (e.g., depth). Many of these perceptual skills are available at birth (Slater, 1995) and were clearly accessible to the infants in the present experiments. With experience and maturation of the visual system, the infant perceives simple occlusion events by linking object edges across a physical gap and registering the persistence of objects that go out of sight. Perceptual challenges are progressively overcome, such as those imposed by increasing occlusion distance and duration, and infants come to perceive other lower level occlusion phenomena such as transparency and illusory contours (Johnson & Aslin, 2000; Johnson & Mason, 2002). Infants also learn about typical appearances of everyday objects and the consequences of their own object-directed actions (Baillargeon, 1995; Needham, Baillargeon, & Kaufman, 1997; Piaget, 1952). From here, with the achievement of more abstract representations, infants have access to higher level characteristics of objects under occlusion, such as identity and permanence (Meltzoff & Moore, 1999; Piaget, 1954; Xu, 1999).

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