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Motion and edge sensitivity in perception of object unity

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Abstract

Although much evidence indicates that young infants perceive unitary objects by analyzing patterns of motion, infants' abilities to perceive object unity by analyzing Gestalt properties and by integrating distinct views of an object over time are in dispute. To address these controversies, four experiments investigated adults' and infants' perception of the unity of a center-occluded, moving rod with misaligned visible edges. Both alignment information and depth information affected adults' and infants' perception of object unity in similar ways, and infants perceived object unity by integrating information about object features over time. However, infants perceived a moving, misaligned, three-dimensional object as indeterminate in its connectedness, whereas adults perceived it as connected behind the occluder. These findings indicate that the effectiveness of common motion in specifying unified surfaces across an occluder is reduced by misalignment of edges. Alignment information enhances perception of object unity either by serving directly as information for unity or by optimizing the detectability of motion-carried information for unity. In addition, young infants are able to retain information about edge orientation over short intervals in determining connectedness via a process of spatiotemporal integration.

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1. Introduction

The last three decades have witnessed a blossoming of research on perceptual development in human infancy (Gibson, 1969, 1991; Kellman & Arterberry, 1998). Discoveries concerning young infants' capacities to perceive depth and motion have challenged longstanding theories of perception, whereby visual experience of a spatial layout depends on a history of associations of momentary visual sensations with actions and perceptions in other modalities (e.g., Berkeley, 1709/1975; Helmholtz, 1867/1962). Discoveries concerning young infants' capacities to perceive unitary, enduring objects similarly have challenged theories proposing that object representations depend on language (Quine, 1960) or on a long history of sensory–motor experience and organization (Piaget, 1954).

Despite much research, however, the early development of two perceptual capacities remains unclear because of two sets of puzzling, conflicting findings, and the conflicting findings in turn raise fundamental questions involving the nature of perception in adults. One dispute concerns the development of the capacity to organize visual arrays into the simplest configurations, in accord with the Gestalt laws of common fate, good continuation, similarity, symmetry, proximity, and closure (Koffka, 1935; Wertheimer, 1923/1958). Behind this dispute is a question that has animated debates since the rise of Gestalt psychology: Are human perceptual systems built to form units in accord with these laws, or does this propensity depend on a history of experience with objects and scenes whose organization has these properties (see Brunswik & Kamiya, 1953; Koffka, 1935)? The other dispute concerns the development of the capacity to integrate information over time so as to recover properties of objects and scenes that are not visible in any momentary array. Behind this dispute is a similarly old and heated question: Are perceptual systems built to process momentary arrays whose significance is discovered only by other, experience-dependent mechanisms that integrate over distinct perceptions, or are perceptual systems built to extract information over space and time (see Gibson, 1961, 1979; Piaget, 1952, 1954)?

The present experiments were undertaken to move toward a resolution of both disputes by investigating young infants' perception of partly occluded objects under different spatial and spatiotemporal conditions. Before describing the experiments, however, we review the conflicting evidence concerning the development of object perception and spatiotemporal integration.

2. Gestalt relations and object perception in infancy

Much of the evidence concerning infants' perception of objects comes from studies employing the method of habituation. Infants first are shown a display repeatedly until their looking times decrease to a predetermined criterion, taken to indicate that they are familiar with the display and less interested in it. Then, infants view two test displays that are each designed to match the original display in different ways. For example, one display might resemble the visible surfaces of an object in the original display, whereas the other display might resemble both the visible and invisible surfaces that adults perceive (see Fig. 1). If infants look longer at one test display than the other, this suggests that the preferred display differs more from what infants perceived during habituation (Bornstein, 1985). By systematically comparing infants' dishabituation patterns across a series of different displays, these perceived similarities and dissimilarities shed light on infants' organization of visual scenes.

A considerable body of research using this method has focused on infants' perception of the unity of an object whose ends are visible and whose center is occluded, as in Fig. 1A. Some early experiments provided evidence that 4-month-old infants perceive the unity of a center-occluded object by detecting the common motion of the object's visible surfaces, but not by detecting the alignment of the edges of those surfaces or the "goodness" of the form that the surfaces combine to create. For example, when the visible ends of a center-occluded rod moved laterally together above and below the occluder during habituation, 4-month-old infants were found to look longer at a fully visible broken rod test display (Fig. 1C), relative to a complete rod (Fig. 1B),

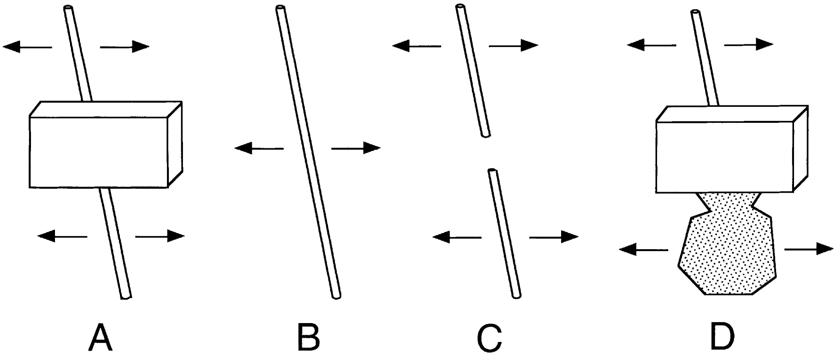

Fig. 1. (A) The rod-and-box habituation display used by Kellman and Spelke (1983) in their original study of infants' perception of partly occluded objects. The top and bottom portions of the rod underwent common lateral translation. (B) Complete rod test display. (C) Broken rod test display. (D) Rod-polygon habituation display. The uppermost rod and lower polygon underwent common lateral translation. Note that the outer edges of the polygon are neither aligned nor relatable with the outer edges of the rod across the occluder. See text for discussion.

implying that the infants had perceived the partly occluded rod as connected (Kellman & Spelke, 1983; Experiment 1; Eizenman & Bertenthal, 1998). The same looking preference was obtained when the ends of the rod moved together vertically or in depth (Kellman, Spelke, & Short, 1986) and when they moved conjointly with the infant such that the image of the rod occupied a constant position in the infant's field of view (Kellman, Gleitman, & Spelke, 1987), although not when the object underwent a more complex, rotary motion (Eizenman & Bertenthal, 1998; Kellman, 1993). The same looking preference was obtained in research presenting a moving, center-occluded object in the shape of an outline square (Slater et al., 1990) or a two-dimensional image of a center-occluded moving rod (Johnson & Náñez, 1995). Finally, the same preference was obtained at younger ages when the size of the occluder (and hence, the distance between the visible rod surfaces) was reduced (2-month-olds: Johnson & Aslin, 1995) or the detectability of the visible portions of the array was enhanced (3-week-olds: Kawabata, Gyoba, Inoue, & Ohtsubo, 1999). All these findings provide evidence that young infants are able to perceive the unity of a partly occluded moving object, provided that the motion relationships on the two sides of the occluder are detectable.

In contrast, a number of experiments provided evidence that 4-month-old infants fail to perceive the unity of a center-occluded object when the object is stationary, even when the object's unity follows from all the Gestalt configurational principles. In Kellman and Spelke's (1983) original studies, 4-month-old infants failed to perceive the unity of a stationary center-occluded rod whose edges were aligned and identical in color, shape and orientation (principles of good continuation and similarity), and they failed to perceive the unity of a stationary center-occluded equilateral triangle composed of three such rods (principles of good continuation, good form, and closure). In both cases, habituation to a center-occluded display was followed by equal looking at the corresponding complete and broken displays, suggesting that infants' perception was indeterminate between a connected and a separated object.

Subsequent experiments have investigated several possible reasons for this failure. First, infants may perceive objects in accord with both the principle of common fate and the principles of good continuation, similarity, and good form, but perceive object unity only when all these principles work together. To investigate this possibility, Kellman and Spelke (1983) presented infants with a center-occluded object whose two visible surfaces moved together but whose outer edges were misaligned (contrary to the principle of good continuation), whose surfaces differed in color, texture, and shape (contrary to the principle of similarity), and whose overall shape was irregular (contrary to the principle of good form; see Fig. 1D). After habituation to this display, infants showed a looking preference for the broken test display that was as strong as in the previous study with the moving center-occluded rod. This finding suggested that the Gestalt configurational principles had no effect on infants' perception of a moving object.

Second, infants may fail to perceive the unity of a stationary object with aligned, similar edges and a simple overall shape because they are not sufficiently attentive to a center-occluded object if the object does not move. To investigate whether the Gestalt configurational principles would influence infants' perception when attention was high, Jusczyk, Johnson, Spelke, and Kennedy (1999) presented 4-month-old infants with a stationary, center-occluded rod whose visible ends underwent synchronous changes in color and/or brightness. In different experiments, lights embedded in the two visible ends of the rod either flashed or changed color in concert throughout the habituation and test trials. Although these changes evoked high levels of attention, infants' looking patterns during test provided no evidence that they perceived a unitary object. Together, these two sets of experiments suggest that motion is both necessary and sufficient for perception of object unity in infancy and that Gestalt configurational properties have no effect on such perception.

A series of experiments by Johnson and Aslin (1996) nevertheless casts doubt on this conclusion. Four-month-old infants were presented with two-dimensional, computer-generated displays of a rod moving behind a central occluder. In different conditions, the ends of the rod were either aligned (principle of good continuation; Fig. 2A), misaligned but connectable by a monotonic curve (Kellman & Shipley's (1991) principle of relatability; Fig. 2B), or nonaligned and connectable only by a curve with two points of inflection (contrary both to good continuation and relatability; Fig. 2C). Subsequent looking times to complete and broken test displays, both consistent with the visible portions of the rod in the habituation displays, revealed that infants looked longer at the broken test display when the edges were aligned, suggesting that they perceived the unity of the moving object. When the edges were misaligned but relatable, in contrast, infants looked equally at the two test displays, suggesting that their perception was indeterminate; when the edges were nonaligned and not relatable, infants looked longer at the connected test display, suggesting that they perceived two separate rods moving behind the occluder. These findings provided evidence that infants' perception of object unity indeed is influenced by the alignment or misalignment of the object's moving edges, in accord with the Gestalt principle of good continuation. More recent experiments have revealed that the effects of edge misalignment can be overcome by a combination of common fate and good form, providing further evidence for 4-month-olds' sensitivity to a variety of Gestalt configurational information (Johnson, Bremner, Slater, & Mason, 2000).

The Johnson and Aslin (1996) findings are important for a further reason, for they call into question a body of findings on infants' perception of depth. An extensive array of experiments by Yonas and colleagues provides evidence that infants first perceive the depth relations between surfaces and objects when those relations are specified by invariant relationships over

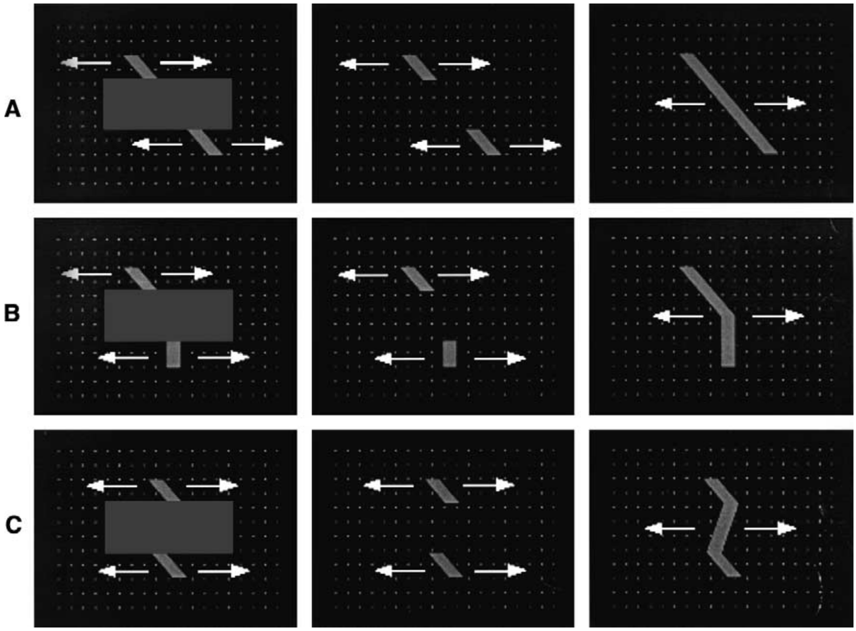

Fig. 2. Rows (A), (B), and (C) depict different displays from Johnson and Aslin (1996). Left to right: habituation displays, broken rod test displays, and complete rod test displays. In all displays, the rod segments underwent lateral translation at the same rate. (A) The rod segments were aligned and (by definition) relatable. (B) The rod segments were misaligned, but relatable. (C) The rod segments were misaligned and nonrelatable. In the complete rod test displays of (B) and (C), one or more novel bends were introduced, in contrast to the absence of bends in the corresponding broken rod test displays.

motion: optical expansion and contraction, motion perspective, and kinetic occlusion (see Arterberry, Craton, & Yonas, 1993; Yonas & Granrud, 1984 for reviews). In contrast, infants do not begin to perceive depth relations specified by pictorial cues such as interposition, relative size, and linear perspective until after 5 months of age (Yonas & Granrud, 1985). Because these pictorial cues are related to the Gestalt configurational principles (for example, interposition depends on a principle of good continuation), these findings further suggested that young infants' perception fails to accord with static Gestalt relationships (see also Bertenthal, Campos, & Haith, 1980). In the Johnson and Aslin experiments, however, the occlusion of the moving rod by the block was specified only by the pictorial cue of interposition.[1]

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[1] In these experiments, infants perceived the unity of the aligned rod when it moved against a textured background but not when it moved against a homogeneous background. This finding is consistent with Yonas's findings that young infants are sensitive to the kinetic depth cue of texture accretion and deletion (Granrud et al., 1984).

Infants' successful perception of object unity (in the experiment with the aligned rod) and object distinctness (in the experiment with the misaligned, nonrelatable rod parts) therefore contrasts with Yonas's findings and hints at an earlier development of sensitivity to pictorial depth information.

What accounts for the contrasting findings of these experiments? We see two general possibilities. First, infants may perceive both objects and pictorial depth in accord with the Gestalt configurational principles, and they may have failed to exhibit this ability in the experiments of Kellman (Kellman & Spelke, 1983; Kellman et al., 1986, 1987), Jusczyk et al. (1999), and Yonas (Yonas & Granrud, 1984, 1985) because of other difficulties posed by those experiments. Second, infants may perceive objects and depth only in accord with the motions and spatial arrangements of surfaces, not in accord with any Gestalt configurational principles, and the apparent evidence for perception in accord with those principles provided by Johnson and Aslin (1996) and Johnson et al. (2000) may stem from specific features of their displays.

We begin with the latter possibility, by noting two potential problems with the Johnson and Aslin (1996) displays. First, the Johnson and Aslin broken test display that followed habituation to the nonaligned rod parts was created by presenting the visible ends of the center-occluded rod with a gap between them, whereas the connected object test display was created by presenting the visible ends of the center-occluded rod display connected by a straight line. This resulted in a rod display with two bends near the center that were never visible during habituation (Fig. 2C). It is possible that infants perceived each habituation display as a connected object with no bends (for example, they may have perceived the two ends as connected by a monotonic or double inflected curve, or they may not have perceived any definite shape in the occluded regions), and then dishabituated to the introduction of novel bends. Because none of the broken displays had bends, infants therefore might have dishabituated *both* to each bend in the complete display as well as to the gap in the broken display, yielding a preference for the broken rod in the aligned condition (no bends), a preference for the connected rod in the nonaligned, nonrelatable condition (two novel bends), and no preference between the two rods in the misaligned, relatable condition (one bend). Experiment 1 was conducted to test this possibility.

A second potential problem with the Johnson and Aslin experiments stems from the use of two-dimensional, computer-generated displays. It is possible that infants misperceived the depth relationships in these displays in either of two ways. First, because the only information for the depth relationship between the rod and block in the occlusion display was the pictorial cue of interposition, it is possible that infants failed to detect this cue in any of the displays (consistent with Yonas's findings) and therefore failed to perceive each visible rod piece as standing behind the block by virtue of this cue. Second, because the broken test display presented conditions in which adults sometimes perceive a unitary object translating behind a slit in the background (see Michotte, Thinès, & Crabbé, 1991) rather than two spatially separated objects moving together, it is possible that infants were subject to the same effect and perceived a connected rod in both test displays: a rod that was fully visible in the complete display and a rod whose center was occluded by a slit in the background surface in the broken display. These possibilities, combined with the Johnson and Aslin findings concerning the effects of alignment and relatability on infants' looking preferences, suggest a different role for Gestalt configurational principles such as good continuation. Such principles may influence infants' perception of depth relationships in two-dimensional displays but not infants' perception of object unity. Experiment 2 was undertaken to test this possibility.

3. Spatiotemporal integration and object perception in infancy

The second dispute in the literature on infant perception and cognition concerns the origins and development of the ability to integrate information about objects over time. Many experiments provide evidence that even young infants form representations of objects that they maintain when the objects go out of view and that they later update these representations as new information appears. For example, Wynn (1992) and her many replicators (Feigenson, Carey, & Spelke, 2002; Koechlin, Dehaene, & Mehler, 1998; Simon, Hespos, & Rochat, 1995; Uller, 1998; see Wynn, 1998, for review), showed young infants a display containing one object, then occluded the display, introduced a second object to the side of the occluder and moved the object behind the occluder, and finally removed the occluder to reveal either one or two objects. Although infants had only seen one object at a time, they looked longer at the one-object test display than at the two-object display, providing evidence that they had represented two objects behind the screen. Infants evidently maintained a representation of the first object, which was updated when the second object appeared so as to construct a unitary representation of two objects behind the occluder. Studies of infants' perception of object boundaries and infants' reasoning about the motions of objects that move fully out of view provide further evidence for early-developing abilities to represent hidden objects and to update those representations as new information appears (e.g., Baillargeon, 1993; Hespos & Rochat, 1997; Spelke, Kestenbaum, Simons, & Wein, 1995; Van de Walle & Spelke, 1996; Wilcox, Rosser, & Nadel, 1994).

In contrast to all the above findings, research by Arterberry (1997) suggests that infants below about 10 months are not able to integrate information about objects when different parts of a scene are revealed over time. In one experiment, for example, Arterberry (1993) presented 10- and 12-month-old infants with a rectangular solid object that moved back and forth behind an opening in two curtains. Because the gap was narrower than the length of the block, the block's length could only be perceived by integrating its velocity with respect to time: The longer the block was occluded and the faster it moved, the greater its length. The older infants proved to be capable of this integration: After habituation to the partial occlusion display, they looked longer at a block of an incorrect length than at a block of the correct length. Ten-month-olds, however, showed no such effect, suggesting that they were incapable of integrating information about the length of the object over time. A subsequent experiment (Arterberry, 1995) following the same logic and method revealed the same developmental change in infants' ability to integrate information over time about object number. Why do younger infants fail the Arterberry integration tasks when they succeed at the apparently more difficult integration tasks of Wynn, Baillargeon, and others?

A further set of experiments suggests an answer (Van de Walle & Spelke, 1996). In these experiments, infants were presented with an object whose visible surfaces were revealed at different places and times, as in the studies by Arterberry. In contrast to the Arterberry studies, however, the infants were tested for their ability to integrate information about the object's *unity*, not their ability to integrate information about display features such as length or numerosity. Five-month-old infants successfully perceived the unity of the object by integrating information about its connectedness over time, providing evidence that early-developing mechanisms for perceiving objects are capable of processing information that is extended over space and time.

We suggest two possible accounts for these contrasting findings. First, infants may form enduring representations of the unity of an occluded object, but no enduring representation of properties of the object such as its length, shape, orientation, or color. If infants fail to remember object properties from one view to the next, then obviously they cannot integrate information about those properties. Second, infants may remember all object properties and combine information about these properties, but they may fail to exhibit these abilities in the Arterberry experiments because of difficulties caused by specific features of those studies. In the length experiment, Arterberry (1993) presented a horizontally moving object with no variation in the vertical dimension, and so only the duration of its motion, in relation to its speed, specified its length. Errors in infants' estimation of duration therefore could underlie failure to perceive object length. In the Arterberry (1995) number experiment, one object moved behind the aperture, and then an object either moved in the same direction or in the opposite direction. Although older infants and adults appear to perceive one object in the first case and two objects in the second case, both displays in fact are ambiguous with respect to object number: Two objects could have moved in alternation in opposite directions, or a single object could have moved in one direction repeatedly by moving rapidly behind the puppet stage and back to its starting point. Accordingly, Experiment 3 presented infants with a single object whose unity could be perceived over time only by integrating information about the alignment of its parts. Like the Arterberry experiments, this task requires that infants integrate information about object properties over time. Unlike those experiments, however, it presented displays that were less ambiguous and required infants to judge object unity rather than other, metric properties such as length or numerosity.

4. Experiment 1

Experiment 1 is an extension of the Johnson and Aslin (1996) study of infants' perception of a center-occluded object with moving but nonrelatable visible parts, using displays that were modified so as to address alternative interpretations of their findings. Infants were habituated to a two-dimensional display of a center-occluded, horizontally moving rod whose visible edges were nonrelatable above and below the occluder (the *two-dimensional spatial* display; Fig. 3A). The infants then were tested with a similar complete rod display as in the Johnson and Aslin study, in which the visible ends of the rod were joined by a straight line, forming two novel bends (Fig. 3C). In contrast to the earlier study, infants also were tested with a broken rod display that contained the same two novel bends (see Fig. 3B). If the infants in the Johnson and Aslin study perceived a connected, center-occluded rod but dishabituated to the complete test display because it presented two novel bends, then infants in the present study should show the opposite dishabituation pattern, looking longer at the broken rod. In contrast, if the infants in the Johnson and Aslin study perceived two separated rods above and below the occluder, then the infants in the present study should show the same dishabituation pattern, looking longer at the complete rod.

A second modification of the displays, designed to furnish supplementary information in support of perception of object unity, concerned the nature of the visible rod segments. In contrast to the Johnson and Aslin displays, each display in the current study presented visible surfaces composed of

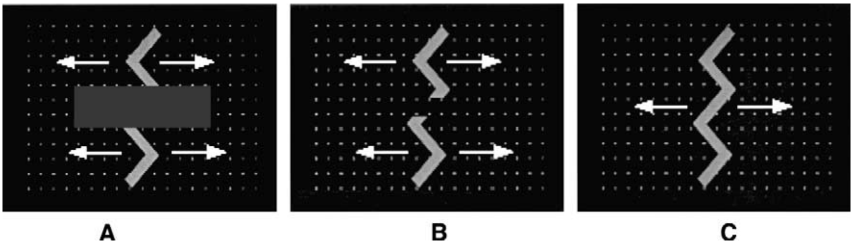

Fig. 3. Displays used in the two-dimensional spatial condition, Experiment 1. (A) Habituation display. (B) Broken rod test display. (C) Complete rod test display.

two rod segments that met at right angles (cf. Figs. 2C and 3A). We hypothesized that the overall configuration of the four visible rod segments might assist infants in perceiving a connected rod, and it might minimize any dishabituation to the presentation of additional bends in the test displays.

Two groups of infants viewed the two test displays after habituation to the occlusion display (two-dimensional spatial condition) or after habituation to an unrelated display (*two-dimensional baseline condition*). If infants perceived a connected rod in the two-dimensional spatial display, they were expected to look longer at the broken test display after habituation. If infants perceived two separated rods, they were expected to show the same looking preferences as in the Johnson and Aslin (1996) experiment: longer looking at the connected test display, after habituation. Infants in the two-dimensional baseline condition were expected to exhibit no test display preference, consistent with other research employing similar designs (e.g., Johnson et al., 2000; Kellman & Spelke, 1983).

4.1. Method

Participants. Thirty-two full-term infants (12 female) comprised the final sample (M age = 127 days, $SD = 12.3$). Three additional infants were observed but not included in the analyses due to fussiness. The infants were recruited by letter and telephone from hospital records and birth announcements in the local newspaper. Parents were paid $5.00 for their participation. Sixteen infants were randomly assigned to the two-dimensional spatial condition, and 16 to the two-dimensional baseline condition.

Apparatus and stimuli. An Amiga 3000 computer and an 80-cm color monitor were used to generate the displays, as in Johnson and Aslin (1996). Two observers viewed the infant through small peepholes cut into either side of a black panel that extended 47 cm from the sides of the monitor. The computer presented the stimulus displays, stored each observer's data, calculated the habituation criterion for each infant, and changed displays after the criterion was met. The computer also recorded how long the infant looked at each display according to each observer's judgments, recorded via two hand-held microswitches connected to the computer's mouse port. Both observers were blind to the stimulus on screen at any given time.

The habituation display in the two-dimensional spatial condition consisted of a 33 × 12.7 cm blue box (15.7 × 6.1° visual angle at the infant's 120-cm viewing distance), oriented with its long axis horizontal (see Fig. 3A). A green zigzag rod, its center portion occluded by the box, underwent lateral translation at a rate of 10.5 cm/s (5.0°/s). The rod's direction reversed every 2 s. The rod consisted of two pairs of 11.7 × 4.3 cm (5.6 × 2.1°) intersecting segments oriented at alternating right angles to each other. The top portion of the rod, visible above the occluder, consisted of two segments: The segment that intersected with the box was oriented 45° clockwise from the horizontal; the attached segment was oriented at 90° from this lower segment (i.e., it was oriented 45° counterclockwise). The bottom portion of the rod (below the box) likewise consisted of two segments joined at a right angle, identical to the upper segments except that they were flipped about a horizontal axis. The habituation display in the two-dimensional baseline condition consisted of a sunflower, with a gray center measuring 19 cm (9.1°) in diameter and 10 yellow petals, each 7.5 cm (3.6°) long. The sunflower rotated through 90°, reversing direction every 2 s. Both the two-dimensional spatial and two-dimensional baseline displays were presented against a black background textured by a regular 12×20 grid of white dots.

There were two test displays. The complete rod contained a center rod segment that joined the upper and lower portions of the rod segments that were visible in the habituation stimulus. The broken rod contained a 4.5 cm (2.1°) gap in this central segment. Both the broken and complete rods had the same number of bends, and both moved laterally against the same textured background as in the two-dimensional spatial habituation display. In the broken rod display the white dots of the background were visible in the gap. Infants in both the two-dimensional spatial and two-dimensional baseline conditions viewed these same test displays after habituation.

Procedure and analyses. The infants were placed in a standard infant seat and tested individually. The habituation display was presented until each infant reached a predetermined habituation criterion. This criterion was calculated as a decline in looking time during three consecutive trials that added up to less than half of the total looking time to the first three trials. If the first three trials summed to less than 12 s, the criterion was based on the first three consecutive trials for which looking time totaled 12 s or more. If an infant had not met the criterion after 15 trials ($N = 1$), the habituation period was terminated and the test period began as with other infants.

Timing of each trial began when the infant fixated the screen after display onset. Each observer indicated independently how long the infant looked at the display by pressing a separate microswitch as long as the infant fixated the screen and releasing when the infant looked away. An individual trial ended when both observers released their microswitches for 2 overlapping seconds. At this point, the screen darkened for 2 s before the next display appeared. When looking times to the habituation display declined to criterion, the computer switched to present the two test displays in alternation, each display being shown three times for a total of six post-habituation trials.

Looking times were calculated by averaging the observers' judgments for each trial. Interobserver agreement was calculated by correlating the two observers' judgments of looking times. The mean interobserver correlation was high ($r = .99$) across Experiments 1–3 (for 15 of the infants, only one observer was available). Infant looking time data are often characterized by positively skewed distributions, due to a few extreme scores. Therefore, all infant data in the present report were log-transformed (base 10) prior to analyses (data presented in the text and in figures are based on raw scores).

4.2. Results

Fig. 4 shows the average looking times during habituation and test in the two-dimensional spatial and two-dimensional baseline conditions. Infants in the two-dimensional spatial condition consistently looked longer at the complete rod test display: 13 of the 16 infants exhibited this preference on the first block of trials (Wilcoxon matched pairs test $z = 2.84$, $p < .01$). In contrast, infants in the two-dimensional baseline condition looked about equally at the two test displays: 9 of the 16 infants preferred the complete rod on the

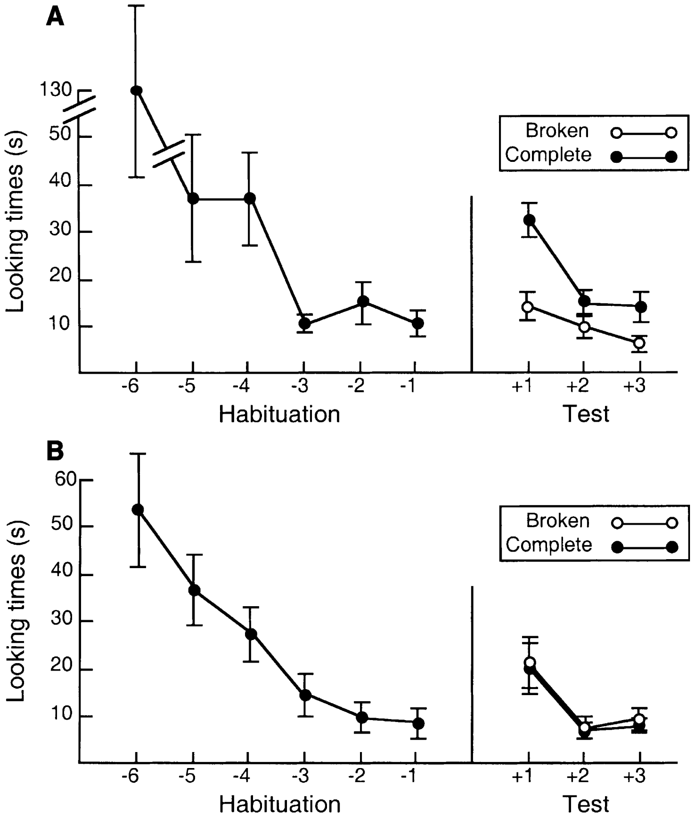

Fig. 4. Mean looking time (in seconds) across infants for the last six habituation trials and the three pairs of test trials in Experiment 1. (A) Results of the two-dimensional spatial condition. (B) Results of the two-dimensional baseline condition.

first trial block ($z < .001$, *ns*), a reliable difference in preference relative to the two-dimensional spatial condition (Mann–Whitney test $z = 2.90$, $p < .01$). These observations were confirmed with a 2 (Condition: two-dimensional spatial vs. two-dimensional baseline) × 2 (Sex) × 2 (Order: complete rod first vs. broken rod first after habituation) × 2 (Display: complete vs. broken) × 3 (Trial: first, second, or third block of test trials) analysis of variance (ANOVA) with repeated measures on the last two factors. There was a significant effect of Display, $F(1,24) = 6.16, p < .05$, reflecting an overall preference for the complete rod, and an effect of Trial, $F(2,48) = 8.14, p < .001$, reflecting a decline in looking across trial blocks. Most importantly, there was a significant Condition × Display interaction, $F(1,24) = 6.14$, $p < .05$. There were no other significant main effects or interactions. Analyses of simple effects revealed a significant preference for the complete rod by infants in the two-dimensional spatial condition, $F(1,30) = 13.91$, $p < .01$ (*M* looking at the broken rod = 12.38 s, $SEM = 3.46$; *M* looking at the complete rod = 24.55, $SEM = 4.97$). In contrast, in the two-dimensional baseline condition, there was no significant preference for either test display, $F(1,30) = .02$, *ns* (*M* looking at the broken rod = 14.29 s, $SEM = 2.81$; *M* looking at the complete rod = 12.71, $SEM = 2.60$).[2]

4.3. Discussion

In Experiment 1, infants in the two-dimensional spatial condition looked longer at the complete rod display, even though both test displays contained the same arrangement of novel bends, and the two displays elicited no sys-

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[2] Despite this outcome, it is possible that the infants' responses to the test displays in the two-dimensional baseline condition were somehow influenced by the habituation displays. As an additional check on the possibility of an inherent preference for one of the two test stimuli, therefore, we conducted a control condition by presenting 16 4-month-olds (6 female, *M* age = 124 days, $SD = 8.0$) the complete and broken rod test displays with no prior habituation experience. Other aspects of the experimental design were identical to those described in the text. A Condition (two-dimensional spatial vs. control) × Sex × Order × Display × Trial ANOVA contrasted data from the two-dimensional spatial and control conditions. This analysis yielded significant effects of Display, $F(1,24) = 9.66$, $p < .01$, reflecting overall preference for the complete rod, and Trial, $F(2,48) = 8.49$, $p < .01$, reflecting a decline in looking times across test trials. Most importantly, there was a significant Condition × Display interaction, $F(1,24) = 5.55$, $p < .05$, the result of reliable differences in test display preferences across the two-dimensional spatial and control conditions. Analyses of simple effects revealed a significant preference for the complete rod by infants in the two-dimensional spatial condition, $F(1,30) = 16.17$, $p < .001$. In contrast, there was no significant test display preference by infants in the control condition, $F(1,30) = .04$, *ns* (complete rod *M* looking time = 17.85 s, $SEM = 2.79$, broken rod *M* looking time = 19.19 s, $SEM = 3.49$). There was also a significant Condition × Trial× Order × Display interaction, $F(1,24) = 3.31$, $p < .05$, reflecting longer looking at the test display presented first, within the first pair of test trials, by infants in the control condition. There were no other significant effects.

tematic baseline preference. These results provide evidence against the possibility that the infants in the Johnson and Aslin (1996) experiments had dishabituated to novel bends in the complete test displays. Instead, the pattern of results suggests that the infants who viewed the two-dimensional spatial display perceived the partly occluded rod as consisting of two disjoint surfaces. The contrast between the present findings and the findings from studies in which infants view moving rod displays with aligned edges provides evidence that information about edge relatability influences infants' perception of object unity.

The infants who were habituated to the two-dimensional spatial display exhibited a reliable preference for the complete rod relative to the broken rod during test. This does not necessarily suggest, however, that the infants formed a clear impression of this particular broken rod configuration behind the occluder. Rather, we can conclude only that the broken rod was more similar to what they perceived during habituation, which we speculate is some arrangement of disjoint objects, separated by a gap. Little is known at present about infants' perception of the precise form of the hidden region of partly occluded objects (but see Craton, 1996). In adults, perception of the location of the hidden intersection of edges, or the hidden contour implied by visible object surfaces, appears to be a function of local interpolation mechanisms (Kellman, Temesvary, Palmer, & Shipley, 2000; Takeichi, 1995).

Because Kellman and Spelke (1983) found no effect of edge misalignment in an experiment following a similar logic to Experiment 1, it is important to consider reasons for the discrepancy. An obvious difference between the Kellman and Spelke studies and the present experiment is that the former used three-dimensional objects whereas the present study presented infants with a two-dimensional display. This difference may have affected infants' perception in two different ways. First, it is possible that infants perceived complete rods in both test displays: one that was fully visible and one whose center was hidden behind a slit in the background (Michotte et al., 1991). Second, it is possible that infants failed to perceive the information for object unity in the two-dimensional display because the depth relations between the rod and occluder were insufficiently specified: Although accretion and deletion of the background texture would have specified that the rod was in front of the background, no such cue specified that the rod was behind, in front of, or in the same depth plane as the block. In experiments using two-dimensional aligned displays, as in Johnson and Aslin (1996), infants may perceive the common motion, perceive a unitary object on the basis of that motion, and thereby resolve the depth ambiguity in the display. When the rod pieces moved together but were misaligned as in Experiment 1, in contrast, infants may perceive all the surfaces in the two-dimensional display as lying in the same depth plane, and therefore perceive the rod pieces to end where the block began. (By the solidity principle, the rod and block cannot occupy the same place at the same time; see Spelke, 1990). This would account for infants' perception of two separated rod parts in this experiment.

These considerations lead to two predictions. First, if infants perceived a complete object in all of the test displays of Experiment 1 because the broken display was perceived as a complete rod partly hidden behind a slit, then infants who are presented with three-dimensional versions of the same displays should look longer at the broken test rod, since there is no possibility of perceiving a complete object in such a three-dimensional display. Second, if the alignment or misalignment of surfaces affects infants' determination of depth ordering which in turn affects their perception of object unity, then misalignment should have a weaker effect on object perception when infants are presented with displays in which the depth ordering is less ambiguous. Experiment 2 tested these predictions by investigating infants' perception of the unity of misaligned, center-occluded rods in a three-dimensional display.

5. Experiment 2

Experiment 2 was a replication of Experiment 1 with three-dimensional displays. One group of infants was habituated to a solid, three-dimensional rod display (the *three-dimensional spatial* display) whose center was hidden behind a box and whose visible ends moved together but were nonrelatable. Except for the misalignment of the ends of the rod and the presence of bends in the visible rod surfaces, this display was designed to resemble that of Experiment 1 of Kellman and Spelke (1983) as closely as possible. Perception of the unity of the display was tested by presenting the infants, after habituation, with solid, three-dimensional complete and broken rod displays like those in Experiment 1, with two novel visible bends in each display. Looking times to the test displays were compared to those of second group of infants (the *three-dimensional baseline* condition), presented with a rotating three-dimensional sunflower during habituation, as in Experiment 1 and then shown the three-dimensional broken and complete rod test displays. If the infants in the Johnson and Aslin (1996) experiments and in Experiment 1 failed to perceive the unity of the object because they misperceived some of the depth relations in the occlusion or test displays, then infants should perceive the unity of the center-occluded object in the three-dimensional spatial display, showing the opposite looking preferences from those observed in Experiment 1. In contrast, if the infants in the above experiments perceived two distinct objects behind the occluder because the displays departed from the Gestalt principle of good continuation, then the infants in the three-dimensional spatial condition also should perceive two distinct objects in the occlusion display and exhibit the same looking preferences as in Experiment 1.

5.1. Method

The procedures followed were identical to those of Experiment 1, except as noted.

Participants. Thirty-two full-term infants (16 female) comprised the final sample (*M* age = 124 days; *SD* = 9.8). Thirteen additional infants were observed but not included in the analyses due to fussiness (10), display malfunction (2), or parental interference (1). The infants were drawn from a similar sample as that for Experiment 1. Sixteen infants were randomly assigned to the three-dimensional spatial condition, and 16 to the three-dimensional baseline condition.

Apparatus and stimuli. A free-standing, rectangular wooden box was used to present the displays. This structure was open on one side to allow infants to see into the display area. The back of the structure (opposite where infants were seated) consisted of white pegboard. A square presentation window, 40.0 × 40.0 cm, was cut into the center of the pegboard. Displays were mounted on square pieces of pegboard of the same dimensions as the presentation window, and were fitted into the window and secured with a clasp not visible from infant's viewpoint. The sides, ceiling, and floor of the display area consisted of white foamboard. At the open side of this structure, a screen consisting of white foamboard was lowered and raised to hide or reveal the display area. Two 40-W fluorescent bulbs, on either side of the display area but hidden from the infant's view, illuminated the displays. A smaller hole, centered above the presentation window, was cut into the box for the lens of a video camera. This camera fed a view of the infant to a video monitor in an adjacent room. Two observers recorded the infant's looking time. One observer viewed the infant on the video monitor, while a second observer viewed the infant through the back of the pegboard. Each observer held a microswitch connected to a computer that calculated the habituation criterion and signaled the end of each trial and the attainment of the habituation criterion.

The habituation display in the three-dimensional spatial condition consisted of a 25.0 × 13.0 cm (14.3 × 7.4° at the infant's 100-cm viewing distance) gray rectangular box with four attached dowels secured into the pegboard, in front of either the complete or broken rod display (see Fig. 5). Broken and complete rods, identical in shape to the test displays of Experiment 1, were cut from foamboard and painted red (length of each segment = 10.0 cm or 5.7°; diameter = 1.3 cm or .7°). Each rod was mounted on a separate square of pegboard by affixing dowels perpendicularly to the rod and fitting the dowels through horizontal slots in the pegboard. Each rod was moved manually back and forth in the slots along a trajectory 22.0 cm (12.6°) in length, either behind the occluder (habituation trials) or without the occluder (test trials). The rod reversed direction every 2 s. The habituation display in the three-dimensional baseline condition consisted

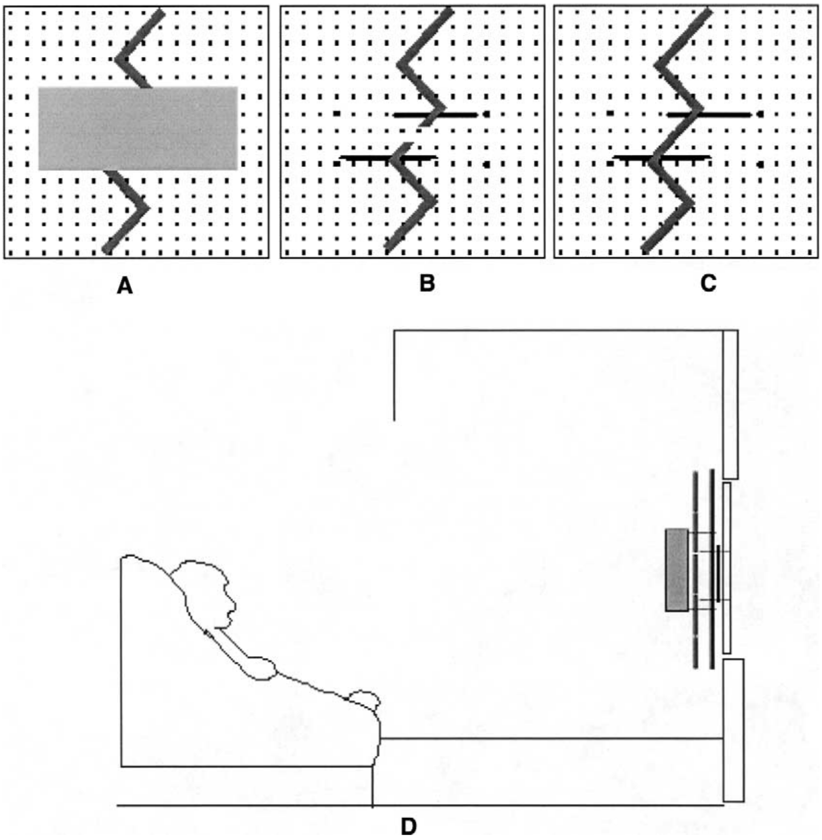

Fig. 5. Schematic depiction of the three-dimensional spatial display from Experiment 2. (A) Habituation display. (B) Broken rod test display. (C) Complete rod test display. In all three displays, the horizontal slots allowed for lateral translation of the rod, which was mounted on plastic dowels perpendicular to the plane of the pegboard. The four slightly larger holes were used to mount the occluder, also affixed to plastic dowels, in the habituation display. (D) Side view of the habituation display mounted in the display case with an infant seated opposite.

of a sunflower that was made from yellow mesh kitchen scrubbers, 7.4 cm in length (4.2°), arranged around a circular piece of gray foamboard 15.0 cm in diameter (8.6°). A single dowel was mounted perpendicularly to this display and fit through a hole in another square piece of pegboard. As in Experiment 1, the sunflower rotated through 90° and reversed direction every 2 s. Also as in Experiment 1, the same broken and complete zigzag rods were used in the test trials for both the three-dimensional spatial and three-dimensional baseline conditions. To ensure that the broken and complete rods appeared to be identical (except for their centers) from the infant's vantage point, the infants in the three-dimensional spatial condition were randomly assigned to one of two habituation groups. For one group, the broken rod was occluded by the box; for the other group, the complete rod was occluded by the box. The performance of the two groups was then contrasted statistically (see below).

Procedure and analyses. The infants were placed in a standard infant seat and tested individually. Displays were placed into position by an experimenter who also controlled the side-to-side motion of the zigzag rods, and the rotation of the sunflower. After each trial, a white screen was lowered in front of the infant for approximately 2 s (during test trials, this screen hid the substitution of one test display for the other into the presentation window). At the beginning of each habituation trial, the experimenter signaled an assistant to raise the screen and began moving the rod or sunflower. Each cycle of motion lasted approximately 4 s. The criteria for ending a trial were the same as in Experiment 1 except that a trial ended after 120 s even if the infant had not looked away for 2 consecutive seconds. The habituation criterion was identical to that in Experiment 1. The habituation phase was terminated after 14 trials if the infant had not otherwise met the criterion ($N = 3$). As in Experiment 1, the order of presentation of the test displays was counterbalanced in both the three-dimensional spatial and three-dimensional baseline conditions, and the observers did not know which test display was positioned in the presentation window.

The log-transformed looking times recorded by the primary observer (i.e., the observer viewing the infant via video monitor) were entered into the analyses. A preliminary 2 (Habituation Display: complete vs. broken) × 2 (Test Display) × 3 (Trial) ANOVA on the three-dimensional spatial looking times revealed no significant main effects or interactions, confirming that looking times at test were not affected by which rod appeared behind the occluder during habituation.

5.2. Results

Fig. 6 shows the average looking times during habituation and test in the three-dimensional spatial and three-dimensional baseline conditions. Infants in the three-dimensional spatial condition appear to have exhibited a slight preference for the broken rod, primarily in the first block of test trials, whereas infants in the three-dimensional baseline condition preferred neither test display. Of the 16 infants in the three-dimensional spatial condition, 7 looked longer at the broken rod on the first trial block, $z = .67$, *ns*; 5 of the 12 infants in the three-dimensional baseline condition exhibited this preference, $z = .78$, *ns*. This difference is not reliable, $z = .92$, *ns*. The data were entered into a 2 (Condition: three-dimensional spatial vs. three-dimensional baseline) × 2 (Sex) × 2 (Order) × 2 (Dis-

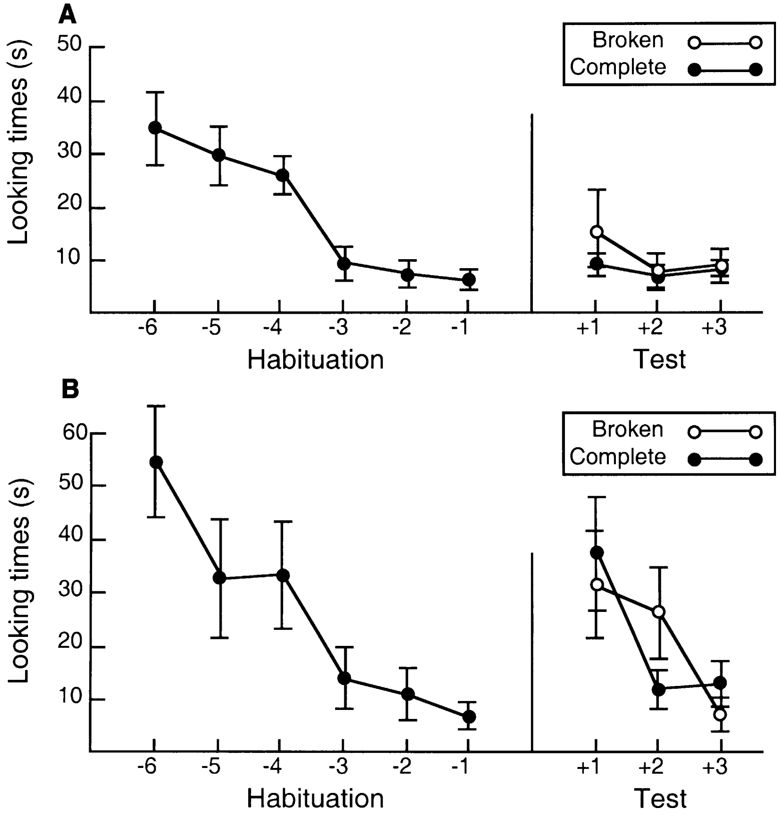

Fig. 6. Mean looking time (in seconds) across infants for the last six habituation trials and the three pairs of test trials in Experiment 2. (A) Results of the three-dimensional spatial condition. (B) Results of the three-dimensional baseline condition.

play) × 3 (Trial) repeated measures ANOVA. This analysis yielded a significant main effect of Condition, $F(1,24) = 6.06$, $p < .05$, reflecting longer looking overall by infants in the three-dimensional baseline condition ($M = 21.56$ s, $SEM = 3.38$) than by infants in the three-dimensional spatial condition ($M = 13.33$ s, $SEM = 1.92$), and a significant main effect of Trial, $F(2,48) = 5.50, p < .01$, the result of an overall decrement in looking across test trial blocks. There was also a significant Order × Display interaction, $F(1,24) = 10.44$, $p < .01$. Infants who viewed the broken rod first after habituation looked longer overall at the broken rod ($M = 19.09$ s, $SEM = 3.22$) than at the complete rod ($M = 16.28$ s, $SEM = 2.22$), whereas infants who viewed the complete rod first after habituation looked longer at the complete rod ($M = 21.54$ s, $SEM = 4.80$) than at the broken rod ($M = 12.46$ s, $SEM = 2.45$). There were no other significant main effects or interactions.

Although the omnibus ANOVA did not reveal reliable differences in test display preference between the three-dimensional spatial and three-dimensional baseline conditions, Fig. 6 appears to reflect longer looking by the three-dimensional spatial group at the broken rod during the first test trial pair. However, this difference did not reach significance, $t(15) = .16$, *ns*. This condition, therefore, fails to provide clear evidence that the infants in the three-dimensional spatial condition perceived the unity of the two visible rod parts. Rather, these results suggest that the unity of the object was ambiguous to infants.

This outcome contrasts with that of the two-dimensional spatial condition in Experiment 1, which resulted in a significant posthabituation preference for the complete rod, providing evidence for perception of disjoint objects. This conclusion was confirmed with a 2 (Condition: two-dimensional spatial vs. three-dimensional spatial) × 2 (Sex) × 2 (Order) × 2 (Display) × 3 (Trial) repeated measures ANOVA. This analysis yielded significant main effects of Display, $F(1,24) = 6.06$, $p < .05$, the result of longer looking overall at the broken rod, and Trial, $F(2,48) = 3.79$, $p < .05$, the result of an overall decrement in looking times across test trial blocks. More importantly, there was a significant Condition × Display interaction, $F(1,24) = 8.45$, $p < .01$. The infants in the two-dimensional spatial condition looked longer during test at the complete rod, and therefore appear to have perceived two separate rod parts in the habituation display, whereas those in the three-dimensional spatial condition provided responses indicating ambiguity with respect to the rod parts' unity or disunity.[3]

5.3. Discussion

Infants exhibited no differential preference for the broken or complete rod in this experiment, an outcome suggesting that perception of the unity of the center-occluded object was indeterminate. The findings of Experiment 2 contrast with those of Experiment 1, in which infants appeared to perceive a two-dimensional display of a misaligned, commonly moving rod as two distinct objects. These findings also contrast with those of Kellman and Spelke (1983), who found that infants perceived the unity of a commonly

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[3] The observers in Experiment 2 reported difficulty judging whether some infants' looks at the outer edges of the display should be coded as "looking" or "not looking." As a check on overall reliability of coding, two new video observers watched videotapes of each infant in the sample and recorded looking times for each trial (demarcated by the raising and lowering of the display screen in front of the infant). These new observers reported potential coding errors with eight infants. Data from four infants in the three-dimensional spatial condition were therefore replaced, and data from four infants in the three-dimensional baseline condition were excluded. These data (from 28 infants) were entered into a new series of analyses which yielded the same pattern of main effects and interactions reported in the main text, differing only slightly in the F and p values. There are no interpretive differences between the two analyses.

moving occluded display whose visible surfaces were not united by the Gestalt relations of similarity, good form, or good continuation.

These findings provide evidence against the thesis that the infants in Experiment 1 perceived a unitary, center-occluded object but generalized to the broken test display because it too was perceived as a unitary, center-occluded object. If that thesis were correct, then the infants in Experiment 2 should have shown a robust preference for the broken test rod, because the rich depth information available precluded such perception. Numerous experiments cast further doubt on this interpretation, and provide evidence that infants do not perceive a unitary object when presented with a broken rod in a two-dimensional display (e.g., Johnson & Aslin, 1995, 1996, 1998; Johnson et al., 2000; Johnson & Náñez, 1995; Jusczyk et al., 1999).

Although the infants in Experiment 2 had no reliable preference for the broken rod, they looked reliably longer at the broken rod than did the infants in Experiment 1. The contrasting findings of Experiments 1 and 2 provide clear evidence that infants' perception of object unity is influenced by information for the depth relationships among the surfaces in the display. On the basis of the outcome of Experiment 2, however, we have no way to assess infants' perception of relative and absolute depth of the visible and hidden surfaces in the three-dimensional spatial display, because multiple sources of depth ordering were available. Some were unique to this display, in comparison to the two-dimensional spatial display (e.g., binocular disparity, convergence, accommodation, motion parallax, shading, and shadowing), whereas others were common to both displays (e.g., accretion and deletion of background texture, interposition). Which of these information sources for depth entered into the infants' perception of object unity is unknown, but it is apparent that the addition of three-dimensional cues shifted infants' perception away from separate objects and toward unity. In Experiment 3, we ask whether the introduction of spatiotemporal information for object persistence over occlusion has a similar effect.

6. Experiment 3

Experiment 3 investigates infants' ability to perceive the unity of a connected object whose surfaces and edges are misaligned in every momentary view and whose connectedness can be apprehended only by integrating information over time. Infants were habituated to the zigzag rod from the two-dimensional spatial display of Experiment 1 and then were tested with the same broken and connected test displays. In Experiment 3, however, this rod moved behind an irregularly shaped occluder that revealed each of its bends at a different time (the *two-dimensional spatiotemporal* display; see Fig. 7). The connectedness of the object never was directly visible and its visible edges never were aligned. Nevertheless, adults perceived the unity of this

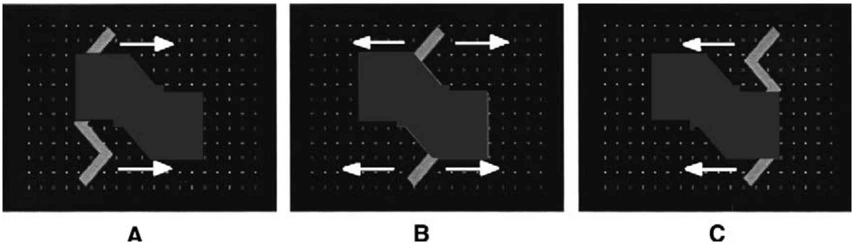

Fig. 7. Three frames from the habituation display used in Experiment 3. (A) depicts the rod's leftmost position in its translation cycle. At this point in the rod's motion, a portion of the central segment adjoining the bottom part of the rod at a right angle is revealed. (B) This central segment is completely occluded as the rod moves behind the occluder. (C) depicts the rightmost position of the rod in its translation cycle. At this point in the rod's motion, the upper portion of the central segment adjoining the upper part of the rod at a right angle is revealed. Only by integrating the outer left and right views of the rod can the alignment of the upper and lower pieces of the central rod segment be perceived. Test displays were identical to those shown in Figs. 3B and C.

object (Experiment 4). If infants have the same ability, then they should respond to connectedness in the two-dimensional spatiotemporal display and look longer at the broken rod than at the complete rod during test, the opposite looking preference to that in Experiment 1. In contrast, if infants lack the ability to integrate information about object unity over time, they should respond to the misaligned occlusion display as they did in Experiment 1, and look longer at the complete rod at test.

6.1. Method

Participants. Sixteen full-term infants (7 female) comprised the final sample (M age = 124 days; $SD = 16.2$). One additional infant was observed but not included in the analyses due to fussiness. The infants were drawn from a similar sample as those for Experiments 1 and 2.

Apparatus, displays, and procedure. Except as noted, these were identical to Experiment 1. The habituation display in the two-dimensional spatiotemporal condition consisted of a 33 × 25.8 cm (15.7 × 12.3°) occluder with its upper right and lower left corners removed, such that the upper and lower angles of the zigzag rod's center portion were visible as it moved right and left, respectively. At no time was the entire length of the rod visible. If infants could integrate the information in the leftmost and rightmost views, however, they would ascertain that the central segments of the rod (hidden for most of the rod's translation) were aligned, and this alignment would support perception of the rod as unified. After habituation to the two-dimensional spatiotemporal display, the infants viewed the same broken and complete test displays as did infants in Experiment 1.

6.2. Results

Fig. 8 shows the average looking times during habituation and test in the two-dimensional spatiotemporal condition. Unlike infants habituated to an unrelated display (the two-dimensional baseline condition), the infants in Experiment 3 looked longer consistently at the broken rod test display (13 of the 16 infants showed this preference on the first trial block, $z = 2.64$, $p < .01$). This observation was confirmed with a 2 (Condition: two-dimensional spatiotemporal vs. two-dimensional baseline) × 2 (Sex) × 2 (Order) × 2 (Display) × 3 (Trial) repeated measures ANOVA. There was a significant effect of Display, $F(1,24) = 8.32$, $p < .01$, reflecting an overall preference for the broken rod, and an effect of Trial, $F(2,48) = 4.19$, $p < .05$, reflecting a decline in looking across trial blocks. Most importantly, there was a significant Condition × Display interaction, $F(1,24) = 8.34$, $p < .01$. Analyses of simple effects revealed a significant preference for the broken rod by infants in the two-dimensional spatiotemporal condition, $F(1,30) = 14.54$, $p < .01$ (*M* looking at the broken rod = 21.48 s, *SEM* = 5.25; *M* looking at the complete rod = 10.57, *SEM* = 2.28). There was no significant preference for either test display in the two-dimensional baseline condition, $F(1,30) = .02$, *ns*. There were no other significant main effects or interactions.

A Condition × Sex × Order × Display × Trial ANOVA compared performance in the two-dimensional spatiotemporal (Experiment 3) and two-dimensional spatial (Experiment 1) conditions. The only significant result was a Condition × Display interaction, $F(1,24) = 26.44$, $p < .001$, reflecting the marked difference in test display preference as a function of exposure to either the two-dimensional spatial or two-dimensional spatiotemporal habituation display. Analyses of simple effects revealed a significant preference for the complete rod by infants in the two-dimensional spatial condition,

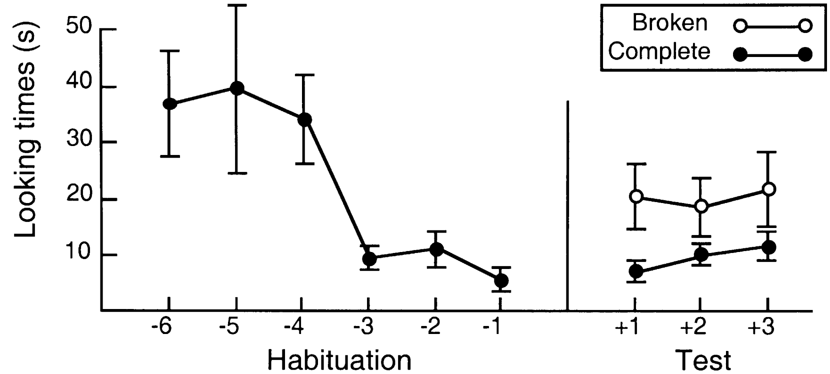

Fig. 8. Mean looking time (in seconds) across infants for the last six habituation trials and the three pairs of test trials in Experiment 3 (the two-dimensional spatiotemporal condition).

$F(1, 30) = 13.11$, $p < .01$, and a preference for the broken rod by infants in the two-dimensional spatiotemporal condition, $F(1, 30) = 13.84$, $p < .01$.

6.3. Discussion

The looking preferences in Experiment 3 provide evidence that infants perceived a unified object behind the occluder. Although the infants in Experiments 1 and 2 appeared unable to use the available common motion patterns to perceive object unity, the infants in Experiment 3 evidently were able to integrate successive views of the rod as it translated behind the occluder, and they retained information about object shape and edge alignment over time so as to perceive the rod's unity. The experiment therefore shows that infants integrate information about edge alignment over time and use that information to perceive a unitary object.

In Experiment 3, the depth ordering of the rod and block was specified by accretion and deletion of the rod as it passed into and beyond the vertical edges of the uniquely shaped occluder. Accretion and deletion of a far surface by a nearer, occluding surface is a robustly effective cue for infants' depth perception and surface segregation (Granrud et al., 1984; Johnson & Aslin, 1996, 1998). Unlike Experiment 1, therefore, the infants in Experiment 3 may more readily have perceived the rod parts as continuing behind the occluder. Once the appropriate depth ordering was perceived, the surface representations constructed over time specified that the rod parts extended behind the occluder, resulting in a representation of a single, connected object. The findings of Experiment 3 contrast with those of past research demonstrating spatiotemporal integration only some time after 10 months of age (e.g., Arterberry, 1993), and they agree with and extend research providing evidence for spatiotemporal integration at younger ages (e.g., Van de Walle & Spelke, 1996). The failure of infants to integrate information about object length or number in Arterberry's experiments therefore appears to reflect a limit on infants' abilities in the specific situations tested in those studies, not a more extensive limit on their ability to integrate information about object properties.

More generally, these results support a view of infant perception as attuned to spatiotemporal invariants in extended arrays. Just as the addition of depth information (Experiment 2) altered infants' perception of object unity, so the introduction of information over time (Experiment 3) allowed infants to see that the central segments of the rod were aligned.

7. Experiment 4

The final experiment probed adults' responses to the displays presented to infants. We were particularly interested in discovering whether adults treated the two- and three-dimensional displays differently, as did infants.

7.1. Method

Participants. Sixteen naive adult observers received course credit or a candy bar for participation. All had normal or corrected-to-normal vision. One additional adult was tested but not included in the analyses due to his failure to understand the instructions.

Apparatus, displays, and procedure. The adults viewed the same displays, under the same viewing conditions, as the infants in Experiments 1–3. Eight adults viewed the two-dimensional displays, and eight viewed the three-dimensional display.

Adult participants were tested individually. Each was first shown a pencil or screwdriver whose center was occluded by an envelope on a nearby table and told that he or she would be assigning numerical ratings to occlusion displays. A 100 was to be assigned to a display in which there was a convincing and unambiguous impression of the connectedness of two surfaces behind an occluder and a 0 to a display in which there was a convincing and unambiguous impression of disjoint objects behind the occluder. Any value from 0 to 100 was permitted, depending on the individual's judgment of unity vs. disunity. All participants agreed that the pencil- or screwdriver-envelope arrangement would receive a high rating ($M = 94.7$, $SEM = 2.21$). The participants then were presented with the two- or three-dimensional displays. Those who viewed the two-dimensional displays provided three ratings, for the two-dimensional spatial display when the rod was either moving or stationary (to gauge the contribution of rod motion to perception of its unity), and for the two-dimensional spatiotemporal display when the rod was moving. Those who viewed the three-dimensional displays provided two ratings for the three-dimensional spatial display when the rod was either moving or stationary. Presentation order was counterbalanced within each group.

7.2. Results

The two-dimensional spatiotemporal display received a high rating ($M = 93.1$, $SEM = 6.19$) that did not differ statistically from the rating of the pencil-envelope, $t(7) = .67$, *ns*. The two-dimensional spatial/stationary display, in contrast, received a much lower rating ($M = 26.25$, $SEM = 9.98$), indicating percepts closer to disunity than unity. The two-dimensional spatial/moving display received a somewhat higher rating ($M = 45.62$, $SEM = 10.23$), reflecting ambiguity with respect to object unity. However, the three-dimensional spatial/moving display received high ratings ($M = 86.25$, $SEM = 4.97$) that did not differ statistically from the screwdriver-envelope, $t(7) = .79$, *ns*. The three-dimensional spatial/stationary rod received lower ratings ($M = 58.75$, $SEM = 5.88$) that differed from the ratings both for the screwdriver-envelope, $t(7) = 5.17, p < .01$, and the three-dimensional spatial/moving display, $t(7) = 5.94, p = .001$. Data from the two-dimensional spatial and three-dimensional spatial conditions were examined with a 2 (Depth: two-dimensional vs. three-dimensional) × 2 (Motion: stationary vs. moving) repeated measures ANOVA, which yielded significant main effects of both Depth, $F(1,14) = 15.88$, $p < .01$, and Motion, $F(1,14) = 11.48$, $p < .01$. The interaction was not significant.

A mean rating of 50 could reflect the fact that either adult observers perceived the displays as indeterminate in connectedness or that some adults perceived the rod ends as connected and others perceived the ends as broken. Of particular concern was adults' perception of the two-dimensional spatial/moving display ($M = 45.62$): An examination of the distribution of responses suggests that ratings were roughly normally distributed: three adults gave a rating of 50, three adults gave the display a rating of 30 or less, and two adults rated the display as 80 or higher. If a given observer perceived the rod ends in this display as either broken or whole, with little ambiguity, then we would expect a more bimodal distribution of responses. Because three of the eight observers rated the display as maximally ambiguous, we conclude that adults tended to agree that this display was indeterminate. The distribution of adults' ratings of the other displays also showed no bimodality.

7.3. Discussion

Adults' perception of object unity was affected by the same factors that influenced infants' perception. Both adults and infants responded to misaligned edges as indicative of disjoint objects in two-dimensional displays, both were moved toward perception of unitary objects by the addition of multiple sources of depth information, and both integrated successive views of edge relatability over time. Adults' judgments in the two-dimensional displays were moved toward unity by the addition of motion, but motion did not provide sufficient information for unity in the absence of edge alignment. These findings replicate those of Johnson and Aslin (1996), who reported a very similar response pattern from both adults and young infants when viewing comparable displays.

The findings with three-dimensional displays nevertheless reveal a contrast between infants and adults. For adults, three-dimensional depth information and common motion of the misaligned rod ends combined effectively to support perception of object unity relative to a display with the same depth information but no motion. For the infants in Experiment 2, in contrast, these information sources did not appear to support unit formation as effectively. Infants did not perceive an unambiguously unified object, even though the visible ends of the three-dimensional misaligned rod ends underwent common motion. These results add to the reports by Kellman and Spelke (1983) of adults' perception of object unity across a range of three-dimensional displays to which infants responded ambiguously.

8. General discussion

The present findings provide evidence that infants' perception of the unity of a partly occluded, moving object is affected by configural information for the misalignment of an object's visible surfaces, by depth information specifying the ordering of surfaces in the three-dimensional layout, and by spatiotemporal information about the orientations of the object's edges over time. We discuss each of these effects in turn.

First, our experiments provide evidence that infants' ability to perceive the unity of a moving, center-occluded object is impaired when the visible surfaces of that object are misaligned. In Experiment 1 (two-dimensional displays), 4-month-old infants perceived the misaligned ends of a center-occluded object as two disjoint objects. In Experiment 2 (three-dimensional displays), infants' perception of the unity of a misaligned, occluded rod was indeterminate. In Experiment 4, adults' unit formation was likewise attenuated by misalignment of edges across an occluder. These findings provide counterexamples to Kellman's (1993) generalization that configural cues such as good continuation have no effect on young infants' processes of unit formation. Like most experiments on perceptual organization in adults (although see Kubovy, Holcombe, & Wagemans, 1998), our findings do not allow us to quantify the relative contributions of edge alignment and common motion to infants' object perception. Nevertheless, the experiments provide clear evidence that a principle of common motion is less effective in unifying edges across a gap when the edges are misaligned, and they raise a general question: Why does misalignment disrupt perception of object unity for infants?

According to the threshold account advanced by Johnson and Aslin (1996), infants' ability to achieve unit formation depends on the ability to exploit a sufficient number of cues supporting perception of unity or disjoint objects in an occlusion display, whether those cues are configural, dynamic, or three-dimensional in nature. Different cues can provide potentially contradictory information about object unity (e.g., when two surfaces move together but are not aligned), or they can provide consistent information (e.g., when surfaces move together and are aligned). Depth cues provide inputs to object unity when they specify that the visible surfaces of an object lie in a different depth plane from the occluder or the background, because depth relations of visible surfaces must be ascertained (in addition to good continuation) to assign continuous or discontinuous contours across the occluder (Johnson, 1997; Nakayama, He, & Shimojo, 1996; Sugita, 1999; Tse, 1999). Alignment, however, does not appear to be sufficient to specify object unity in a stationary display, even when three-dimensional depth cues are available (Jusczyk et al., 1999; Kellman & Spelke, 1983). Young infants can achieve unit formation in the absence of alignment, provided there is sufficient information from other sources, such as motion and good form (Johnson et al., 2000).

Under a different interpretation of the processes involved in unit formation, alignment is not a cue for object unity, but it influences infants' perception of moving objects by modulating the detectability of common motion. Like adults (e.g., Field, Hayes, & Hess, 1993), infants may be more sensitive to relations between edges that are aligned or relatable than relations between edges that are nonrelatable, and therefore may be more sensitive to the common motion of aligned than of misaligned edges. Experiments on younger infants provide evidence that perception of object unity is influenced by the detectability of surface relations across the two sides of the occluder (2-month-olds: Johnson & Aslin, 1995; 3-week-olds: Kawabata et al., 1999). If perception of object unity also is affected by the detectability of common motion, and if 4-month-old infants fail to perceive that the top and bottom portions of a misaligned, center-occluded object are in common motion, then a purely motion-based process for perceiving object unity would be disrupted, both in Experiments 1 and 2.

The second principal finding of our experiments concerns the effects of depth information on infants' perception of object unity: In two-dimensional displays, infants perceive two misaligned object parts as two distinct objects; in three-dimensional displays, their perception is indeterminate between two distinct objects and one connected object. In contrast, adults who viewed the latter display (Experiment 4) overwhelmingly perceived the misaligned, moving rod ends as forming a single, connected object. The difference between infants' and adults' perception of this display leaves two issues unresolved: Why does the introduction of three-dimensional depth change both infants' and adults' perception? And what developmental changes in perception occur such that adults unambiguously see the moving, three-dimensional misaligned rod ends as connected?

To begin with the second question, the thesis that infants have limited abilities to detect the common motion of misaligned object parts provides a natural answer. With development, humans may become sensitive to patterns of correlated motion over greater distances and greater angular separations (cf. Johnson & Aslin, 1995; Johnson & Náñez, 1995). Therefore, although common motion may specify object unity both for infants and adults, adults will detect the common motion and perceive unitary objects in a greater range of circumstances (see Eizenman & Bertenthal, 1998, for a similar argument concerning detection of rotary motion). Concerning the first question, the thesis that alignment relations influence infants' detection of common motion also could account for the differences between infants' perception of the two- and three-dimensional displays presented in Experiments 1 and 2. Because the depth ordering of the rod and block is well specified in the three-dimensional displays, infants who failed to detect the common motion of the rod should have the same perception of the connectedness or separateness of the rod as shown by previous infants presented with three-dimensional stationary, aligned displays (Kellman & Spelke, 1983), perception that is indeterminate between connectedness and separateness (although infants might well perceive a stationary rod-polygon display, depicted in Fig. 1D, as disjoint). In the two-dimensional displays, in contrast, the depth ordering of the rod in relation to the block is specified only by interposition, and so infants may fail to perceive the rod pieces as behind the occluder. If infants perceive each rod part to stop where it intersects with the occluder, then the principle of solidity (Spelke, 1990) would specify that the rod parts cannot penetrate the block and must end where the block begins. This account implies that infants who view an *aligned*, commonly moving rod in a two-dimensional display resolve the depth ambiguity differently, using the common motion to perceive the rod as a unit behind the block. Common motion and alignment therefore may affect depth perception as well as perception of object unity.

An alternative account posits that processing depth and boundary information *precedes* unit formation, rather than the converse. A wealth of psychophysical and neurophysiological evidence suggests that the visual system codes edge continuation behind an occluder after first processing information about the relative depths of visible surfaces (e.g., He & Nakayama, 1992; Nakayama, Shimojo, & Silverman, 1989; Sugita, 1999; Tse, 1999; see Nakayama et al., 1996 for review). On this account, information that specifies the segregation in depth of the occluder and rod surfaces will tend to support perception of object unity, and so this perception is more likely in a three-dimensional than a two-dimensional display, given the additional depth information. For adults, resolving depth relations among display elements is aided by a greater sensitivity to the full range of depth information, and so adults' perception of object unity in three-dimensional displays is further enhanced, relative to infants.

Finally, we conclude that 4-month-olds can integrate information about object properties over time, remembering those properties while they are out of view and processing them in relation to information about other, currently visible properties to arrive at a unitary representation of an object. Although Experiment 3 is not the first demonstration of this skill (see Van de Walle & Spelke, 1996), it provides one of the most stringent tests of it. In every momentary view, infants were presented with a display that they appeared to see as two separate objects (in Experiment 1): That is, in every momentary view of the partly occluded rod of Experiment 3, infants saw misaligned rod ends. Nevertheless, they were able to put together these momentary views (thus allowing them to see the edge alignment revealed over time) to perceive a single unitary object.

Just what kind of structure needs to be present in visual arrays for such integration to occur? At present we can offer only preliminary answers to this question. Several converging lines of evidence suggest that infants learn about the physical world first by representing objects as coherent, solid, and continuous bodies and later integrating this information with knowledge that other object attributes such as form and color adhere to spatiotemporally bound entities. Thus, we conjecture that infants will first exhibit spatiotemporal integration of properties fundamental to building a representation of an object as an object and only later will they exhibit the ability to integrate information that serves to individuate different object kinds from one another (cf. Xu & Carey, 1996). Attributes such as length and form fall into this latter class: Only at older ages do infants appear to integrate information about these properties over space and time (Arterberry, 1993; Van de Walle & Spelke, 1996).

Whereas significant progress has been made in understanding how the visual system builds surface and object representations (see Kellman & Shipley, 1991; Nakayama et al., 1996), we hope that the present findings will draw renewed attention to investigating the mechanisms that construct these representations and their development. Developmental studies can serve not only to chart the emergence of perceptual mechanisms but also to guide hypotheses about the nature of those mechanisms in the adult. Answers to the questions raised here should move us forward in understanding how perceptual systems handle visual structure at any age.

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