Spatiotemporal Integration and Object Perception in Infancy: Perceiving Unity versus Form

Gretchen A. Van de Walle and Elizabeth S. Spelke

Cornell University

Van de Walle, Gretchen A., and Spelke, Elizabeth S. *Spatiotemporal Integration and Object Perception in Infancy: Perceiving Unity versus Form.* Child Development, 1996, **67**, 2621–2640. 3 experiments investigated 5-month-old infants' perception of an object whose center was fully occluded and whose ends were visible only in succession. Infants perceived this object as one connected whole when the ends of the object underwent a common motion behind the occluder, but not when the ends were stationary. Although infants perceived the connectedness of the object, they did not appear to perceive the object's shape. These findings suggest (*a*) that young infants are capable of integrating information over time to perceive object unity but not object form, (*b*) that young infants perceive object unity in accord with basic constraints on object motion, and (*c*) that a common process underlies infants' perception of objects that are fully visible, objects that are partly occluded, and objects that move fully out of view.

It has often been observed that we live in an environment cluttered with objects on top of, in front of, adjacent to, and behind other objects, many of which move into and out of sight over time. Adults perceive our cluttered and changing environment as a stable layout of coherent, unified, and enduring objects; without this ability, it would be nearly impossible to carry out even the simplest routines of day-to-day living. Moreover, adults often perceive the forms of objects accurately and effortlessly, even when only a small portion of an object is visible. Adults accomplish these tasks by detecting a wide array of perceptual information specifying surface layout. In addition, adults' perception of objects is facilitated by information stored in memory, accumulated over years of experience in perceiving and interacting with a wide range of objects. Information about the characteristic shapes and functional properties of different kinds of objects guides adults' perception of objects' hidden or overlapping shapes (Vecera, 1993) and of figure-ground relations in a scene (Peterson & Gibson, 1993). The abundance of information about objects complicates the task of studying object perception in adults. Over the past 25 years, studies of young infants, who have had comparatively little experience either perceiving or interacting with objects, have begun to shed considerable light on the origins and fundamental bases of this ability.

Object perception begins to emerge quite early in development (see Baillargeon, 1993, and Spelke & Van de Walle, 1993, for discussions). Under certain conditions, infants are able to perceive the unity and boundaries of partially hidden objects (e.g., Kellman & Spelke, 1983), to perceive object properties such as size and form (e.g., Baillargeon & Graber, 1987; Craton & Yonas, 1990), to represent object identity and object number (e.g., Spelke, Kestenbaum, Simons, & Wein, 1995; Wynn, 1992; Xu & Carey, 1996), and even to reason about relations between objects that are no longer in view (e.g., Baillargeon & DeVos, 1991; Ball, 1973). These early developing abilities are by no means complete: Young infants are not sensitive to all the kinds of visual information specifying objects and object properties to adults. In particular, configurational properties that specify both the unity and the form of partially occluded objects to adults (e.g., common color and texture, smooth alignment of edges, and simplicity of form) do not appear to influence infants' percep-

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tion of the unity or form of partially hidden objects, or the persistence of fully hidden objects, until at least the second half of the first year (Craton, in press; Craton & Baillargeon, 1992; Kellman & Spelke, 1983; Schmidt, 1985; Xu & Carey, 1996, but see also Johnson & Aslin, 1996). Young infants nevertheless are quite adept at using patterns of common motion between two partially visible surfaces to perceive those surfaces as belonging to a single, unitary object (Johnson & Aslin, 1995; Johnson & Nañez, 1995; Kellman, Gleitman, & Spelke, 1987; Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986; Slater et al., 1990).

Infants' early sensitivity to motion-carried information for object unity accords well with research showing that kinematic information plays a fundamental role in young infants' perception of a variety of aspects of the visible layout, including the ordering of surfaces in depth (Craton & Yonas, 1988; Granrud et al., 1984), three-dimensional surface structure (Arterberry & Yonas, 1988; Kellman, 1984; Kellman & Short, 1987; Owsley, 1983), the boundaries of fully visible objects (von Hofsten & Spelke, 1985; Xu, Carey, & Welch, 1995), the animacy of visible objects (Bertenthal, 1993), and the identity of objects that move in and out of view (Spelke et al., 1995; Xu & Carey, 1996). These and other findings have led a number of researchers to conclude that motion-carried information provides a fundamental basis for perceptual development (Arterberry, Craton, & Yonas, 1993; Bertenthal, 1993; Craton & Yonas, 1990; Kellman, 1993).

Contrary to this conclusion, a growing body of research suggests that young infants are unable to perceive properties of partly occluded objects such as their size and form when such perception requires the temporal integration of motion-carried information. For example, 4-month-old infants do not appear to perceive the shape of a circular object when the object moves behind an aperture such that all parts of the object appear at different times but the whole object never appears at once (Craton & Yonas, 1990). This failure contrasts with infants' successful perception of the same object as retaining its form when it moves from a state of complete visibility to a state of complete occlusion behind a single surface (Craton & Yonas, 1990). Similarly, when presented with a rectangular object moving behind an aperture in such a way that its entire surface is presented over time but never all at once, infants under 1 year of age are unable to perceive the object's length (Arterberry, 1993; for similar findings from studies of perception of object form, see Craton & Baillargeon, 1992; Kaufmann-Hayoz, Kaufmann, & Walther, 1990). These negative findings accord well with research suggesting that young infants do not perceive the outline shape of an object that is presented over time (Rose, 1988; Skouteris, McKenzie, & Day, 1992), or the numerosity of distinct objects that pass behind an aperture (Arterberry, 1995). All these findings challenge theories of early perceptual development: How can one reconcile infants' apparent inability to perceive object properties over time with the wide body of evidence suggesting the primacy of motion-carried information in infancy?

One approach to this challenge, offered by Baillargeon (1993) and others, appeals to differences in the processing requirements of the above tasks. Infants may have difficulty constructing a representation of a single object when its parts are visible only in succession, because such construction requires that infants maintain several incomplete representations and integrate them into a unitary whole. In contrast, when an object's parts are visible all at once, infants may form one complete representation, which is then easier to retain in memory when the object is subsequently occluded. A second approach is our focus here: Integration of kinematic information may not be an all-or-none ability that infants either possess or lack. Instead, infants' patterns of success and failure may depend on the perceptual task that confronts them and the information available to accomplish it. In particular, infants may perceive the *unity* but not the *form* of an object when the object's unity is specified by fundamental constraints on object motion.

Our proposal first distinguishes between perception of object unity and perception of object properties such as size and form. This distinction has been urged by Kellman (1993), who suggests that young infants possess a "primitive" process of unit formation that permits them to use kinematic relations between spatially separated parts of an occluded object to perceive the connectedness of those parts. In contrast, he suggests that young infants lack an "edge sensitive" process, available to adults, for relating spatially separated visible contours to perceive the particular form of an occluded object (see also Kellman & Shipley, 1991). Although previous, successful studies of in-

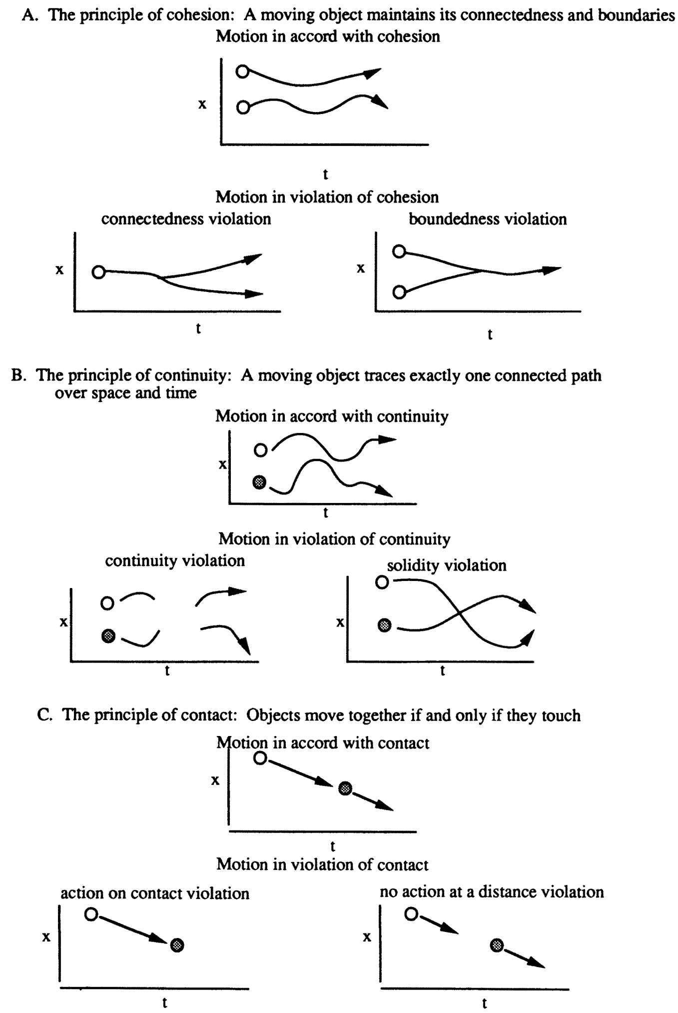

FIG. 1.—Principles of object perception. Arrows depict the path of an object over one-dimensional space and time (after Spelke & Van de Walle, 1993).

fants' perception of partly occluded objects have focused on infants' perception of object unity, all previous studies of integration of spatiotemporal information have focused on infants' perception of object properties such as size and form. Because this spatiotemporal integration requires sensitivity not only to kinematic information but also to the static, configural relations between the object's successively revealed edges, it may be beyond young infants' capacities.

Our proposal next distinguishes among different types of motion-carried information, singling out a particular class of events that may be especially informative about objects. We have proposed (Spelke & Van de Walle, 1993) that infants' perception of objects is guided by three principles encompassing basic physical constraints on how objects move (Fig. 1). The principles of *cohesion* and *continuity* capture constraints on the connectedness, boundedness, continuous motion, and solidity of objects; these principles can account for infants' use of motion to perceive objects in many situations in which objects are fully visible (e.g., von Hofsten & Spelke, 1985; Xu & Carey, 1995) or move fully out of view (e.g., Spelke et al., 1995; Xu & Carey, in press). The principle of *contact* is our focus here: It captures the constraints of no action at a distance (objects do not influence one another's motion if they are not in contact) and action on contact (objects do influence one another's motion if they touch).

The contact principle can account for infants' perception of and reasoning about objects across a wide range of circumstances. First, this principle can account for reasoning about the causal relations between fully visible objects. A wealth of research provides evidence that infants infer that one visible object sets another object in motion if and only if the second object begins to move on contact with the first (e.g., Baillargeon, 1993; Kotovsky & Baillargeon, 1994; Leslie, 1984; Leslie & Keeble, 1987; Oakes, 1994, but see also Oakes & Cohen, 1990). Second, this principle can account for infants' causal reasoning about two objects that move in succession behind an occluder. If the second object instantly continues the motion of the first, infants infer that the two objects made contact behind the occluder at the moment when the movement transferred between the objects (Ball, 1973; Van de Walle, Woodward, & Phillips, 1994; Woodward, Phillips, & Spelke, 1993). This inference follows from the principle that objects undergoing common motion at the instant of transfer must be in contact at that instant. Third, the contact principle can account for infants' perception of the unity of a center-occluded object whose visible ends move together (e.g., Johnson & Aslin, 1995; Kellman & Spelke, 1983). The ends of such an object undergo the same motion throughout the event and not just at a single instant, as in the studies of causality; thus the contact principle dictates that the ends of the object are continuously in contact behind the occluder because surfaces that are not in contact do not move together. Finally, the contact principle can account for the findings of studies of infants' perception of objects explored bimanually in the haptic mode. The contact principle specifies that bimanually explored handles that move in unison are connected to one another, whereas handles that move independently are not connected. Five-month-old infants' haptic perception of such assemblies is consistent with both of these predictions (Streri & Spelke, 1988, 1989; Streri, Spelke, & Rameix, 1993). This principle therefore can account both for infants' reasoning about events involving distinct moving objects and for infants' perception of the spatially separated surfaces of a single moving object (see Spelke & Van de Walle, 1993, for a discussion).

Based on these findings, we predicted that even young infants would perceive object unity by integrating kinematic information over time under circumstances where such perception follows from the contact principle. As in studies of perception of causality, we focused on infants' perception of two partly occluded motions that are visible in succession, in which the velocity at the point where the first motion disappears is instantly followed by an identical velocity at the point where the second motion appears. As in studies of perception of object unity, we presented these motions under conditions that favor perception of a single, connected object, because the visibly moving surfaces were never seen to be separated or to move separately.

Infants were presented with two successively visible surfaces that underwent motion in the same direction, at the same speed, and in immediate succession. Because these two motions could be temporarily grouped into a single, continuous displacement, the contact principle specifies that the surfaces undergoing this displacement are connected. We predicted, therefore, that infants would perceive that the surfaces did not lie on two spatially separated objects but on a unitary, connected object. Because the contact principle specifies that commonly moving surfaces are connected in some manner but does not specify the form of the connection, we further predicted that infants would perceive the *unity* of the object but not necessarily its *form*. That is, infants may perceive the two successively visible surfaces as connected but have no definite impression of the form of that connection. Three experiments tested these predictions.

Experiment 1

The first study investigated infants' perception of a continuously moving object whose ends were visible in succession. Because the object's surfaces underwent a pattern of common motion over time, its unity was specified by the contact principle. Unlike previous studies of integration of kinematic information over time, the experiment investigated infants' perception of object unity using a task that did not require perception of the object's form.

Five-month-old infants were habituated to a display consisting of a center-occluded, complete or broken square object that translated laterally in and out of sight behind a larger occluding block: The two sides of the object were successively visible on the sides of the occluder and the central portion of the object (or the gap in the broken display) was always hidden (Fig. 2). As the object moved

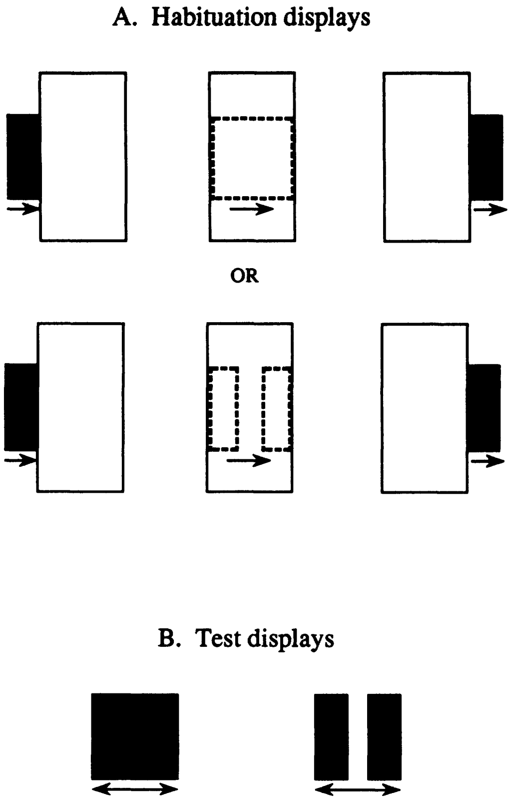

FIG. 2.—Schematic depiction of the displays used in Experiment 1. The upper diagrams present each display at the beginning, middle, and end of a half cycle of motion; dotted lines indicate the parts of the display that are hidden; arrows indicate the direction of motion of the objects.

behind the block, it was progressively hidden until it was entirely occluded. Part of the object then immediately reappeared on the other side of the occluder. To adults, this display appeared to consist of a connected square that moved smoothly and steadily behind the occluder.[1]

Following habituation to this display, infants were presented with two test displays: a single, unified square and two broken parts of a square with a gap centered in the region of the habituation display that was never visible to the infant. Both test displays matched the visible areas of the original habituation display. To assess any intrinsic preferences between the two test displays, a separate group of infants in a baseline condition viewed only the two test displays in alternation, following participation in an unrelated habituation experiment.

If infants are able to integrate the information for object unity over time, they should have perceived the two spatially and temporally separated views of the occluded object in the habituation display as a single, unified body translating behind the block. Their habituation to the occlusion display therefore should generalize in part to the fully visible complete object. This partial generalization of habituation should produce a difference in test trial looking preferences between the experimental and baseline groups. Generalization of habituation effects can only be assessed relative to baseline preferences between the test displays. Therefore, infants in the experimental condition should show a greater looking preference for the broken object over the complete object than those in the baseline condition. If infants are unable to use information given over time to perceive the connectedness of the object, they might perceive the two successively visible parts of the habituation display as two spatially separated surfaces. If this were the case, babies in the experimental condition should show a greater preference for the complete square over the broken square than those in the baseline condition. Finally, if infants have no clear perception of the habituation display, we would expect no difference in looking preferences between the experimental and baseline conditions.

Method

Subjects.—Thirty-two infants participated in the experiment. All resided in the Ithaca, New York, area, and all were born of full-term pregnancies. The infants came from a variety of ethnic and economic backgrounds. The infants ranged from 4 months, 16 days to 5 months, 14 days, with a mean age of 4 months, 28 days. An additional 13 infants participated in the study but were not included in the analyses: 10 because of computer or apparatus failure, one because

[1] A group of 10 adults naive to the purpose and hypotheses of the research were shown this moving occlusion display. Their impressions of the connection between the surfaces on either side of the occluder and their impression that the top and bottom contours of the red surfaces formed a straight edge were rated. On a scale of 1 to 7, with 7 being completely confident, the mean response was 6.2 for impression of connection and 6.1 for impression of a straight edge. Adults also were asked to draw the object or objects that they perceived to be moving behind the occluder; all 10 subjects drew a single square.

of mother interference, and two because of fussiness.

Displays and apparatus.—The displays were presented within a display box with a painted white wooden floor (100 cm wide × 79 cm deep), 87 × 79 cm side walls of white foamcore, and an 87 × 100 cm back wall of painted white pegboard. Each of the displays was mounted on a 40 cm square surface of white pegboard that could be fit into a window in the back wall of the display. Located 10 cm below this opening was a circular hole through which a video camera filmed the infant throughout the study, so as to permit post-hoc analyses of observer blindness (see below). The infant was seated in a semi-reclining seat, 100 cm from the center of the display.

The displays were created to resemble as closely as possible those used by Kellman and Spelke (1983) in their studies of infants' perception of center-occluded objects with respect to size and color of occluder, rate of object motion, and arrangement of the display in depth. In one habituation display, the left and right extremities of either a red square object or two red rectangular objects moved laterally in a smooth, continuous fashion behind a stationary, gray occluding block (see Fig. 2*A*). The alternately visible surfaces of the partly occluded object(s) were 13 cm tall and 4.5 cm wide, and the objects were 3 cm thick. The occluding block was 25 cm tall, 13 cm wide, and 3 cm thick. Each partly occluded object was suspended on glass rods 5 mm in diameter 10 cm in front of the back surface of the display box. The rods extended to the back of the display through a slit 9 cm long and 6 mm wide and were attached to a Plexiglas plate that slid smoothly along the back surface of the display. The occluder was suspended so that its front surface was 16 cm from the background, creating a 3 cm difference in depth between the front of the object and the rear edge of the occluder. At the infants' viewing distance, the occluder subtended a visual angle of 14.2° vertically and 7.4° horizontally. Each side of the partly occluded object subtended a visual angle of 2.6°. The square traversed 9 cm from side to side at the real speed of approximately 5.5 cm/sec (angular velocity: 3.2°/sec), pausing approximately 0.5 sec at each extreme. A 4 cm vertical portion of the square's center was never visible to the infant, and the left and right portions of the square were alternately visible and occluded.

Both test displays were fully visible, presented the same red, 3 cm thick objects used to create the two habituation displays, and followed the same pattern of motion as in the habituation displays (Fig. 2*B*). One test display consisted of a red square, 13 cm on a side. The other test display ("broken square") consisted of two separate portions of a square, each of which measured 13 cm vertically and 4.75 cm horizontally, separated by a 3.5 cm vertical gap. Both test displays were designed to match completely the visible areas of the above habituation display. The motion was produced by a trained experimenter who stood behind the displays and moved the objects by manipulating the Plexiglas plate connected to the rods on which the objects were suspended.

Design.—Sixteen subjects were randomly assigned to each condition, experimental and baseline. Half the infants in the experimental condition were habituated to the partly occluded complete square and half to the broken square: These two displays were indistinguishable for adults and were responded to equivalently by infants. Then all the infants in the experimental condition were presented with the complete and broken test displays in alternation for a total of six trials. Infants in the baseline condition viewed the same test sequence following participation in an unrelated habituation experiment. Order of presentation of test trials was counterbalanced in both the experimental and the baseline conditions.

Procedure.—At the beginning of the study, the infant was placed in a standard infant seat centered in front of the display box. A screen was raised to reveal the square translating behind the occluding block, and looking time was recorded. An infant-controlled habituation of looking time procedure was used. Following an initial fixation of 0.5 sec, the trial continued until the infant looked away from the display for 2 sec continuously up to a maximum of 120 sec. When the infant had looked away from the display for 2 sec, the computer signaled the end of the trial with a soft tone, and the screen was lowered. After approximately 3–5 sec, the screen was again raised, and the next trial was begun. This sequence was repeated until the criterion for habituation was met or until a total of 14 habituation trials had been presented. The criterion was a 50% decline in looking time, calculated by summing the looking times across the first three trials, dividing the total in half, and summing all subsequent sets of trials until three consecutive trials were obtained for which total looking time was less than or equal to this value. If the total looking time over the first three trials was less than 12 sec, the criterion was based on the first three trials for which the total looking time exceeded 12 sec. Following habituation, the occluding block was removed, and the test trials were presented.

Infants in the baseline condition were shown the six test trials with no habituation sequence. The procedure for presentation of the test trials was otherwise identical to that followed in the experimental condition.

Looking times were independently recorded by two observers, stationed behind and slightly to the right and left of the center of the display, who observed the baby through holes in the pegboard. A total of eight assistants served as primary observer in the experiment. The observers recorded looking time by depressing button boxes connected to a microprocessor. The observers were unable to see the test displays and were not informed of the order of the two test displays. Interobserver agreement, calculated as the proportion of time during which the two observers both judged that the infant was or was not looking at the display, was calculated over 28 subjects and averaged .91. One observer was designated as the primary observer: Her recorded times were used to determine when a trial should end and when the habituation criterion had been met. The secondary observer's times were used only to calculate agreement. The primary observer also judged when a baby was fussy and needed a break or when the baby was so fussy that the experiment should be terminated. Short breaks were allowed at any time during the habituation period and between pairs of test trials. (Over the 80 infants who participated in the present experiments, a single break was given to four subjects between pairs of test trials.) If a baby became sufficiently fussy to require that a break be taken during a test trial or within a pair of trials, the baby's data were eliminated from the sample.

Tests for observer blindness.—Recent research and discussion casts doubt on the adequacy of standard procedures for ensuring observer blindness such as those described above: Observers who begin an experiment unaware of the order of displays to be presented, and unable to see the displays as infants view them, may nevertheless become aware of the test displays seen by infants in either of two ways. One potential problem is that observers may become aware of the order of test displays during an experiment if a display makes a distinctive noise or is glimpsed as it is positioned in the apparatus (Fernald & McRoberts, in press).

To assess whether this occurred, a new procedure was instituted for this experiment and all other concurrent studies in the laboratory: Immediately after the experiment, observers indicated in writing whether any events occurred that made them aware of the test display order at the end of the study. Observers were encouraged to state that they were aware of the test order, because knowing this would help us improve our procedures. In the present study, all 32 statements of the primary observers and 27 of 28 statements of the secondary observers indicated that observers did not become aware of the test order.

A second potential source of information about the test displays comes from the behavior of the infants themselves. Apart from any novelty reactions to the test displays, infants may react to the displays in different ways. For example, infants may make more horizontal eye movements when they view the broken test display than when they view the connected display; by detecting this eye movement pattern, observers may come to know the test display order.

The existence of this information is difficult to assess, for two reasons. First, the information available from infants' ancillary reactions to displays (e.g., horizontal eye movements) must be distinguished from the information available from infants' novelty reactions: Observers' ability to guess the display order from the latter reactions is not a source of concern but rather a measure of the experimental effect. Second, the information available from infants' reactions, if it exists, is not likely to lead to clear and explicit awareness of display order but rather to vaguer impressions. Accordingly, we tested for the presence of this information by conducting a further experiment using a method recommended by Fernald and McRoberts (in press). After the completion of the present series of experiments, seven primary observers from these and related studies were presented with videotapes of 16 babies looking at the complete and broken test displays in alternation during the six-trial test sequence. The infants to be coded were se-

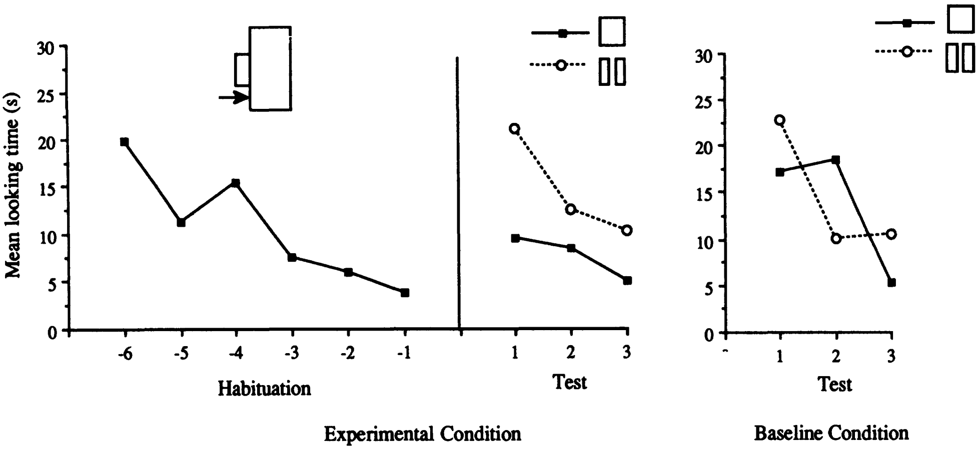

FIG. 3.—Mean looking times on the last six habituation trials and on the six test trials for the experimental condition (left and center), and on the six test trials for the baseline condition (right) of Experiment 1.

lected from the experimental and control conditions of this experiment and Experiment 2, based on their recorded looking times to the two test displays: Eight of the infants had looked longer at each test display. Observers were asked to guess, after each trial, whether the infant viewed a connected or a broken display. At the end of the test sequence for each infant, observers also were asked to guess the order of test displays (connected first or broken first). A cash reward was offered for guessing the test order at greater-than-chance accuracy (12/16 correct or better).

These seven observers correctly guessed the test display viewed by infants on a mean of 49 out of 94 trials (chance = 47, $p > .2$). The mean number of test trial orders guessed correctly was 8.9 out of 16 trial sequences (chance = 8, $p > .2$). No subject guessed the trial order correctly for more than 10 of the 16 infants. The slight elevation of mean scores above 50% could be due to chance variation, to the existence of detectable novelty reactions in the videotapes despite the controls for overall looking time, or to the existence of biasing information. If the last possibility is correct, the amount of detectable information appears to be extremely small.

Dependent measures and data analyses.—Because the looking times were positively skewed,[2] they were log-transformed for all the parametric analyses. The analyses focused on infants' looking time during the six test trials, as assessed by the primary observer. Trial-by-trial looking times were subjected to a 2 (condition: experimental vs. baseline) × 2 (order: connected test display first vs. broken test display first) × 3 (trial pair) × 2 (test display: complete vs. broken) repeated-measures analysis of variance (ANOVA) with the last two factors within subjects.

Because the looking times were positively skewed and because the variance across conditions differed approximately by a factor of 2, we also conducted nonparametric analyses on the data (Siegel & Castellan, 1988). Looking preferences within each condition were assessed by the Wilcoxon signed-ranks test. The difference in looking preferences between the experimental and control conditions was tested by calculating, for each subject, the proportion of test trial looking time that was devoted to the broken object display, and by comparing the looking proportions of infants in the experimental and baseline groups by means of a Wilcoxon-Mann-Whitney test.

Results

Mean looking times during the last six habituation trials for the experimental condition, and during the six test trials for both conditions, are shown in Figure 3. After habituation to the partially occluded display, infants appeared to prefer the broken display. In the baseline condition, they showed no such preference.

[2] Mean skewness value calculated for the six trials for the experimental condition was 1.81, SD = .59. For the baseline, the average skewness value was 1.32, SD = .64.

The analysis of variance comparing the two conditions revealed a significant main effect of trial pair, $F(2, 56) = 15.18$, $p < .001$, indicating that looking time decreased over the test sequence, and a significant effect of test display, $F(1, 28) = 8.67$, $p < .01$, indicating that the subjects showed an overall preference for the broken display. Most important, there was a significant interaction of condition × test display, $F(1, 28) = 4.21$, $p < .05$: Infants in the experimental condition showed a greater preference for the broken test display than those in the baseline condition.

Findings from the nonparametric analyses fully corroborate the above patterns. Infants in the experimental condition showed a strong preference for the broken test display (Wilcoxon $T = 10$, $p < .002$, two-tailed). In contrast, infants in the baseline condition looked approximately equally at the two test displays (Wilcoxon $T = 58$, $p > .2$). The looking preferences of the two groups differed at a borderline level of significance (Wilcoxon-Mann-Whitney $z = 1.60$, $p = .05$). Fifteen of 16 infants in the experimental condition looked longer at the broken test display, whereas eight infants in the baseline condition looked longer at each test display ($p < .01$, Fisher's exact test).

Discussion

Following habituation to a square that translated laterally behind an occluding block in such a way that portions of its surface were successively visible, infants in the experimental condition looked longer at a fully visible broken square than a unitary square relative to baseline. These infants appeared to treat the single, connected test display as familiar, responding to the novelty of the two surfaces separated by a gap. This finding provides evidence that 5-month-old infants are able to make use of motion relations between spatiotemporally separated views of an object to perceive the two successively visible surfaces as belonging to a unitary object. Infants appear to integrate information presented over time under circumstances where that information specifies the contact relations between two surfaces of a single object.

Nonetheless, at least two alternative explanations can also account for the findings of Experiment 1. First, infants' perception of object unity may not have depended on temporally extended, kinematic relations between the two surfaces but on static, configurational properties of the display such as common color, smooth continuation of object boundaries, or simplicity of the overall form of the partly hidden object. Although a number of previous studies cast doubt on this possibility (Craton, in press; Craton & Baillargeon, 1992; Kellman & Spelke, 1983), it has never been tested in the present situation, in which one object successively moves into and out of view. Second, infants may not have perceived the two views of the partly hidden object as related at all. Rather, they may have perceived and become habituated to a single red surface that was visible in two different locations. Dishabituation to the broken object, on this account, is not a response to the novelty of the spatial separation between the two objects that had been perceived as connected during habituation, but to the novelty of two red surfaces as opposed to one.

Our hypothesis, and these two alternatives, make contrasting predictions about infants' perception of stationary versions of the present occlusion display. On either of the above alternative accounts, presentation of alternating stationary views of the partly occluded object at its extremes of motion also should provide the information necessary to evoke the looking patterns obtained in the first study. As in the moving display, static configurational information is available when the object remains at rest. Similarly, stationary views present the infant with a single red surface alternately visible at two different times and locations. Thus, if either of these sources of information plays a role in infants' responses to the test displays, then infants habituated to stationary views of the display used in Experiment 1 should exhibit looking patterns similar to those of infants habituated to the moving display. In contrast, if the common motion over time of the two visible portions of surfaces underlies perception of their connectedness, then infants habituated to stationary displays should show less preference for the broken display than those habituated to the moving display. Experiment 2 tested these predictions.

Experiment 2

In Experiment 2, infants were presented with stationary views of the same partly occluded object display that was used in the first experiment (Fig. 4). On alternating habituation trials, the square appeared at either the right-most or the left-most extreme position presented in Experiment 1, where it remained at rest. Following habitu-

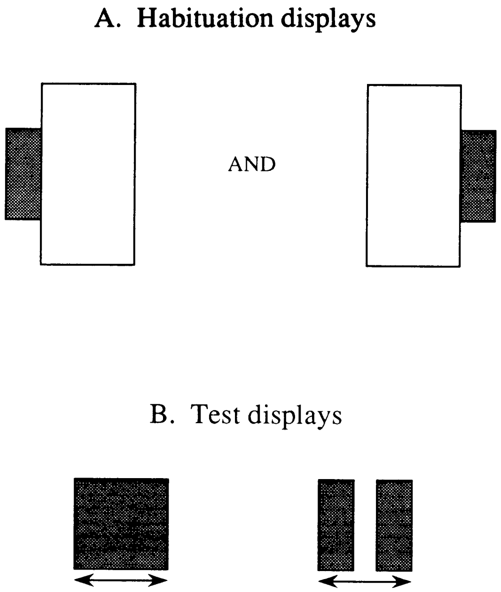

FIG. 4.—Schematic depiction of the displays used in Experiment 2. The upper diagrams present the displays that appeared on alternating habituation trials.

ation, the infants were presented with the same moving test displays as used in Experiment 1. Their looking times to these displays were compared, and their preferences between the test displays were compared to the preferences exhibited by infants in each condition of Experiment 1. If motion relations between the successively visible surfaces of a partly occluded object are critical for infants' perception of contact relations between those surfaces, then infants habituated to stationary views should show the same equal looking times to the two test displays as infants in the baseline condition of Experiment 1 and should contrast with the looking preferences obtained in the experimental condition of that study. On the other hand, if static, configurational properties of the display specify object unity or if infants simply habituate to successively presented single patches of red, then they, like infants in the moving condition of Experiment 1, should show a greater-than-baseline preference for the separated test display.

Method

The method was the same as in Experiment 1, except as follows.

Subjects.—Sixteen infants drawn from the same population as that reported in Experiment 1 participated in the experiment. The infants ranged from 4 months, 17 days to 5 months, 10 days, with a mean age of 4 months, 28 days. An additional three infants participated in the study but were not included in the analyses: one because of technical error and two because of fussiness.

Displays and apparatus.—The habituation displays in Experiment 2 were the same as those used in Experiment 1 except that the occluded complete or broken square was stationary and was presented on alternating trials at its left- and right-most extremes of motion (Fig. 4*A*). The appearance and motion of the test displays were as in Experiment 1 (Fig. 4*B*).

Design, procedure, and analyses.—As in Experiment 1, half the infants were habituated to stationary views of the complete object, and half were habituated to stationary views of the broken object; these occlusion displays again looked identical to adults and were responded to equivalently by infants. Following habituation, infants were presented with the same moving test displays as in Experiment 1. Order of presentation of right and left habituation trials and order of test trials were counterbalanced across babies. Four assistants served as primary observer in the study; all primary and secondary observers reported that they remained blind to the test displays throughout the study. Interobserver agreement, calculated across 12 cases, averaged .92. Looking times to the two test displays were log transformed[3] and were compared both with one another and to looking times of infants in the experimental and baseline conditions of Experiment 1 by means of the same parametric and nonparametric analyses as in that experiment.

Results

Mean looking times during the last six habituation trials and the six test trials are presented in Figure 5. First, a 2 (order) × 3 (trial pair) × 2 (test display) ANOVA of the log-transformed looking times in Experiment 2 revealed no significant effects: In particular, there was no preference between the two test displays, $F < 1$, and no pair × test display interaction, $F(2, 28) = 1.25$, $p > .2$.[4] Second, looking times from Experiment

[3] The skewness value averaged across trials for Experiment 2 was 1.59, SD = .84.

[4] The suggestion from the test trial means in Figure 2 that infants preferred the broken test display on the first pair of test trials results from the high looking times of two infants on this trial.

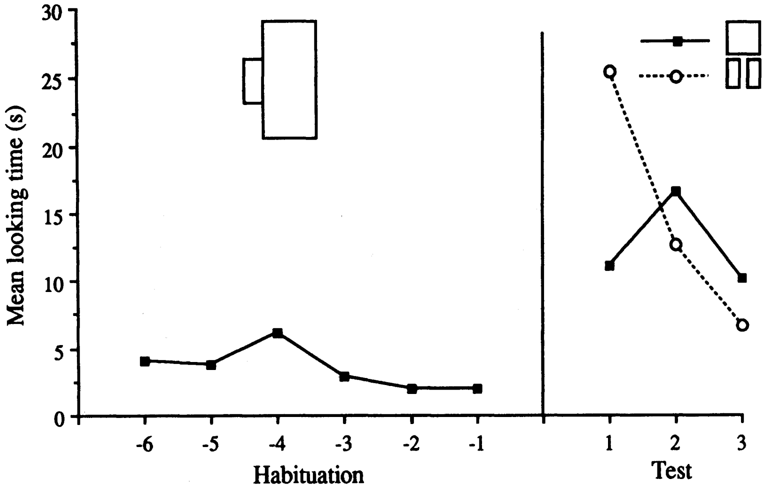

FIG. 5.—Mean looking times on the last six habituation trials and on the six test trials of Experiment 2.

2 were compared with those in the baseline condition from Experiment 1 with a 2 (condition) × 2 (order) × 3 (trial pair) × 2 (test display) ANOVA. This analysis revealed a significant overall effect of trial pair, $F(2, 56) = 7.01, p < .002$, but no significant condition × test display interaction, $F < 1$. Finally, a third ANOVA compared Experiment 2 with the experimental condition from Experiment 1. This analysis revealed a significant overall effect of trial pair, $F(2, 56) = 5.04, p < .01$ and a significant effect of test display, $F(1, 28) = 14.68, p < .001$. Looking time decreased over the test session, and was greater overall for the broken test display. Most important, this analysis revealed a significant condition × test display interaction, $F(1, 28) = 7.45, p < .02$: the looking preference for the broken display was greater following habituation to the moving partly occluded display than after habituation to the stationary partly occluded display.

The nonparametric analyses gave concordant findings. Infants in Experiment 2 showed no preference for the broken test display (Wilcoxon $T = 63, p > .2$). Their looking preferences did not differ from those of infants in the baseline condition of Experiment 1 (Wilcoxon-Mann-Whitney $z < 1$). In contrast, the looking preferences of infants habituated to the stationary display (Experiment 2) differed significantly from those of infants habituated to the moving display (Experiment 1) (Wilcoxon-Mann-Whitney $z = 2.62, p < .005$; Fig. 6). Seven of the 16 infants in Experiment 2 looked longer at the broken display and nine looked longer at the complete display, compared to 15 infants and one infant showing these respective preferences in Experiment 1 ($p < .005$, Fisher's exact test).

Discussion

The results of Experiment 2 provide evidence against two possible alternative interpretations of the findings obtained in Experiment 1. First, infants did not use the static configurational properties of the two visible portions of the partly occluded square such as common color and texture, smooth alignment of edges, or simplicity of form to perceive those surfaces as a single, connected object. Second, infants did not dishabituate to the test display consisting of two separated surfaces, as would be predicted if they had simply become habituated to a single red surface visible at two different times and places. These findings suggest that when the parts of an object are visible in succession, the common motion of these parts is necessary to perception of the object's connectedness, in accord with the contact principle.

Although the successive presence of the stationary square in two different locations might suggest to adults that the object had moved during the time that the display was hidden behind the curtain, infants did not

Nonetheless, because we thought it prudent to investigate this disparity further, we conducted a t test on the log-transformed data for this trial pair. There was no significant difference in the looking times to the two test displays for this pair, $t(15) = 1.72, p > .1$, two-tailed.

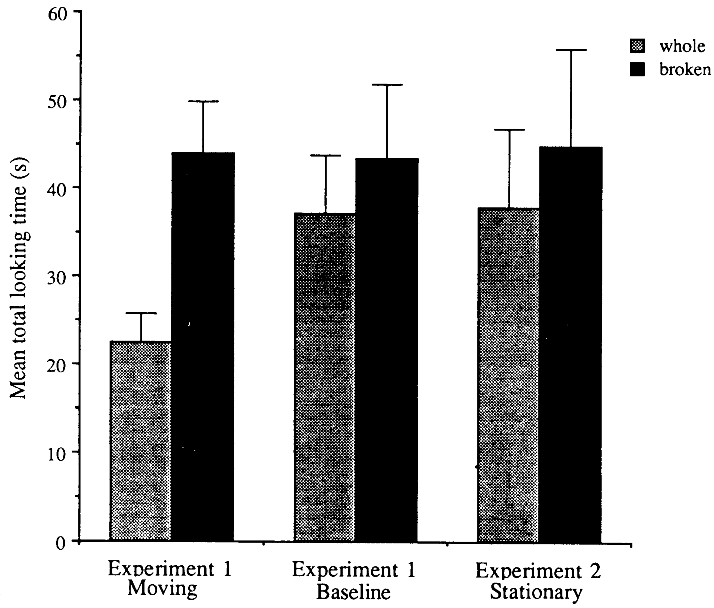

FIG. 6.—Mean total looking time directed to the whole and the broken test displays, for Experiments 1 and 2. Bars indicate standard errors.

appear to make use of this information concerning the object's motion. Infants' apparent inability to infer object motion from the present succession of static arrays accords with the findings of a variety of studies of kinematic perception (e.g., Kellman, 1984), in which infants perceive surface and object properties from a pattern of continuous motion but not from a succession of static views (see Kellman, 1993, for discussion).

The significant difference between the moving condition of Experiment 1 and the stationary condition of Experiment 2 provides evidence that motion influences infants' object perception, but the nature of this influence is not clear. One possibility, consistent with past research on infants' perception of center-occluded objects whose ends are visible simultaneously, is that motion provides information about object unity (Kellman & Spelke, 1983). A second possibility, consistent with studies of visual attention and visual preferences, is that motion heightens infants' attention to objects, and that configurational properties of the displays in these experiments, such as the alignment of the visible surfaces or the simplicity of the overall form, led infants to perceive the occluded object's unity.

The final experiment in this series begins to distinguish these possibilities. If motion merely heightens infants' attention to configurational properties of a display, then the infants in Experiment 1 should have perceived not only the unity of the object but also its form. Configurational properties such as alignment and figural simplicity specify not only that the moving, partly occluded object is connected, but also that it is a square. In contrast, if object perception in the present situation depends only on the contact principle, then the infants should have perceived the two successively visible ends of the object as connected, but they should have had no determinate perception of the form of that connection. Experiment 3 therefore investigated whether infants who view the moving occlusion display of Experiment 1 perceive a connected object of a definite shape: a square.

Experiment 3

Infants in one condition were familiarized with the moving occlusion display from Experiment 1, infants in a second condition were familiarized with the stationary occlusion display from Experiment 2, and then all the infants were tested with two connected, fully visible displays. Although both test displays corresponded in their visible areas to the visible areas of the partly occluded habituation display, the forms of the test displays differed. One test display was in the form of a square and was identical to the

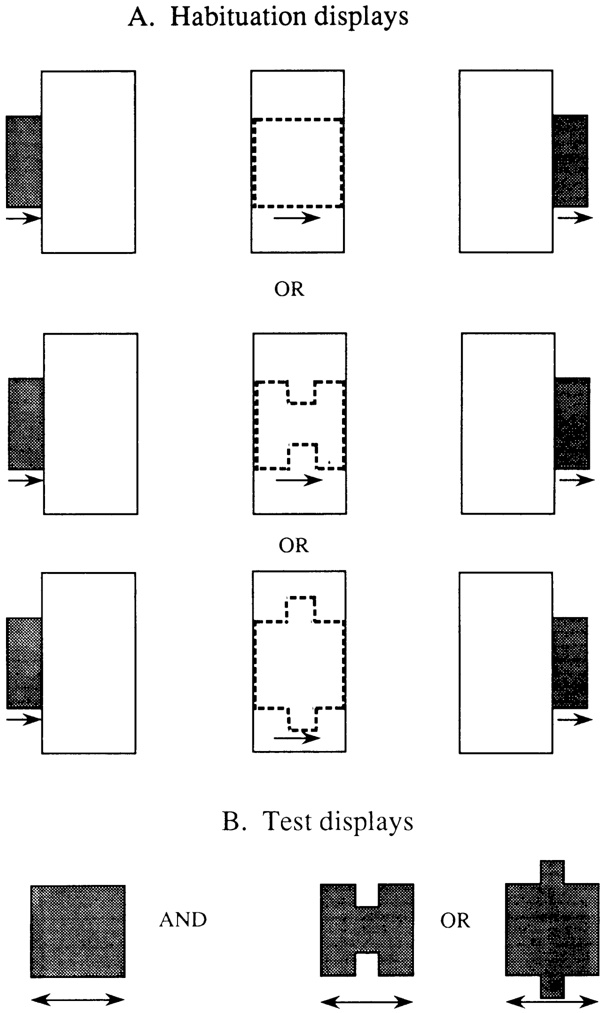

FIG. 7.—Schematic depiction of the displays used in Experiment 3. The upper diagrams present each display at the start, middle, and end of a half cycle of motion.

connected test display of Experiments 1 and 2. The other test display was more complex: It had either indentations or protuberances in the area that had been occluded during habituation (Fig. 7).

The test trial looking preferences of infants in the moving and stationary conditions were compared to each other and to the looking preferences of infants in Experiments 1 and 2, on the following assumptions. First, given that the infants in the stationary condition of Experiment 2 did not perceive the unity of the partly occluded object, it is extremely probable that they did not perceive the object's form, and therefore those in the stationary condition of Experiment 3 also should not perceive the object's form. The stationary condition therefore is the best control condition with which to assess baseline preferences and extraneous habituation effects.[5] Second, if infants perceived a defi-

[5] The stationary habituation condition is a better control condition than a no-habituation baseline condition, for two reasons. First, the stationary condition familiarizes infants with all static configurational properties that are present in the moving condition and that might influence form preferences during the test session. Second, comparing the looking preferences of infants habituated to the moving and stationary displays allows the most focused test of infants' ability to perceive object form by integrating information over time, because only the presence or absence of the critical motion patterns distinguishes these displays.

nite form in the moving occlusion display, then the form they perceived most likely was a square. The square is the simplest form that is consistent with this display (e.g., Koffka, 1935), and it is formed by extrapolating the most direct and smooth connection between the visible surfaces of the occlusion display (Kellman & Shipley, 1991). If infants integrate information about object form over time, therefore, the infants who viewed the moving square should have generalized habituation from the partly occluded form to the fully visible square. Two comparisons across the conditions of Experiments 1 and 3 should reveal this effect: (*a*) The infants in the moving experimental condition of Experiment 3 should show the same generalization of habituation from the occluded display to the square object across the two experiments, and (*b*) the infants in the moving experimental condition of Experiment 3 should show a reliably greater preference for the complex object than those in the stationary control condition of Experiment 3.

In contrast, if infants perceive the unity but not the form of an object by integrating information over time, then the infants in the moving condition of Experiment 3 should show equal dishabituation to the two test displays, because the test displays should be seen as equally novel. Two comparisons should reveal this effect: (*a*) The infants in the moving condition of Experiment 3 should show a significantly smaller preference for the complex object than the infants in Experiment 1 showed for the broken object, and (*b*) the infants in the moving experimental and stationary control conditions of Experiment 3 should not differ in their preferences.

Method

The method was the same as in Experiments 1 and 2, except as follows.

Subjects.—Participants were 32 infants ranging in age from 4 months 18 days to 5 months 15 days (mean age, 5 months, 2 days). The infants' ethnic and economic backgrounds were similar to those of infants in Experiment 1. An additional four infants participated in the study but were not included in the analysis because of fussiness (1) or experimenter error (3).

Displays.—The habituation displays consisted of either the square or one of the two more complex shapes placed behind the occluder such that only its ends were visible in succession. For the moving experimental condition, each object moved as in Experiment 1; for the stationary control condition, each object was presented stationary as in Experiment 2. In both the moving and the stationary conditions, the occlusion displays involving the square, the indented shape, and the protruding shape were visually indistinguishable to adults. The square test display was the same as in Experiments 1 and 2. The test display with indentations was identical to the broken test display of the previous experiments, except that its left and right sides were connected by a central region 5 cm in height. The test display with the protuberances also was identical to the broken test display, except that its sides were connected by a central region 21 cm in height (see Fig. 7). As in the previous studies, both test displays corresponded to the visible areas of the partly occluded object in the habituation display.

Design, procedure, and analyses.—The design was the same as in Experiment 1. Half the infants in each condition were habituated to the partly occluded square and half were habituated to a partly occluded object with an irregular shape. These partly occluded displays looked identical to adults and were responded to equivalently by infants. Moreover, half the infants in each condition were tested with the square and the indented object, and half were tested with the square and the object with the protuberances. Eleven assistants served as primary observer in the experiment. Of the 46 signed statements by observers at the end of the study, 43 indicated that the observer remained blind to the test displays throughout the study. Interobserver agreement, calculated over 18 cases, averaged .94.

As in Experiments 1 and 2, the analyses were conducted on log-transformed looking times[6] and tested for looking preferences within each condition and for differences in looking preferences across the two conditions. Further analyses compared the looking preferences of infants in the experimental condition of Experiment 3 to those of infants in the experimental condition of Experiment 1, in order to compare infants' perception of object unity (Experiment 1) and object form (Experiment 3).

[6] The skewness value for the stationary control condition of Experiment 3 was 1.81, SD = .89. The value for the moving condition was 1.53, SD = .60.

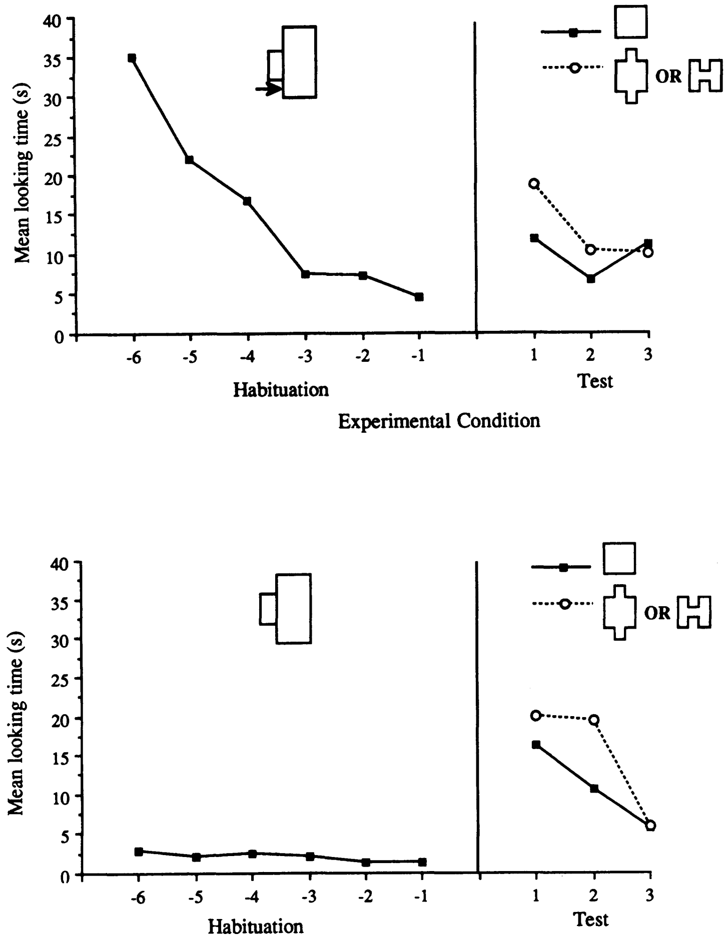

FIG. 8.—Mean looking times on the last six habituation trials and on the six test trials for the experimental (top) and the control (bottom) conditions of Experiment 3.

Results

Figure 8 presents the mean looking times during the last six habituation trials and during the six test trials for both the moving experimental and the stationary control conditions. An ANOVA on the log-transformed looking times comparing looking patterns to the two test displays across the two conditions revealed significant main effects of pair, $F(2, 56) = 8.67$, $p < .001$, and test display, $F(1, 28) = 6.79$, $p < .02$: Looking time decreased over the test session, and infants in both conditions preferred the complex form. No other effects were significant in this analysis: In particular, there was no interaction of condition and test display, $F < 1$.

Nonparametric analyses corroborated the parametric results. The infants in the experimental condition tended to look longer at the more complex form than at the square, but this difference was not significant (Wilcoxon $T = 37$, $p < .10$, two-tailed). In addition, this preference appears to be due to a baseline effect and not to habituation to the partly occluded object, because a significant preference for the irregular form was obtained in the stationary control condition (Wilcoxon $T = 31$, $p < .05$, two-tailed). Preferences in the two conditions did not differ (Wilcoxon-Mann-Whitney $z < 1$). Eleven of 16 infants in the experimental condition and 10 of 16 infants in the stationary control condition looked longer at the more complex object ($p > .2$, Fisher's exact test).

Figure 9 presents the mean total looking

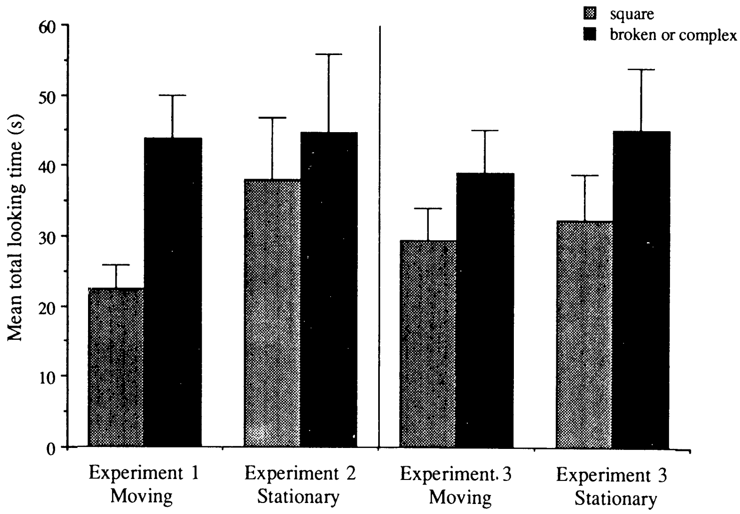

FIG. 9.—Mean total looking times directed to each test display in the moving and stationary habituation conditions of Experiments 1–3. Bars indicate standard errors.

times at the two test displays in the two conditions of Experiment 3 and in the corresponding conditions of Experiments 1 and 2. The first analysis comparing the present looking patterns to those of infants in the previous experiments focused on the stationary control conditions. A 2 (condition) × 2 (order) × 3 (trial pair) × 2 (test display) ANOVA comparing looking times of the infants in the stationary control condition of Experiment 3 with those in the stationary condition of Experiment 2 revealed significant effects of trial pair, $F(2, 56) = 6.71, p < .005$, and test display, $F(1, 28) = 6.16, p < .02$: Looking time decreased over the test session, and infants preferred the more complex form (the broken square or the complex figure) over the simple square. There was no significant interaction of condition and test display, $F(1, 28) = 1.82, p > .1$. A 2 × 2 × 3 × 2 ANOVA comparing the looking times of infants in the moving condition of Experiment 3 to those in the moving condition of Experiment 1 also revealed significant main effects of trial pair, $F(2, 56) = 7.65, p < .002$, and test display, $F(1, 28) = 14.74, p < .001$: Infants in both groups preferred the more complex test display. Most importantly, however, the interaction of condition × test display also was significant, $F(1, 28) = 4.60, p < .05$: The preference for the broken square in the experimental condition of Experiment 1 was reliably greater than the preference for the complex object in the experimental condition of Experiment 3.

The nonparametric analyses fully corroborated the parametric results. Although infants in the stationary condition of Experiment 3 looked longer at the more complex display, their preference for this display was not significantly greater than the preference for the broken display shown by infants in the stationary condition of Experiment 2 (Wilcoxon-Mann-Whitney $z < 1$). Analyses next compared the looking preferences of infants in the experimental condition of Experiment 3 to those in the experimental condition of Experiment 1. After habituation to the moving occlusion display, the preference for the broken object in Experiment 1 was significantly greater than the preference for the complex object in Experiment 3 (Wilcoxon-Mann-Whitney $z = 2.25, p < .02$).

Discussion

Experiment 3 provides no evidence that 5-month-old infants perceive the form of a moving, partly occluded object whose ends are visible in succession. After habituation to such an object, infants showed the same preference between a square and a more complex form as did the infants who had seen only stationary views of the occlusion display. Although infants appeared to have an intrinsic preference for the more complex object, the lack of difference between the conditions provides no evidence that the infants in the experimental condition perceived the shape of the partly occluded object by integrating information over time.

The comparison of Experiment 3 with Experiment 1 provides evidence that infants are better able to perceive the unity of a moving object whose parts are successively visible than to perceive the particular form of that object. Although the infants in the experimental conditions of Experiments 1 and 3 were habituated to the same moving occlusion display, and although adults perceived this display both as connected and as regular in shape (see footnote 1), the infants in Experiment 1 showed a reliably greater preference for the broken display than those in Experiment 3 showed for the display with the irregular form. Given that these conditions were identical in method and displays except for the critical form with which the complete square display was contrasted, it appears that perception of object unity surpasses perception of object form in this situation.

The negative suggestion from this study—that young infants fail to perceive object form by integrating information over time— must be regarded with caution for three reasons. First, one can never conclude decisively that an ability is lacking in infancy, because it is always possible that further experiments with more compelling displays or a more sensitive method will reveal its presence. Second, the existence of a (nonsignificant) difference in control-group preferences between the test displays of Experiments 1 and 3 may make Experiment 3 a less sensitive test of object perception than Experiment 1. It is possible that an experiment with equal control-group preferences would have produced an effect of habituation to the moving occluded object on test trial form preferences.[7] Finally, it is possible that the negative findings of Experiment 3 stemmed from an unfortunate choice of test forms. Infants may have perceived a definite form in the habituation display from Experiments 1 and 3, but that form may have differed from the form perceived by adults and predicted by theories of perceptual organization. If infants perceived a form that did not correspond to either of the present test displays, then Experiment 3 does not validly test infants' perception. For all these reasons, we cannot conclude that 5-month-old infants are incapable of perceiving the form of an object by integrating information over time.

Despite these qualifications, the lack of evidence for perception of a simple, square-shaped object in the present display is of interest for three reasons. First, infants failed to show evidence of perception of object form when tested with the same display, and the same method, that gave evidence of successful perception of object unity. Second, although there are no significant differences between test preferences in the moving and stationary conditions of Experiment 3, there was a significant difference between the preferences in the moving conditions of Experiment 3 and Experiment 1. This difference is consistent with the thesis that young infants perceive the unity but not the form of an object by integrating information over time. Third, the negative findings of Experiment 3 accord with the negative findings obtained from a spectrum of experiments using a variety of methods and displays, that have probed infants' ability to perceive object form by integrating information over time (Arterberry, 1993; Craton & Yonas, 1990; Rose, 1988; Skouteris et al., 1992). Although the negative findings of any one of these studies must be viewed with caution, this broad array of converging results paints a consistent picture of the development of object perception. Faced with the task of integrating information over time and over occlusion, infants appear to perceive the connectedness and unity of an object before they perceive the object's form.

General Discussion

Taken together, the results of Experiments 1 and 2 provide evidence that 5-month-old infants are able to integrate patterns of common motion presented over time to perceive the unity of a partially occluded object. These findings cast doubt on the thesis that infants cannot construct representations of objects from successively available information (Baillargeon, 1993). Spatiotemporal integration does not appear to be an all-or-none ability, but an achievement that depends on the perceptual task presented to infants and the information available to them.

Two features of Experiment 1 appear to account for infants' ability to integrate information over time and motion. First, the experiment tested infants' perception of object unity, whereas studies of spatiotemporal integration with negative findings— both Experiment 3 of the present series and studies

[7] During considerable piloting, we attempted to find other complex forms that (*a*) corresponded in their visible areas to the occlusion display, and (*b*) produced no baseline preference relative to a simple square. We were not able to find any such display: All the irregular forms we tested evoked more looking time from 5-month-old infants than did the regular square.

from other laboratories (e.g., Arterberry, 1993; Rose, 1988; Skouteris et al., 1992)—tested infants' perception of object shape. In this situation, as in others (e.g., Craton & Baillargeon, 1992; Kellman & Spelke, 1983, but see Needham, 1994), perception of object unity may be a more basic ability than perception of object form (Kellman, 1993). Second, the experiment tested infants' integration of kinematic information under conditions in which the arrangement of object surfaces is specified by the contact principle (Spelke & Van de Walle, 1993). The contact principle thus appears to guide not only infants' perception of objects whose parts are perceptible simultaneously (Kellman et al., 1986, 1987; Kellman & Spelke, 1983; Streri & Spelke, 1988, 1989), but also infants' integration of information about an object whose parts are visible in immediate succession.

The common patterns of success and failure found in the present studies and in earlier studies of object perception are consistent with the thesis that a single body of principles, each capturing regularities in material objects' behavior, underlies infants' perception of objects in a wide range of circumstances. If this thesis is correct, then one may use the findings of studies of the development of object perception in other situations to make predictions about the conditions under which infants will perceive the unity of an object by integrating information over time. For example, studies of young infants' perception of center-occluded objects (Kellman & Spelke, 1983, although see Needham, 1994) and of adjacent objects (Needham & Baillargeon, in press; Spelke, Breinlinger, Jacobson, & Phillips, 1993; Xu et al., 1995) lead to the prediction that perception of the unity of an object whose parts are visible over time will be unaffected by configurational properties of the object's visible surfaces. Thus, young infants should perceive a unitary object not only when the two successively visible ends of the object are aligned and share a common color, texture, and form, but also when they are misaligned and differ in color, texture, and form. Further experiments from our laboratory support this prediction (Van de Walle & Spelke, 1995).

The present findings accord not only with the findings of other studies of object perception, but also with the findings of studies of physical reasoning. The contact principle has been found to guide infants' representation of causal relations among objects (Leslie, 1984; Leslie & Keeble, 1987) and infants' inferences about the motions of hidden objects (Baillargeon, 1995; Ball, 1973; Kotovsky & Baillargeon, 1994; Van de Walle et al., 1994; Woodward et al., 1993). Indeed, the present studies appear to present infants with a task that stands midway between tasks that are commonly viewed as "perceptual" (e.g., perceiving the unity of an object whose parts are visible simultaneously) and tasks that are commonly viewed as involving "reasoning" (e.g., inferring the location and the behavior of an object that has moved fully out of view). The existence of common principles underlying performance in all these tasks calls into question the traditional distinction between perception and reasoning and lends credence to recent attempts, from diverse theoretical perspectives, to link these abilities early in development (e.g., Kellman, 1993; Mandler, 1992; Pick & Heinrichs, 1989; Smith & Heise, 1993; Spelke & Van de Walle, 1993).

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