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Philip J. Kellman; Elizabeth S. Spelke; Kenneth R. Short

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Philip J. Kellman
Swarthmore College

Elizabeth S. Spelke
University of Pennsylvania

Kenneth R. Short
Swarthmore College

KELLMAN, PHILIP J.; SPELKE, ELIZABETH S.; and SHORT, KENNETH R. *Infant Perception of Object Unity from Translatory Motion in Depth and Vertical Translation.* CHILD DEVELOPMENT, 1986, **57**, 72–86. Previous research indicated that 4-month-old infants perceive the unity of a center-occluded object when its visible ends share a common lateral translation in space. The present work investigated the class of motion relationships that can specify object unity to infants, specifically, asking whether it includes all rigid translations. 3 experiments tested the informativeness of 2 axes of translation not previously studied: translation in depth and vertical translation. These motions also allowed assessment of certain interpretations of previous results that invoke specific sensory consequences of lateral movement, rather than perceived motion, as underlying perceived unity. Experiment 1 provided evidence that a small extent of translation in depth specified the unity of an object, but only to the subgroup of infants who detected the motion. Experiment 2 used a greater displacement in depth and found clear evidence for perception of object unity. Experiment 3 indicated that vertical translation, in which the 2 visible areas of the partly hidden object undergo dissimilar changes, also specifies object unity to infants. These results suggest that infants' perception of object unity depends on perceived coherence of motion, no matter how specified, and that the class of informative motions includes all rigid translations.

Kellman and Spelke (1983) reported that young infants perceive the unity of partly occluded objects by detecting the motion relations of their visible parts. When 16-week-old infants were habituated to a center-occluded object the visible surfaces of which underwent a common lateral translation, they generalized habituation to a connected, fully visible object and dishabituated to a broken object—a display in which the two visible surfaces appeared fully in view and were separated by a gap where the occluder had been. In contrast, static variables that can indicate object unity to adults—alignment of contours, regularity of shape, and similarity of surface color—were found to be uninformative to young infants. When 16-week-old infants were habituated to a center-occluded stationary object of a uniform color and regular shape, they showed equal dishabituation to a complete and a broken object (Kellman & Spelke, 1983; Schmidt & Spelke, 1984).

What is the class of motions that gives rise to perception of object unity in infancy? One natural possibility is that perceived unity depends on perceived coherence of movement: Infants may perceive two surfaces as connected when they undergo a common rigid translation (Kellman & Spelke, 1983). Since many objects tend to move rigidly and to maintain their coherence as they move, the use of rigid translation as an indicator of object unity and boundaries would often result in accurate perception. Such a dependence of perceived unity on perceived motion might be an example of "percept-percept coupling" (Epstein, 1982; Hochberg, 1974), that is, de-

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pendence of one percept on another rather than on stimulus variables. This coupling need not be learned (Rock, 1977); indeed, the available evidence suggests that, contrary to many constructivist accounts of object perception (e.g., Piaget, 1954), the perception of unity from motion arises in the absence of extensive haptic experience (von Hofsten & Spelke, in press; Kellman & Spelke, 1983).

Despite its plausibility, this interpretation cannot be strongly evaluated on the basis of previous experiments because lateral translation in the frontal plane is the only pattern of movement that has been investigated. It is possible that object perception depended not on perception of the rigid displacement of an object but on detection of some of the sensory changes that are produced by an object that moves laterally. First, object perception may have depended on detection of a common lateral translation of images across the retina, rather than on perception of a common lateral translation of an object in space. Whenever the images of two visible surfaces undergo the same shift at the infant's eye, they may be perceived as connected. Second, object perception may have depended on detection of the similarity of the changes in the images of the object at the eye. Whenever the images of the two visible ends of an object are subjected to similar transformations, infants may perceive those ends as connected. Although similarity of static aspects of objects such as color, texture, and orientation does not provide useful information to infants (Kellman & Spelke, 1983; Schmidt & Spelke, 1984), a similarity principle defined over optical transformations may underlie infants' perception of objects.

The present research was undertaken to investigate the class of rigid motions that give rise to perception of a unitary object. Since previous experiments showed that lateral translation is effective, the present experiments focused on translations along the other spatial axes: vertical translation and translation in depth (see Fig. 1). If all three orthogonal translations were found to give rise to perception of a unitary object, that finding would strongly suggest that the class of effective motions includes at least all of the simple translations.

Furthermore, studies of motion in depth and of vertical motion serve to investigate whether perception of object unity depends on the perception of some pattern of movement of an object or on detection of some sensory consequence of object movement. Lateral translation, vertical translation, and translation in depth are specified by very different patterns of optical and oculomotor information (see below), and they are accompanied by very different sensory consequences. If all three motion patterns lead to perception of a unitary object, it would appear that object perception depends on perception of motion, not the detection of particular sensory changes.

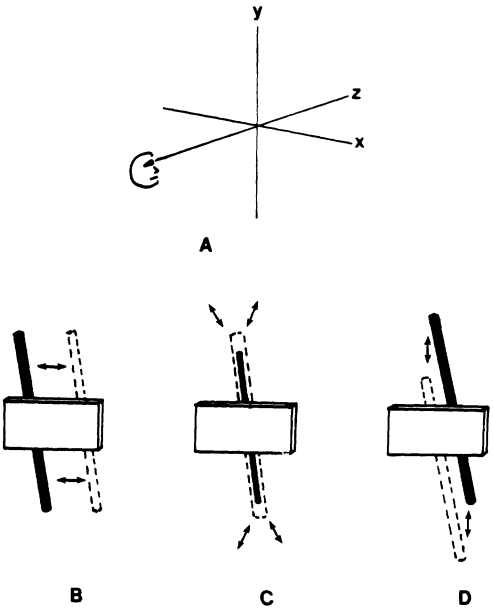

FIG. 1.—Three axes of translation of an object in three-dimensional space and the optical consequences of each. *A*, the three orthogonal axes. Following Braunstein (1976), the Z (depth) axis is the line of sight; the X (horizontal) axis is defined as parallel to the line connecting the two eyes of the observer and perpendicular to the Z axis; the Y axis (vertical) is perpendicular to both the X and Z axes. *B*, lateral translation. *C*, translation in depth. *D*, vertical translation. (Filled and dotted rods indicate the extreme positions of the moving rod in each case.)

More specifically, studies of vertical and depth motion permit one to test the two sensory interpretations outlined above. When a center-occluded object moves in depth, the images of its visible surfaces do not undergo any common lateral displacement; rather, they progressively shrink and expand at the infant's point of observation. When an object moves vertically, the images of its surfaces do not undergo the same pattern of change; rather, the image of one of its surfaces grows while the image of the other surface shrinks. If either sensory interpretation is correct, then one of the new patterns of translatory motion should fail to lead to perception of a unitary object.

Translation in Depth

For adults, the perception of translation in depth arises from a variety of stimulus conditions, including optical expansion or contraction of the projection of a moving object, changes in convergence and accommodation, changes in binocular disparity, and others. There is evidence that binocular disparity is informative to young infants (Birch, Gwiazda, & Held, 1982; Fox, Aslin, Shea, & Dumais, 1980), as are differences in binocular convergence (von Hofsten, 1977), although these studies did not involve motion in depth. There is also evidence that young infants perceive movement from translation in depth of real objects (Carroll & Gibson, 1981) and from projected optical expansion patterns (Ball & Tronick, 1971; Dunkeld & Bower, 1980; Yonas, Pettersen & Lockman, 1979). These sources of information about motion in depth are quite different from the conditions of retinal displacement, optical pursuit, and relational changes in the positions of objects that underlie perceived lateral movement. Experiment 1, therefore, focused on infants' perception of a partly occluded object undergoing a translation in depth, in order to investigate whether this motion gives rise to perception of the unity of the object.

Experiment 1

To test the effectiveness of translation in depth, this experiment used the same rate and extent of real motion as did previous studies of lateral translation (Kellman & Spelke, 1983). As in those studies, perception of the partly hidden object was assessed by a habituation-of-looking-time method (Gibson, Owsley, & Johnston, 1978; Horowitz, 1974). A partly hidden object was repeatedly presented until a clear decline in looking time occurred. Afterward, test trials were conducted with no occluding object present. These consisted of alternate presentations of a complete object and an object with a gap (broken object) where the occluder had been (see Fig. 2).

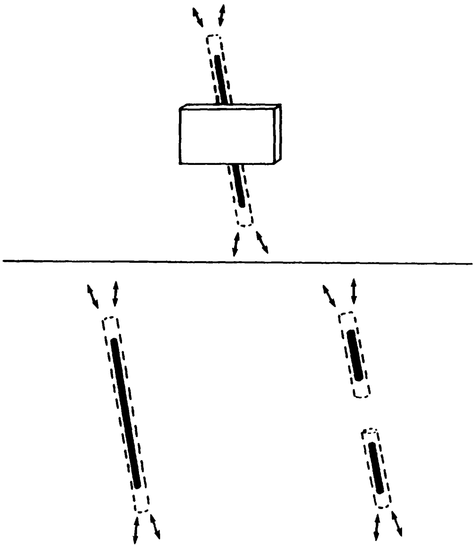

FIG. 2.—Displays and design in Experiment 1. The upper figure depicts the occlusion display; the complete and broken rod test displays are pictured below. (Arrows indicate translation in depth.)

If infants perceived the visible surfaces of the partly hidden object as connected, they were expected to generalize habituation to the complete object and to dishabituate to the broken object. If infants did not perceive the visible surfaces as connected, they were expected to show equal dishabituation to the two test displays. In no studies, with stationary objects or objects in motion, regular objects or irregular objects, have infants generalized habituation from a partly occluded object to a display with a gap where the occluder had been (Kellman, Gleitman, & Spelke, 1985; Kellman & Short, 1985; Kellman & Spelke, 1983; Schmidt & Spelke, 1984; Termine, Hrynick, Gleitman, & Spelke, 1985).

Although the extent of motion in depth used in this study matched the extent of lateral translation used in earlier studies (about 15 cm), this extent of motion in depth could be more difficult for infants to perceive than is the same extent of lateral motion. This would be the case if the optical information specifying the motion (changes in binocular disparity, optical expansion and contraction, and so forth) were difficult for infants to detect. Infants would not be expected to perceive a complete object based on motion information if that information were below threshold or of very low salience. Therefore, in the present study we attempted to assess perception of motion as well as perception of object unity by examining infants' duration of looking at the partly occluded rod as it moved. Infants typically look longer at moving displays than at stationary displays (Carpenter, 1974; Volkmann & Dobson, 1976). In our own previous work with rod and block displays, looking times to moving displays have been two to three times longer than looking times to stationary displays, on average (Kellman & Spelke, 1983). Accordingly, looking times to the rod moving in depth, in the present study, were compared to looking times to the same rod in previous studies, both when the rod was stationary and when it moved laterally. These comparisons were used to give some indication whether the infants detected the translation in depth.

Method

Subjects.—Subjects were 16 infants aged 105–137 days (mean age: 123 days). An additional four infants did not complete the experiment due to fussiness (3) or equipment failure (1).

Displays.—The habituation display consisted of a black wooden dowel, the middle of which was partly occluded by a tan wooden block (see Fig. 2). (For half of the subjects the display actually contained two aligned rod pieces with a gap between them behind the occluder. The two versions of the habituation display were indistinguishable to adult observers.) The rod was 53 cm long and 1.3 cm in diameter, oriented at a 20° angle from the vertical. The block was 23.4 cm wide, 11.7 cm high, and 2.5 cm thick. The rod and block were presented in front of a white pegboard surface, 76 cm high and 86 cm wide. The infant was seated with the occluding block at eye level, 81 cm from the block and 105 cm from the background. The rod moved toward and away from the infant through a distance of 15.2 cm at a real velocity of about 7.5 cm/sec, with a .5-sec pause at each end point. Relative to the infant, the rod's distance varied from 86 cm to 101 cm. At its far point, the rod subtended visual angles of 27.7° (length) and .87° (width). The velocity of the moving (expanding and contracting) rod contours on the retina was about 4 min/sec. The occluding block subtended 16.1° (horizontal) and 8.2° (vertical).

In addition to the habituation display, there were two test displays: a moving complete rod and a moving broken rod presented without the block (see Fig. 2). The complete rod was the same as that in the habituation display in all respects. The broken rod display consisted of two 21.5-cm pieces with a 10-cm gap between them.

All displays were presented at the back of a large display box with a plain white floor and tan sides. It was illuminated from overhead by one 100-watt and one 60-watt sunlight bulb through a translucent diffusing cover. Stimulus presentation was controlled by a motor-driven curtain that opened and closed between the subject and the display box. All display movements were made by hand from behind the display box by a trained assistant after extensive practice with a metronome. The display mover could not see the subject.

Design.—Infants were habituated to the partly occluded rod display in which the two visible parts of the rod moved toward and away from them in depth. After habituation, infants were tested with the complete and broken rods undergoing the same translatory movement in depth. The complete and broken test displays were shown three times each in alternation, and half of the subjects saw the complete display first.

Procedure.—Each subject was tested individually, seated in a standard infant seat centered in front of the display box. On each trial throughout the experiment, the curtain opened to reveal the display and remained open until the infant registered a look at the display of at least .5 sec and subsequently looked away for 2 sec continuously. If the infant was still looking at the display after 120 sec, the trial was also terminated. The intertrial interval was 3 sec, not including 1.5 sec each required for closing and opening the curtain.

The partly occluded display was shown repeatedly until a criterion of habituation was met. This criterion was a 50% decline in looking time, calculated by summing looking times on the first three trials, dividing this total in half, and summing sets of subsequent trials until three consecutive trials were obtained in which the total looking time was less than or equal to this value. If looking time on the first three trials was less than 12 sec, the criterion was based on the first three trials for which total looking exceeded 12 sec. After the criterion was met, the block was removed, and infants saw the two test displays three times each on alternating trials. The test displays were changed during the 3-sec period that the curtain was closed. The test trials were otherwise identical to the habituation trials.

Looking time was recorded by two observers who viewed the infants through holes in the pegboard background. The observers used push buttons connected to a microcomputer. Interobserver agreement (proportion of total time both observers were registering a look or nonlook) ranged from .83 to .98 and averaged .91. Observers were unable to see the display objects and were not told which display was being presented. One observer was designated as the primary observer: His or her responses were used by the computer to determine when a trial should end and when the criterion of habituation was met.

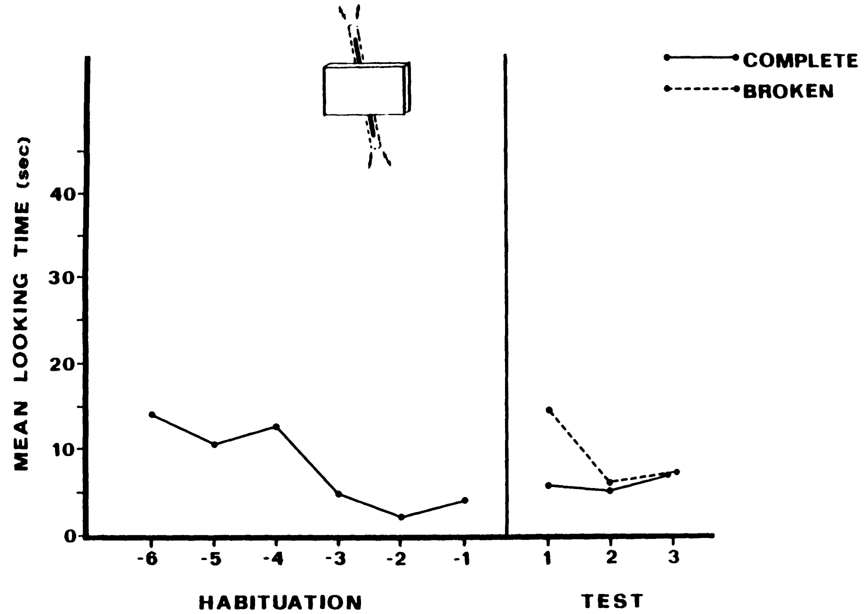

FIG. 3.—Looking times in Experiment 1. (Habituation trials are plotted backward from the trial on which the criterion of habituation was met.)

The primary observer also decided whether to suspend or terminate the experiment if an infant became fussy. The display mover changed the displays at the appropriate times.

If an infant became fretful during the first three trials, the experiment was stopped for several minutes and was begun anew if possible. If the infant became fretful later in the habituation series, the experiment was interrupted and resumed if possible, with at least three new trials required to meet the habituation criterion. If the infant became fretful during the test series, the experiment was terminated and the subject was replaced. No subject had more than one break during the habituation period.

Results

Habituation and test period looking times are shown in Figure 3. After habituation to a partly occluded rod translating in depth, infants showed some tendency to look longer at a broken rod translating in depth than at a complete rod. An analysis of variance comparing the last habituation trial, the first broken rod test trial, and the first complete rod test trial showed a marginal effect of trial, $F(2, 30) = 2.90$, $.05 < p < .10$. Individual comparisons revealed that looking time on the first broken rod test trial was marginally greater than on the first complete rod test trial, $t(15) = 1.62$, $.05 < p < .10$ (one-tailed); only 8 of 16 subjects looked longer at the broken rod on the first test trial.[1] Looking time on the first broken rod test trial exceeded that on the final habituation trial, $t(15) = 1.79$, $p < .05$ (one-tailed), and looking time on the first complete rod test trial and the final habituation trial did not differ, $t(15) = 1.28$, N.S. Ten of 16 infants looked longer at the broken rod test display than at the final exposure of the habituation display (N.S.), while 9 of 16 looked longer at the complete display than at the habituation display (N.S.).

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[1] The marginal superiority of looking time to the broken test display over looking time to the complete test display, despite the equal numbers of subjects who preferred each display, is due to the magnitude of the preferences in each subgroup. Infants who preferred the broken display averaged 19.5 sec more looking to it than to the complete display, whereas the average difference for infants who preferred the complete display was 2.1 sec. This asymmetry is consistent with the hypothesis (see below) that the experiment contained two subgroups of infants, only one of which perceived the motion in depth. If some infants perceived motion and consequently object unity, we would expect them to show a robust difference between looking to the broken and complete test displays. The subgroup not perceiving motion would be expected, on the basis of previous results, to show minimal preferences in either direction.

Analysis of looking times during all three test trials showed even less evidence that infants perceived the partly occluded object as complete. An ANOVA with factors of test display (broken vs. complete) and trial (first, second, or third) showed no reliable main effects of test display, $F(1,15) = 2.31$, N.S., or trial, $F(2,30) = 1.06$, N.S., and no interaction, $F(2, 30) = 1.47$, N.S.

Looking levels in this study were compared with two groups from previous studies as an indicator of whether infants perceived the motion of the rod. The infants in one of these groups (Kellman & Spelke, 1983, Experiment 2) were habituated to a stationary partly occluded rod and were tested with stationary broken and complete rods ("stationary group"). The infants in the other group (Kellman & Spelke, 1983, Experiment 1) were habituated to a laterally translating, partly occluded rod and were tested with laterally translating broken and complete rods ("motion group"). The infants in the present experiment ("depth group") showed looking levels more similar to those in the stationary group than to those in the motion group. Total looking time on the first two test trials did not differ between the depth group and the previous stationary group, $t(30) = 1.03$, N.S., but was reliably lower in the depth group than in the movement group, $t(30) = 2.16$, $p < .025$. On the habituation measures, the depth group was reliably lower than the motion group in mean looking time per trial, $t(30) = 3.14$, $p < .01$, total looking time in habituation, $t(30) = 2.41$, $p < .025$, and length of first habituation look, $t(30) = 2.01$, $p < .05$. The motion group also required fewer trials to reach the habituation criterion, $t(30) = 1.76$, $p < .05$ (one-tailed).[2] The depth group did not differ reliably from the stationary group on any of these measures, all t's$(30) < .85$, N.S.

Additional Analyses

Two aspects of the data led us to perform additional analyses. The marginally significant tendency of the depth group to look longer after habituation at a broken rod display on the first test exposure suggested that a complete object may have been perceived during habituation, at least by some subjects. Such a result does not occur with stationary rods (Kellman & Spelke, 1983). Yet, the similarity of looking levels observed in this study to a previous study with stationary displays raises the question whether motion was perceived at all from our translation in depth. We hypothesized that the small extent of movement in depth used in this study may have been very near threshold for infants at this age. With some individual differences in thresholds or attentional skill, some infants may have perceived the movement of the displays while others may have perceived no movement at all. The marginal tendency toward complete object perception would be understandable if the depth group consisted of two subgroups of infants: those who perceived the motion and also perceived the partly occluded object as complete, and those who did not perceive motion and also did not perceive unity. To check this hypothesis, we looked for a correlation between total looking time on the first two test trials, as an index of perceived motion, and preference for the broken test display, as a measure of perceived unity. When subjects' scores were categorized as above the median or below the median on each of these two measures, the correlation (tetrachoric correlation, Ferguson, 1959) was $.92$, $p < .01$.[3] No significant correlations between total looking time and strength of preference for the broken test display have been found in earlier studies, where presumably no threshold problems occurred.

Discussion

Experiment 1 did not provide clear evidence that common translatory motion in depth specifies the unity of a partly hidden object to 4-month-old infants. It seemed that a translation in depth was not equivalent to a lateral translation of the same physical extent in its effect on infants' object perception. The effects of depth motion and lateral motion might be different either because motion in depth did not provide information to infants about object unity, or because the depth motion used was too near threshold to be detected by all subjects.

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[2] Greater numbers of trials to criterion tend to characterize looking patterns to stationary displays. Since our procedure requires a certain minimum amount of looking to establish a habituation criterion, the most common cause of large numbers of trials is failure to show 12 sec or more of looking time during the first three trials.

[3] The correlation was calculated on dichotomized data because the hypothesis makes no prediction about the strength of subjects' preferences within the subgroup that perceived motion or within the subgroup that did not. The correlation between these variables when not dichotomized is also significant, however, $r = .58$, $p < .05$.

It is difficult to evaluate the latter possibility on the basis of available evidence about motion detection in infancy. Experiments with optical expansion patterns (e.g., Ball & Tronick, 1971; Yonas et al., 1979) have not addressed questions either about velocity thresholds or displacement thresholds. The extent of expansion and contraction in the width of the rod in this study—about 8 min of visual angle—is very close to the low end of the range of estimates of early visual acuity (Dayton, Jones, Aiu, Rawson, Steele, & Rose, 1964; Lewis & Maurer, 1977). Perhaps more directly relevant, 4-month-olds' average vernier acuity, that is, acuity for retinal alignment differences, is about 5.5 min of arc (Shimojo, Birch, Gwiazda, & Held, 1984). In the studies by Shimojo et al., misalignment was actually created by lateral movement of part of the display, making the situation even more comparable to the retinal position changes given by motion in depth. However, stereoscopic information might also be relevant to perceiving motion in depth, at least for some subjects. While the moving rod's change in depth (about 6° of convergence angle) is well above the stereoacuity threshold for infants who demonstrate stereopsis at this age, a large percentage of infants do not yet display stereopsis at 16 weeks (Birch et al., 1982).

Our own findings suggested that motion thresholds were the limiting factors in the experiment. Those infants who seemed to perceive movement in this study showed a preference for the broken object during the test period. When infants perceive a unitary translation in depth, therefore, they may perceive the unity of the translating object. If the overall findings of the experiment were weakened by the inability of some infants to detect the movement, then an experiment in which infants were presented with more easily perceptible motion in depth should provide stronger evidence for complete object perception. Experiment 2 was undertaken to investigate that possibility.

Experiment 2

To enhance the detectability of motion in depth, the real extent of the object movement was increased, the width of the rods was increased, and the subjects were positioned slightly closer to the displays. These changes increased both the extent of expansion and contraction of the retinal projections of the moving rods and the retinal velocity of the motion.

In addition to the occlusion group, a baseline group was run to determine infants' intrinsic interest in the two test displays apart from habituation effects. For this group, looking times to the two test displays were measured with no prior habituation to an occluded display. Although previous research with broken and complete rod displays moving in a variety of ways has shown no differences in their baseline attractiveness, no specific comparison of these displays translating in depth had been made previously. If infants in the occlusion group perceived the partly occluded rod as complete, then they were expected to show greater preference for the broken rod relative to the complete rod than were infants in the baseline group.

Method

The method of Experiment 2 was the same as in Experiment 1, except as noted below.

Subjects.—Participants were 32 infants aged 104–135 days (mean age: 123 days). An additional 11 infants began the experiment but were not counted in the final sample due to fussiness (7), equipment failure (3), or parental interference (1).

Displays.—The habituation and test objects differed from those in Experiment 1 only in the thickness of the rods, which was increased from 1.3 cm to 2.5 cm. Displays moved at the same real speed as before, but the rods traversed 25.5 cm in depth, from 71–96.5 cm away from the subject. The distance from the subject's viewing position to the occluding block was 66 cm, and to the background it was 102 cm. The occluding block, closer to the subject than in Experiment 1, subtended a vertical visual angle of 10.1° and a horizontal visual angle of 19.5°. The visual angle of the complete rod ranged from 1.5° (width) and 28.8° (length) at its furthest position to 2° (width) and 36.7° (length) at its nearest position. The speed of real movement was about 7.5 cm/sec, as in Experiment 1. In terms of retinal velocity, the width of the rod expanded and contracted by 9 min/sec.

Design and procedure.—As in Experiment 1, 16 infants (occlusion group) were habituated to the partly occluded rod translating in depth and tested afterward in alternating test trials with fully visible complete and broken rods. Half of the infants saw the broken rod display first in the test trials. The baseline group was tested in the same way but with no preceding habituation period. Interobserver agreement ranged from .78 to .97 and averaged .87.

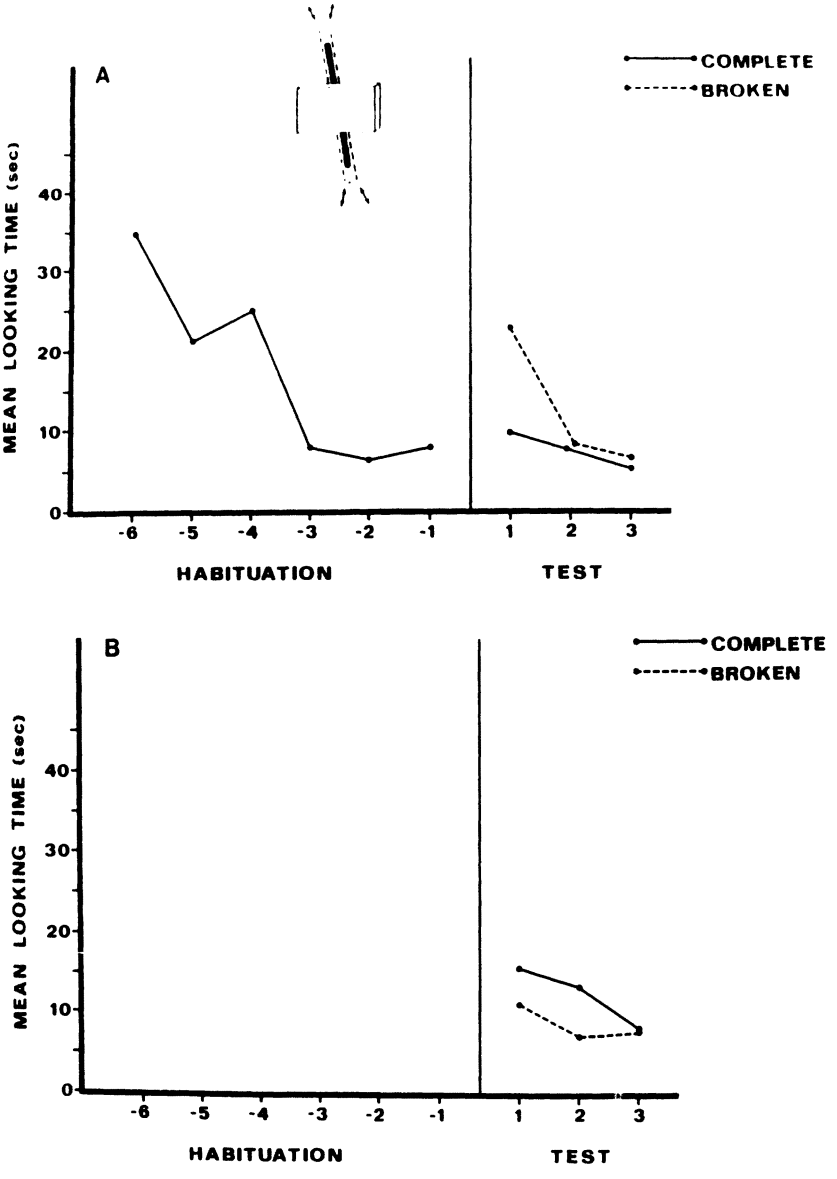

FIG. 4.—Looking times in Experiment 2. *A*, depth occlusion group. *B*, depth baseline group.

Results

Figure 4 shows looking times during the habituation and test periods in the occlusion and baseline groups. After habituation to a partly hidden object translating in depth, occlusion-group infants dishabituated markedly to a broken object but not to a complete object. Infants in the baseline group showed no preference for the broken object and in fact showed some tendency to look longer at the complete object. A 2 × 2 × 3 (group × test display × trial) ANOVA comparing the two groups showed a significant main effect of trial, $F(2,60) = 4.74$, $p < .05$. There were also significant interactions of group and test display, $F(1,30) = 5.45$, $p < .05$, and group, test display and trial, $F(2,60) = 3.41$, $p < .05$. There were no other reliable main effects or interactions. The main effect of trial indicates that looking times in general decreased across the three pairs of test trials. Individual comparisons showed that both interaction effects derived from the occlusion group's greater looking time to the broken rod display than to the complete rod display on the first test trial, $t(15) = 3.09$, $p < .01$. Broken rod looking times did not reliably exceed complete rod looking times on either the second or third test trials, both t's < 1.0. The finding of a strong experimental effect on the first test trial after habituation and weaker or negligible effects afterward is consistent with previous studies (Kellman & Spelke, 1983). In the baseline group, looking times to the complete rod slightly exceeded those to the broken rod on all three trials, but not reliably on any trial, all t's$(15) < 1.31$, N.S.

To assess the relation of test trial looking times in the occlusion group to final habituation levels, a one-way ANOVA compared the last habituation trial, the first complete rod test trial, and the first broken rod test trial. There was a reliable effect of trial, $F(2,30) = 5.06$, $p < .025$. Individual comparisons showed no difference between looking time at the end of habituation and looking time to the complete object, $t(15) = .31$, N.S., while looking time to the broken object was reliably greater than looking time on the final habituation trial, $t(15) = 2.43$, $p < .025$. Fifteen of 16 infants looked longer on the first broken rod test trial than on the first complete rod test trial ($p < .001$); nine looked at least twice as long at the broken display. Fourteen of 16 subjects looked longer on the first broken rod test trial than on the final habituation trial ($p < .001$), while only 9 of 16 subjects looked longer on the first complete rod test trial than on the final habituation trial (N.S.). In the baseline group, 5 of 16 subjects looked longer at the broken display than at the complete display on the first test exposure.

Overall looking times were compared to those of previous studies as an index of perceived motion. Looking times on the first two test trials in Experiment 2 reliably exceeded those observed for stationary rod displays, $t(15) = 1.88$, $p < .05$ (one-tailed), and did not differ from those observed for laterally translating displays, $t(30) = 1.10$, N.S. On the habituation period measures, the occluded depth movement group in Experiment 2 more closely resembled the motion group than the stationary group. There were no differences between the depth group and the lateral movement group on any of the four measures, all t's$(30) < 1.13$, N.S., but the depth group differed reliably from the stationary group in mean look per trial, $t(30) = 2.94$, $p < .01$, total looking time, $t(30) = 2.56$, $p < .01$, and first look duration, $t(30) = 2.53$, $p < .01$. These two groups did not differ reliably in number of trials to habituation, $t(30) = .95$, N.S. Finally, as a check on the hypothesis about motion detection in Experiment 1, the correlation between total looking time on the first two test trials and preference for the broken display was calculated, $r = .38$, N.S. A high correlation between these two variables held only in Experiment 1, as the motion-detection hypothesis would predict.

Discussion

After habituation to a partly occluded rod moving in depth, infants showed clear generalization of habituation to a complete rod and a clear pattern of dishabituation to a broken rod. No preference for the broken rod translating in depth emerged when the same two test displays were shown without habituation to an occluded display. We conclude that young infants can perceive the unity of a partly hidden object that undergoes a rigid translation in depth.

In light of the results of Experiment 2, the inconclusive findings of Experiment 1 appear to have resulted from the motion being too near threshold. The increase in Experiment 2 of extent of displacement, velocity of retinal expansion/contraction, or both, produced a clear completion result. The hypothesis that many infants did not perceive the motion in Experiment 1 is bolstered by the finding that overall looking times in Experiment 2 were comparable to those observed in previous work with moving displays and greater than those previously observed with stationary displays. Experiments 1 and 2 together give some indication of the range in which infants' thresholds for perceptible motion in depth are located. The closeness of this range to the vernier detection thresholds reported by Shimojo et al. (1984) is consistent with the possibility that perceiving motion in depth at this age is limited primarily by spatial resolution.

The present findings extend our understanding of the role of motion in early object perception. Infants perceive the unity of an object from motion in depth as well as lateral motion. Since the retinal events produced by motion in depth are quite different from those for lateral translation, perception of object unity would seem to depend on the perceived translatory movement of the object. Certainly, perception of unity does not seem to require detection of any lateral shift in the images of the object at the infant's point of observation.[4]

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[4] Although the stimulus for translation in depth includes a lateral, retinal displacement of the outer contours of the object, the symmetrical expansion and contraction of the image around a stationary center is very different from translation of the entire image across the retina. Infants are quite sensitive to this difference in tests of their perception of approaching objects (Ball & Tronick,

While the finding of complete object perception from motion in depth is consistent with the hypothesis that perceived unity depends on perceived motion, an alternative account can encompass this and earlier findings. In displays with common lateral translation and common translation in depth, the visible parts of the partly hidden objects undergo similar changes. Similarity of changes or events, rather than unitary motion per se, may underlie perception of unity. One way to compare the hypotheses of perceived motion and event similarity is to examine a stimulus situation in which the visible parts of a partly hidden object undergo dissimilar changes as part of a unitary movement. The hypothesis that perceived unity depends on some class of motion relationships characteristic of coherent objects would predict unity perception in such a case, while the similarity notion would not. Experiment 3 addressed these issues. It also investigated the effects of translatory motion along the one orthogonal axis that is so far untested: vertical translation.

Vertical Translation

When a center-occluded rod moves up and down in the frontal plane, its two visible parts undergo quite different changes. During the upward movement, for example, more of the top part becomes visible, while more of the bottom becomes occluded. If infants' perception of the unity of a partly hidden object depends on the detection of similar changes in the visible surfaces of the object, then infants viewing this vertically moving object should not perceive its unity: Different changes are occurring above and below the occluding object. In terms of unitary movement, however, the top and bottom surfaces of a vertically moving rod undergo the same rigid translation. If infants perceive the unity of a partly occluded object by detecting any common rigid translation of the object, then the vertical translatory motion should have the same effect as the lateral and depth translations studied previously.

Experiment 3

Experiment 3 tested infants' perception of a vertically oriented partially hidden rod moving vertically.[5] This display is depicted in Figure 5. The rod never moved so far as to bring its central area—the area where a gap could appear—into view. Although adults clearly perceive a unified partly hidden object from this display, it provides only the most minimal information for object unity. During vertical translation, the images of the vertical edges and the surfaces of the rod undergo no changes at all: no shrinking or expanding or lateral displacement. Only the top and bottom edges of the rod are displaced. The parallel displacements of the top and bottom edges and the consequent lengthening and shortening of the upper and lower surfaces provide the only information for a common rigid displacement.

Method

The method followed that of the two previous experiments, except as noted below.

Subjects.—Participants were 32 infants aged 102–137 days (mean age: 121 days). An additional 13 infants failed to complete the study, because of fussiness (12) or experimenter error (1).

Displays.—The habituation display consisted of a black wooden dowel, 47.4 cm long and 1.5 cm in diameter, oriented vertically (see Fig. 5). Occluding its middle was a tan wooden block 16 cm high, 25.4 cm wide, and 2.5 cm thick. (Once again, a broken rod was actually used in the habituation display for half the subjects.) The block was 81 cm away from the observer and 4 cm in front of the rod. The rod moved up and down 8.7 cm at a real velocity of about 7.5 cm/sec, with a .5-sec pause at each end point. The center of the rod (or the gap) never became visible. At the observer's viewing distance, the rod subtended 31.9° (length) and 1.0° (width), while the block subtended 11.5° (height) and 17.4° (width).

The test displays consisted of the fully visible complete rod, described above, and a broken rod display, consisting of two 20.4 cm long pieces (14.0°) separated by a 6.6-cm gap.

Design and procedure.—The 16 infants in the occlusion group were habituated to the

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1971; Yonas et al., 1979). For a case in which there is no lateral retinal displacement at all, see Experiment 3.

[5] Our initial attempt to test vertical motion used rods tilted 20° from the vertical as in previous experiments. The partly occluded display, however, gave rise to an illusory lateral component of motion of the rod along the horizontal borders of the block. This illusion, the same sort of illusory movement found on a rotating barber's pole (Robinson, 1972), frequently gave adult observers the impression that the visible rod parts were misaligned, unconnected, or sometimes nonrigidly connected. Since this ambiguity with adults would make interpretation of infants' responses problematic, the vertical orientation was used.

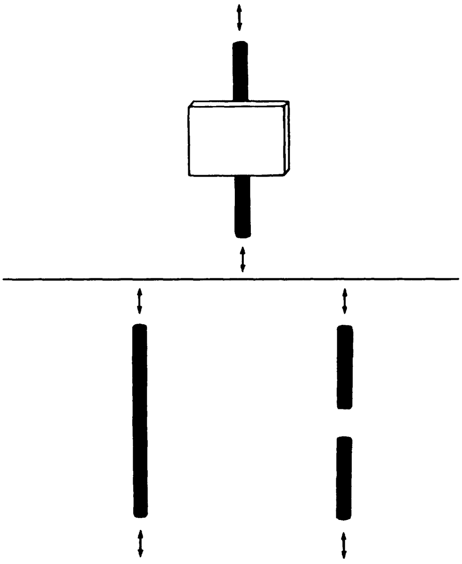

FIG. 5.—Displays and design in Experiment 3. (Arrows indicate vertical translation.)

vertically moving partly occluded rod and tested afterward with vertically moving complete and broken rod displays. Sixteen infants in a baseline group received only the test trials. Interobserver agreement ranged from .79 to .98 and averaged .89.

Results

Figure 6 presents the looking times during the habituation and test periods for the occlusion group and test trial looking times for the baseline group. After habituation to a vertically translating, partly hidden object, infants in the occlusion group looked longer at the broken test display than at the complete test display. In contrast, infants in the baseline group looked about equally at the two test displays. These patterns were confirmed by the analyses. A 2 × 2 × 3 (group × test display × trial) ANOVA revealed a reliable main effect of test display, $F(1,30) = 4.42$, $p < .05$, and a marginally significant group × test display interaction, $F(1,30) = 3.56$, $.05 < p < .10$.[6] There were no other reliable main effects or interactions.[7] Individual comparisons showed that both the effects of test display and group × test display were primarily due to longer looking by the occlusion group at the broken test display. Occlusion group infants looked longer at the broken display than at the complete display over the three test trials taken together, $t(15) = 2.25$, $p < .025$. Comparisons by trials showed reliable effects on the first test trial, $t(15) = 2.27$, $p < .025$, and on the second test trial, $t(15) = 1.93$, $p < .05$ (one-tailed), but not on the third test trial, $t(15) = 1.55$, N.S. In contrast, infants in the baseline group showed no reliable difference in looking times to the complete and broken displays across the three test trials, $t(15) = .30$, N.S., nor on any one of the three test trials, all t's(15) < 1.54, N.S.

Comparisons of the occlusion group's test trial looking times with final habituation levels showed that after habituation, complete display looking, but not broken display looking, was comparable to looking time on the final habituation trial. A one-way ANOVA by trial showed a reliable main effect, $F(2,30) = 5.87$, $p < .01$. Individual comparisons revealed that looking time on the first broken rod test trial reliably exceeded looking time on the first complete rod test trial, $t(15) = 2.27$, $p < .025$, and also exceeded looking time on the final habituation trial, $t(15) = 2.77$, $p < .01$. There was no difference between looking time on the first complete rod test trial and the final trial of habituation, $t(15) = .82$, N.S. In terms of numbers of infants, 14 of 16 looked longer at the broken test display on the first exposure than at the complete dis-

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[6] The marginal significance of the overall interaction effect in the general ANOVA prompted further examination of the data. While the overall variances did not differ between the two groups, inspection of the data, and an analysis of variance using the variance as a descriptive statistic, indicated different variances in looking times as a function of group and test display. Accordingly, the analyses of the looking time data were repeated after logarithmic transformation of all looking times. These analyses showed the same reliable effects as the raw data analyses, although the magnitudes of all effects were larger with the transformed data. For the group × test display interaction, $F(1,30) = 13.4$, $p < .001$.

[7] The absence of a reliable interaction with trials in this study, along with Figure 6A, suggest that the occlusion group's preference for the broken test display did not decrease across the three test trials, as is usually the case with such effects. However, the high occlusion-group mean for broken display looking on trial 3 resulted mainly from extremely long looks by two infants. The remaining 14 subjects showed roughly equal looking times to the two test displays by trial 3 (means = 9.0 sec for broken, 7.2 sec for complete). Statistically, the occlusion group's preference for the broken test display was strongest on the first test trial and weakest on the last (see below), as would be expected from prior studies.

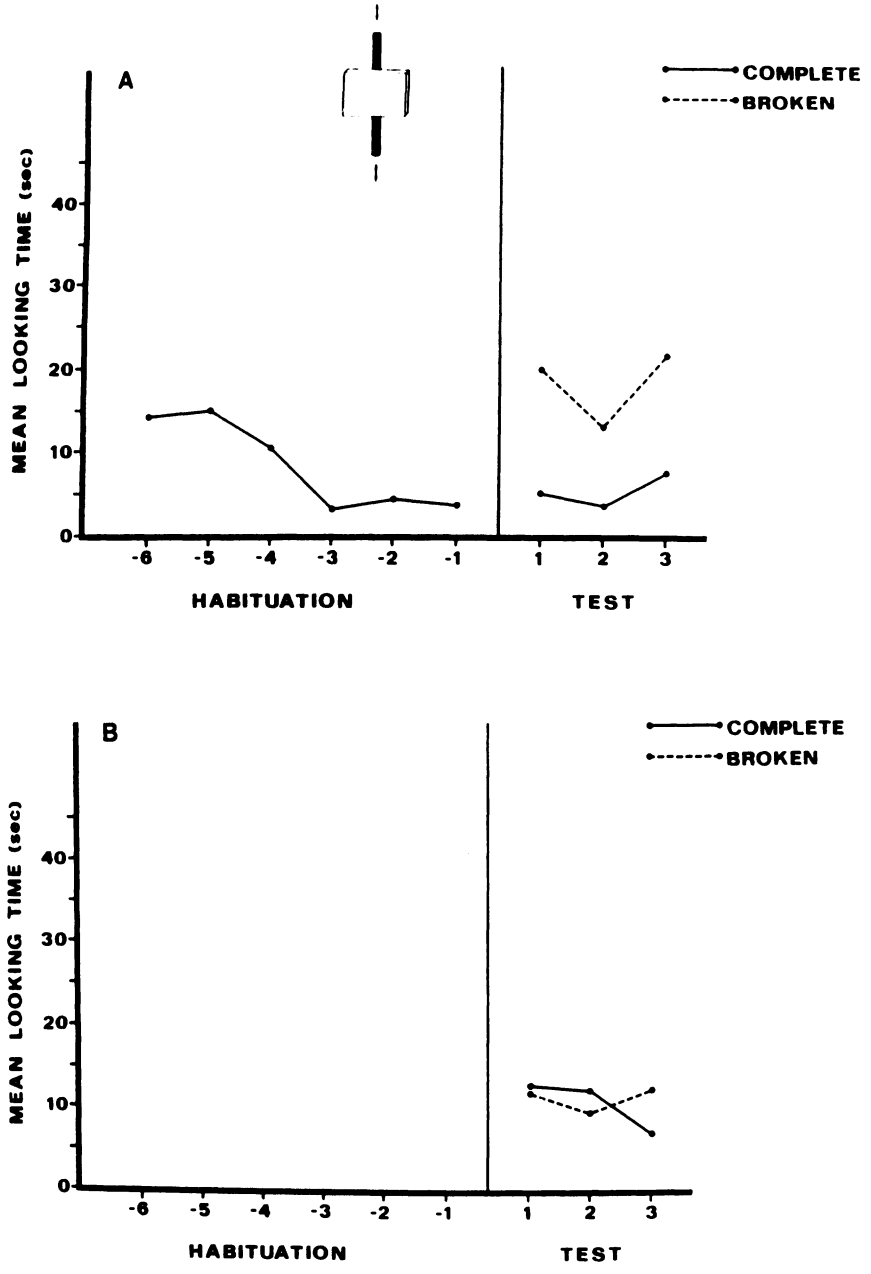

FIG. 6.—Looking times in Experiment 3. *A*, vertical movement occlusion group. *B*, vertical movement baseline group.

play, $p < .01$, and 15 of 16 looked longer at the broken display than at the final exposure of the habituation display, $p < .001$. Eight of 16 infants looked longer at the complete test display than at the final exposure of the habituation display, N.S. In the baseline group, 7 of 16 infants looked longer at the broken than at the complete display on the first test trial, N.S.

Discussion

The results of this study suggested that rigid translatory motion of a partly hidden object provides information about the object's unity, even if the object's visible parts undergo dissimilar proximal stimulus changes. Infants perceived a vertically translating rod as a single connected object, even though the light-reflecting areas of the rod changed in different ways during their movement.

The results also indicate that infants can perceive object unity from motion in a display in which the movement is accompanied by no lateral displacement. Unlike the motions in Experiments 1 and 2, the motion was not accompanied by any lateral movement of the rod's edges as its image shrank or expanded. The results of Experiment 3 therefore provide strong evidence that infants perceive objects by detecting real object motions that preserve object coherence, rather than by detecting some simple motion or other change in the images reflected to the eyes by an object's visible surfaces.

General Discussion

The findings of these experiments clarify and extend our understanding of infants' perception of the unity of partly occluded objects. The generalization supported by this research is that early perception of object unity depends on perceived motion, and that the class of effective motions includes, at least, the rigid translations of an object in three-dimensional space. The effective motions may be specified by very different sources of stimulus information: image displacement and visual pursuit, shifts in binocular convergence and disparity, image expansion and contraction. What all the effective motions have in common is that they preserve the rigidity and coherence of the moving object as it is displaced in the three-dimensional layout.

The informativeness of motion relationships in the early perception of unity has also been indicated in a different context: displays in which static contour and surface information are eliminated by the use of moving light points (Johansson, 1975). Infants seem to perceive a walking person specified by moving light points by 9 months of age and may extract some information about unity of the moving points as early as 3 months (Bertenthal, Proffitt, Spetner, & Thomas, 1985; Fox & McDaniels, 1982). Since most of this research has used complex animate motions, such as a person walking, the underlying perceptual principles and their relation to rigid motions have remained unclear. Recently, Kellman, von Hofsten, and Soares (1985) sought to test basic principles determining perception of rigid motion in depth (Börjesson & von Hofsten, 1973, 1975). They found that retinal motions of simple dot patterns that specify unitary translation in depth to adults are also effective for 4-month-olds. These results, along with the present research, suggest considerable generality of the principles linking motion relationships to infants' perception of unity.

It is not yet clear how inclusive is the class of coherent motions that functions in early object perception, especially during the first several months of life. Whether this class includes other rigid motions, such as rotations, or any nonrigid motions, such as jointed or elastic motions, will be treated in future reports (e.g., Kellman & Short, 1985).

While our experiments and related findings are very compatible with theories asserting considerable innate perceptual competence, they do not rule out some contribution of learning in the perception of objects. It is possible, for example, that infants learn during the first few months to perceive objects under conditions of occlusion. Nevertheless, the present experiments and their predecessors sharply constrain possible learning accounts. As we have argued elsewhere (Kellman & Spelke, 1983), the results of our experiments are not consistent with the claims of Piagetian theory or of major empiricist theories that infants learn to perceive objects through active manipulation. Four-month-old infants are not capable of effective reaching and manipulation, yet they are able to perceive the unity of partly hidden objects by detecting the objects' patterns of three-dimensional movement. Infants' abilities to perceive the complete shapes of partly hidden objects seem likely to depend on perceptual mechanisms or conceptions that are not products of learning.

The dependence of perceived object unity on perceived object motion may be an instance of "percept-percept coupling" (Epstein, 1982; Hochberg, 1974), since our results suggest that perceived unity does not depend on any single stimulus variable but on a single perceptual variable: perceived motion. Alternatively, it is possible that some more complex stimulus variable defined over relations in optical flow patterns (c.f. Lee, 1974) might encompass what currently seem to be various stimulus conditions leading to perceived unitary motion. If so, it would be possible for infants to perceive objects by detecting this variable directly. Whether object perception is direct or based on percept-percept linkages, there appears to be a concordance between the conditions under which motion is perceived and the conditions under which object unity and boundaries are perceived.

The findings of our research are consistent with the suggestion that early object perception is rooted in unlearned conceptions of the physical world (Kellman & Spelke, 1983; Spelke, 1985). If infants conceive the world as composed of things that are coherent and independently movable, then some class of coherent motions, rather than a particular stimulus variable, should be informative about object unity and boundaries. The present work suggests that this is indeed the case.

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