

Object and Observer Motion in the Perception of Objects by Infants

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Sixteen-week-old human infants distinguish optical displacements given by their own motion from displacements given by moving objects, and they use only the latter to perceive the unity of partly occluded objects. Optical changes produced by moving the observer around a stationary object produced attentional levels characteristic of stationary observers viewing stationary displays and much lower than those shown by stationary observers viewing moving displays. Real displacements of an object with no subject-relative displacement, produced by moving an object so as to maintain a constant relation to the moving observer, evoked attentional levels that were higher than with stationary displays and more characteristic of attention to moving displays, a finding suggesting detection of the real motion. Previously reported abilities of infants to perceive the unity of partly occluded objects from motion information were found to depend on real object motion rather than on optical displacements in general. The results suggest that object perception depends on registration of the motions of surfaces in the three-dimensional layout.

Recent research has revealed an early capacity for object perception that depends on the presence of changing stimulation. Kellman and Spelke (1983) found that human infants in the early months of life perceive the unity of a partly hidden object from certain motion relations of its visible surfaces. When the visible surfaces of a center-occluded object undergo a common lateral translation, infants perceive the partly hidden object as complete: They generalize habituation of looking time to an unoccluded complete object but dishabituate to a display consisting of the formerly visible surfaces separated by a gap. (These data are reproduced here in Figure 3a.) In contrast, infants at this age do not seem to perceive the unity of a partly hidden object in stationary arrays; after habituation to a stationary, center-occluded object, infants exhibit no preference between a broken and a complete object display (Figure 3b).

Perception of a complete object depends on a restricted class of informative motions. Infants show no evidence of complete object perception when the occluding and occluded objects share a common motion, when the visible surfaces of the partly occluded object undergo different motions, or when those surfaces undergo a rigid rotation with no translatory component, despite their high levels of attention to the occlusion display (Kellman & Short, 1985; Kellman & Spelke, 1983). Subsequent investigations have indicated that an object's unity can be perceived not only from lateral translation of its visible parts but

also from translation along any axis, including translation in depth (Kellman, Spelke, & Short, 1986).

These findings are subject to two different interpretations. On one hand, infants may perceive the unity of a partly hidden object by analyzing the three-dimensional motion of its visible surfaces. On this view, object perception would occur rather late in the course of visual analysis, after information about the three-dimensional arrangements and motions of surfaces has been obtained (see Marr, 1982). This account seems plausible because translatory motions along different axes give rise to different retinal changes; yet all specify the unity of an object to infants (Kellman et al., 1986). Alternatively, perception of the unity of a partly hidden object may depend directly on detection of changes in the optical array. Mechanisms sensitive to retinal image expansion/contraction and retinal image displacement may register common patterns of change in the projections of an object's visible surfaces; perception of continuous units may result from the registration of these patterns of change.

These possibilities can be distinguished experimentally, because retinal changes can arise from either of two sources: motion of an object or movement of the observer. When an observer moves laterally while viewing a stationary array, for example, objects at different distances displace differentially across the retina. If perceived unity depends on certain correspondences in the retinal displacements of the object's visible parts, however these are produced, then neither actual nor perceived motion of objects would be necessary determinants of object unity. Accordingly, in the present study we investigated infants' perception of objects during self-motion in order to determine whether their perception of the unity of an object depends upon registration of the real motion of its visible surfaces or upon the detection of the optical changes in the projections of those visible surfaces.

The possibility that object perception is based on detection of real motion raises issues regarding theories of perception.

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Rules of optical displacement specifying unity could be subsumed by direct perception theories (Gibson, 1979; Johansson, 1970), in that perception depends directly on relations in the transforming optic array. In contrast, perception of unity based on detection of objective motion, regardless of how it is specified, would be difficult to interpret this way, because a single pattern of objective motion will give rise to very different optical patterns, depending on the distance, orientation, and motion of the observer. If perceived unity depends on perceived motion, a more plausible account of object perception would be one that posited an intermediate representation of surfaces and their displacements (for discussion, see Epstein, 1982; Hochberg, 1974; Kellman, 1987; Spelke, 1987). As Rock (1977) has pointed out, explanations asserting the dependence of one perceptual outcome on another need not imply that this relation results from learning. Available evidence about perception of object unity from motion is consistent with its dependence on unlearned mechanisms (Kellman & Spelke, 1983).

The question of whether real or retinal displacement underlies early object perception is tied to another issue in perceptual theory: the question of visual position constancy. Since the analysis of Helmholtz (1885/1925), it has been argued that the perceptual meanings of optical displacements produced by motion of the self are indistinguishable to the inexperienced infant from those produced by moving objects. Only through extensive learning might an infant come to know that some displacements indicate moving objects while others indicate movement of the self, with visible objects remaining in a stable position. Helmholtz suggested that one basis for this learning is the reversibility of self-movement. A perceiver might learn to discount optical displacements that can be created and reversed by self-movements. Similar viewpoints have many adherents today (e.g., Wallach, 1985). If such a view is correct, then object perception might necessarily depend on retinal displacement early in life.

A different theory of the origin of the ability to distinguish object and observer motion has been proposed by Gibson (1966, 1979). According to Gibson, the transforming optic array provides information about whether it is an object, the observer, or both that are moving. For example, uniform retinal motion of all parts of the visual field almost never arises from motion of the environment but arises commonly from rotation of the eye in its orbit. Because the variables relevant to distinguishing object and observer motion depend on enduring properties of the ecology and the visual system (such as the axes of eye and head movements), evolution may have furnished mechanisms for detecting them. On this view, retinal displacement arising from object motion should be perceptually very different from that arising from observer motion, even early in life.

Outside of the present work, we know of no research that has investigated infants' ability to perceive a stable world during their own motion. It is clear from a number of studies that infants can perceive motion when they are stationary (see Gibson & Spelke, 1983, for a review), but whether the infant's perceptual world appears stable or shifting during self-motion is unknown. Concerning this aspect of William James's "blooming, buzzing confusion," research on infant perception so far has had little to say.

One final issue closely related to both position constancy and motion-carried information about objects concerns multiple stimulus conditions for the perception of motion. Adults perceive motion under a variety of stimulus conditions including image displacement, optical expansion/contraction given by an object translating in depth, displacement of one object relative to another, and others. A particularly interesting situation arises when a moving observer detects a moving object, because the observer must at once use information about self-movement, about the stationary parts of the environment, and about the moving object (Gibson, 1979; Shebilske, 1977; Wallach, 1985). For adults, object motion can be detected even when the observer moves so as to maintain a constant relation to the object. In this case, real motion of the object is perceived despite the absence of any image displacement. Both recent and traditional empiricist theories of perception suggest that humans must learn the multiple cues for motion perception, especially by coordinating object manipulation and self-movement with visual experience (Harris, 1983; Helmholtz, 1885/1925; Piaget, 1954; Wallach, 1985). From the Gibsonian view, however, relations in optical stimulation indicate the motions or unchanging positions of objects, even during movement of the observer, without learning (Gibson, 1979; Johansson, 1970, 1984; Lee, 1974).

In the present research, we investigated the relation of object perception and motion perception by focusing on two questions: (a) Does early perception of object unity depend on the real motion of an object through the spatial layout or on the displacement of its image in the visual field? (b) Do infants distinguish the optical effects of displacements of an object and of the observer, perceiving object motion only in the former case? We addressed these questions in two conditions in which infants moved while viewing partly occluded displays. The former question was assessed by habituating moving infants to partly hidden, stationary, or conjointly moving objects and measuring dishabituation to unoccluded complete and broken objects. Greater dishabituation to the broken object was taken to indicate perception of unity in the initial display. Perception of motion was assessed by comparison of infants' spontaneous looking times to events in which they moved around a center-occluded object that was stationary (producing retinal displacement) or that moved conjointly with them (producing no subject-relative displacement). Consistent differences in duration of attention to moving and stationary objects have been found in a variety of contexts (Carpenter, 1974; Volkman & Dobson, 1976). In our experiments, infants typically look 2–3 times longer when a center-occluded object moves than when it is stationary (Kellman & Spelke, 1983; Kellman et al., 1986; see Table 1).

Method

Subjects

Thirty-two full-term infants ranging in age from 108 to 127 days ($M = 118$ days) were tested, with 16 infants in each of two conditions. An additional 14 infants did not complete the experiment because of fussiness (9) or equipment failure (5).

Table 1
Habituation and Test Trial Looking Times (in Seconds) and Ranges in Occlusion Studies With Stationary and Moving Displays

Group	Source ^a	Habituation trials		Test trials	
		<i>M</i> look	Interquartile range	<i>M</i> look	Interquartile range
Stationary displays					
Rod occlusion	(1), Exp. 2	7.8	4.3–8.4	5.3	3.2–5.8
Rod occlusion ^b	(1), Exp. 3	6.6	3.8–10.4	6.9	2.2–6.5
Unoccluded rod	(1), Exp. 2	8.0	4.5–7.6	7.1	2.6–6.3
Occluder movement ^c (stationary rod displays)	(1), Exp. 5	—	—	3.6	2.4–4.5
Observer Movement	(4)	5.8	3.7–6.4	5.4	3.7–7.1
Moving displays					
Lateral translation	(1), Exp. 1	25.3	10.6–38.9	20.6	6.6–27.5
Lateral translation of rod and occluder	(1), Exp. 5	14.5	6.2–18.1	13.4	6.7–14.4
Vertical translation	(2), Exp. 3	9.1	4.6–12.8	11.7	4.9–13.1
Depth translation	(2), Exp. 2	18.2	7.4–23.7	9.9	5.6–10.0
Frontoparallel rotation	(3), Exp. 1	24.2	10.1–28.8	9.9	5.8–11.9
Conjoint movement	(4)	12.8	8.3–16.0	11.1	5.6–12.8

Note. Exp. = Experiment.

^a Sources: (1) = Kellman and Spelke (1983); (2) = Kellman, Spelke, and Short (1986); (3) = Kellman and Short (1985); (4) = Kellman, Gleitman, and Spelke (1987), present article.

^b In this condition, the habituation display was identical to the rod occlusion display above; the only difference from that condition was that the broken object test display in this condition contained smaller pieces.

^c Habituation data are omitted because the display contained a moving occluder.

Displays and Apparatus

The habituation display in both conditions was a long, narrow object whose center was occluded (see Figure 1). The partly hidden object was a black dowel rod, 40.6 cm long and 1.3 cm in diameter, and the occluding object was a tan block—7.6 cm high, 76 cm wide, and 2.5 cm thick. The rod was 21.6 cm in front of the background and 14.6 cm behind the block. At the infant's viewing distance (68.6 cm to the rod), the block subtended visual angles of 8° (height) and 70.3° (width), while the rod subtended 33° (length) and 1.1° (width). There were two test displays shown with no block present. The complete test rod was the same as in the habituation display, and the broken test rod consisted of two 17.1-cm pieces, separated by a 6.4-cm gap where the occluding block had been.

All displays were presented in a rectangular display case, 51 cm deep, with a front opening 69 cm (width) × 61 cm (height). The back panel was 90 cm from the observer in the central position along the subject's arc of movement (see *Design and Procedure* section.). Rod displays extended from the back panel of the display case by means of 3-mm diameter, rigid metal rods, painted the same color as the background. The block was supported from the sides of the display case. Illumination was provided by two vertical 58-cm long 20-W fluorescent lights placed in the front corners of the display case and kept from the subjects' direct view by 5-cm wide wooden strips placed in front of them. Display presentation was controlled by a motor-driven curtain that opened and closed between the subject and the display box.

In both experimental conditions, subjects were seated in a chair that moved. In the observer movement condition, the subject's chair was moved back and forth 47.7 cm along an arc around a point 30.5 cm away (see Figure 2a). (In terms of lateral movement parallel to the occluding block and the display background, the subject moved 43 cm.) The subject was moved at a rate of about 12 cm/s. The display was arranged so that during the observer's movement the relative retinal

displacement between the occluding block and the rod, and also between the rod and the background, matched exactly the corresponding relative displacements in a previous experiment (Kellman & Spelke, 1983, Experiment 1) where stationary observers viewed a moving rod. Specifically, during a half cycle of observer movement, the difference in retinal displacement between the projections of the rod and the occluding block, and also between the projections of the rod and the background, was 8.9° of visual angle. In the conjoint movement condition, there was a rigid connection, not visible to the infant, between the occluded rod and the infant's chair. The hidden connecting bar pivoted around a point between the infant and the object, so that there was virtually no subject-relative motion¹ by the rod (see Figure 2b). The subject's chair was moved 38.1 cm along an arc around a point 30.5 cm away (lateral displacement 35.6 cm), at about 12 cm/s. (This extent of movement was slightly less than in the observer movement condition, due to apparatus limitations when the display objects and the infant chair were rigidly connected.) The partly occluded rod moved rigidly with the infant, around a pivot point 30.5 cm from the infant and 38.1 cm from the object.

The moving chair was a standard infant chair resting on wheels atop a wooden platform. A vertical metal bar, rigidly attached to the bottom

¹ By "subject-relative movement" we refer to movement initiated by the experimenter that changes the relation between the observer and an object. We do not mean to imply that there are no other eye or head movements by the subject (although the seating arrangement precluded large head movements). Self-produced movements, such as visual pursuit of some stationary object, do not change the logic of the experiment. As in the case of retinal displacement, the question with pursuit movements is whether they arise from object motion or observer motion, and whether, in these two cases, the perceptual consequences are different.

of the chair, extended downward through an arc-shaped hole in the platform. Subjects were moved by hand via a long metal handle, located beneath the seating and display areas, that was rigidly attached to the bar extending from the infant chair. This handle extended beyond the back of the display case and rotated around a point between the chair and the display. Movement of the display objects along with the chair was achieved in the conjoint motion condition by rigid attachment, behind the display case, of the handle and the support rods holding the display objects by means of another vertical bar. Timing of the movement was practiced by the display mover with a metronome before the experiment. The display mover could not see the subject at any time.

Design and Procedure

Subjects in both conditions were habituated to the partly occluded rod display and tested afterwards with the broken and complete rod test displays shown three times each in alternation. Sixteen subjects in the observer movement condition were moved back and forth while viewing stationary presentation of these displays in both the habituation and test periods. In the conjoint movement condition, 16 subjects were also moved back and forth, but the rod displays moved to compensate for the observer motion in both the habituation and test periods.

Each subject was tested individually. On each trial in the experiment, a curtain opened to reveal the display, and the subject movement was begun. After an initial 0.5-s look, the trial continued until the subject looked away for 2 continuous seconds, at which time the curtain closed. A trial was also terminated if the infant was still looking after 120 s, which occurred very rarely. The intertrial interval was 7 s, not including 1.5 s each required for closing and opening of the curtain.

In the habituation period, repeated presentations of the partly occluded display continued until a criterion 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 whose total looking time was less than or equal to this value. If looking time on the first three trials was less than 12 s, the criterion was based on the first three trials for which total looking exceeded 12 s. After the criterion was met, the block was removed, and infants saw the two test displays in alternation three times each. Test displays were changed during the intertrial interval; half of the subjects saw the complete rod first in the tests. Test displays always had the same movement characteristics as the visible parts of the partly hidden object in the habituation period. In all other respects, test trials were identical to habituation trials.

Looking times were recorded by two observers using push-button inputs to a computer and viewing subjects through holes in the pegboard background. The computer determined the ends of trials and of the habituation period from the button pushes of one observer who was designated as the primary observer. The computer also calculated inter-observer agreement, which averaged .93 and ranged from .83 to .99. The primary observer decided whether to suspend or terminate an experimental session if an infant became fussy. Observers were unable to see the display objects and were not told which display was being presented.

If an infant became fussy during the first three trials, the experiment was stopped for several minutes and was begun anew if possible. If the infant became fussy 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. No subject had more than one break during the habituation period. If the infant became fussy during the test trials, the session was ended and the subject was replaced.

Dependent Measures and Data Analyses

Motion perception was assessed from overall looking times during the habituation and test periods. Looking times in the two conditions were compared with each other and with those obtained in previous experiments, in which stationary infants were shown either stationary or moving rod displays. Perception of object unity was assessed from infants' looking times to an unoccluded complete rod and broken rod after habituation to the partly hidden display. Dishabituation (recovery of looking time) to the broken display but not to the complete display was taken to indicate perception of object unity.

Results

Perception of Motion

The observer movement group showed a pattern of looking times in the habituation and test periods characteristic of those previously obtained with stationary observers viewing stationary rod displays and quite different from those obtained with moving rod displays (see Figure 3c). Table 1 shows the mean habituation and test trial looking times, along with interquartile ranges, from nine previous studies with moving and stationary displays using identical or very similar display objects. The two groups in the current study were statistically compared with the most comparable stationary and moving object groups from previous research (which viewed the same rod displays with stationary observers), labeled "rod occlusion" group and "lateral translation" group in Table 1. (Comparisons with other stationary and moving groups yielded similar results.) The observer movement group did not differ from the previous stationary rod group in looking time per habituation trial, first-trial looking time, or total looking time on the test trials, all $t_s(30) < 1.18$,

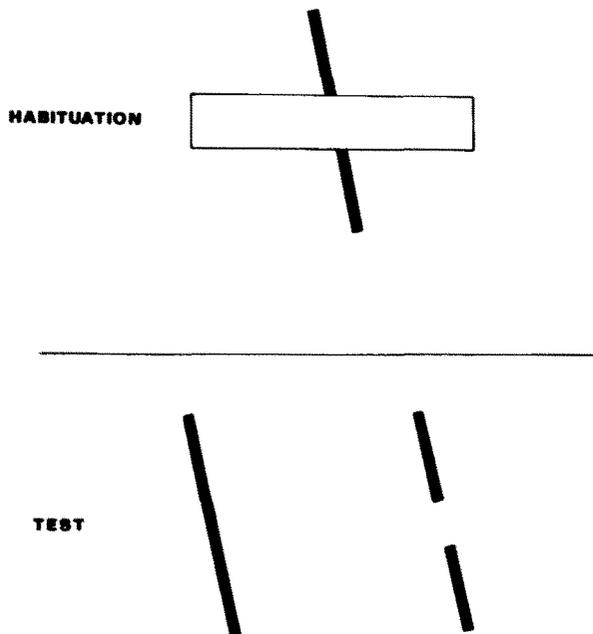


Figure 1. Habituation and test displays in the experiment: The upper portion of the figure depicts the partly occluded rod shown during habituation; the lower portion depicts the complete and broken rod test displays shown on alternating test trials after habituation.

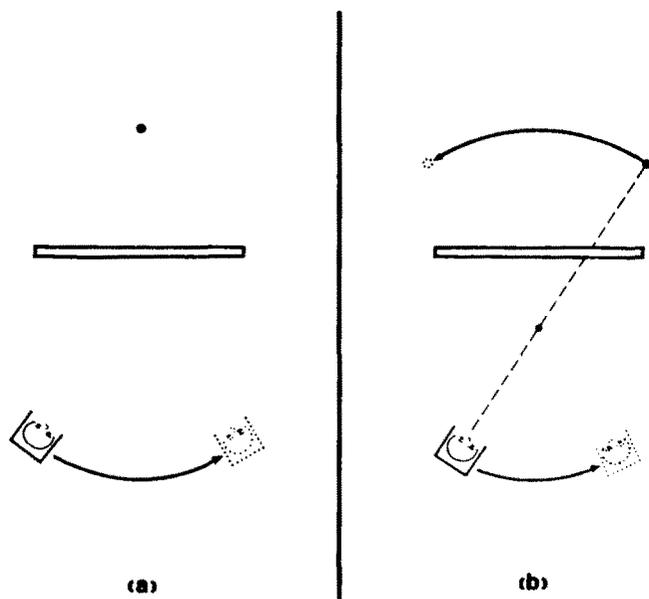


Figure 2. Display conditions in the experiment. Panel a: Observer movement condition. Panel b: Conjoint movement condition. (Top views of the object and observer positions at one extreme of movement are shown, with positions at the other extreme shown by dotted figures.)

ns. The observer movement group was far lower on all of these measures than the previous lateral movement group, all $ts(30) > 3.17$, $p < .005$. In contrast, looking times by the conjoint movement group were 2–3 times higher than in the observer movement group (Figure 3d). The conjoint movement group reliably exceeded the observer movement group in mean length of looking per habituation trial, $t(30) = 3.91$, $p < .001$; first habituation look, $t(30) = 3.11$, $p < .005$; and total looking time on the test trials, $t(30) = 2.83$, $p < .005$. The conjoint movement group also reliably exceeded the previous stationary group on all of these measures, all $ts(30) > 2.28$, $p < .025$. However, looking times in the conjoint movement group were not as high as in the previous lateral movement group, all $ts(30) > 2.14$, $p < .025$. This latter finding may indicate that both subject-relative and object-relative components of real motion may be related to infant's interest in motion.

The differences between the observer movement and conjoint movement groups held for individuals as well as for the group averages. As Table 1 shows, there was little overlap between the distributions of looking times per trial in the habituation period or in the test trials for subjects in the observer movement group and the conjoint movement group.

Perception of Object Unity

Infants in the observer movement group, like those previously studied in the rod occlusion group, did not respond in the test trials as if they had perceived the partly occluded object as complete. They looked equally at the broken and complete test displays, dishabituating somewhat to both. In contrast, infants in the conjoint movement group showed strong evidence

of complete object perception. They dishabituated to the broken test rod and not to the complete test rod.

These observations were confirmed by the analyses. The dishabituation data were analyzed by a two-way (Group \times Test Display) analysis of variance. There was a reliable main effect of test display, $F(1, 30) = 14.54$, $p < .001$, and a reliable Group \times Test Display interaction, $F(1, 30) = 14.42$, $p < .001$. Subsequent individual comparisons showed that there was no difference in dishabituation to the broken and complete displays by the observer movement group, $t(15) = 0$, *ns.* That group dishabituated somewhat to both test displays; when tested against the hypothesis of zero dishabituation, both $ts(15) > 2.50$, $p < .025$. The findings of no difference in dishabituation to the broken and complete displays, and some dishabituation to each, indicate neutrality about the hidden parts of the initial display (see Kellman & Spelke, 1983). In the conjoint movement group, dishabituation to the broken display exceeded dishabituation to the complete display, $t(15) = 4.16$, $p < .001$. Dishabituation to the complete display did not differ from 0, $t(15) = .28$, *ns.*, whereas dishabituation to the broken display exceeded 0, $t(15) = 5.06$, $p < .001$, and exceeded dishabituation by the observer movement group to either test display, both $ts > 3.01$, $p < .005$. Analyses of looking times over the three test trials taken together in all cases revealed the same patterns as the first-trial data.

The dishabituation patterns were characteristic of individual subjects as well as the group averages. Fourteen of 16 infants in the conjoint movement group looked longer at the broken test display than at the complete display (all more than twice as long), $p < .01$ (binomial test), while only 8 of the 16 infants in the observer movement condition looked longer at the broken display.

Discussion

Our findings suggest that infants are capable of position constancy, that infants perceive object motion while they themselves are in motion, and that infants use the perceived motions of surfaces as information for the unity of partly hidden objects. We consider each suggestion in turn.

First, the analysis of looking times in the observer movement condition provides evidence that infants perceive an object as stationary when its optical displacement relative to them and to other objects results from their own motion. The looking times shown by the observer movement group were in all respects comparable to previous groups viewing stationary rod displays from a stationary position and different from the levels shown to moving objects. These results suggest position constancy; subjects did not respond to large subject-relative and object-relative displacements given by their own movements as they respond to these same displacements when given by moving objects. To our knowledge, the present study is the first to investigate the capacity for position constancy in prelocomotor infants. In contrast to the claims of many theorists (Harris, 1983; Piaget, 1954; Wallach, 1985), it suggests that position constancy does not develop as a consequence of the acquisition of independent locomotion but rather predates that acquisition.

Second, the analysis of attention levels in the conjoint movement condition furnishes evidence that infants perceive real ob-

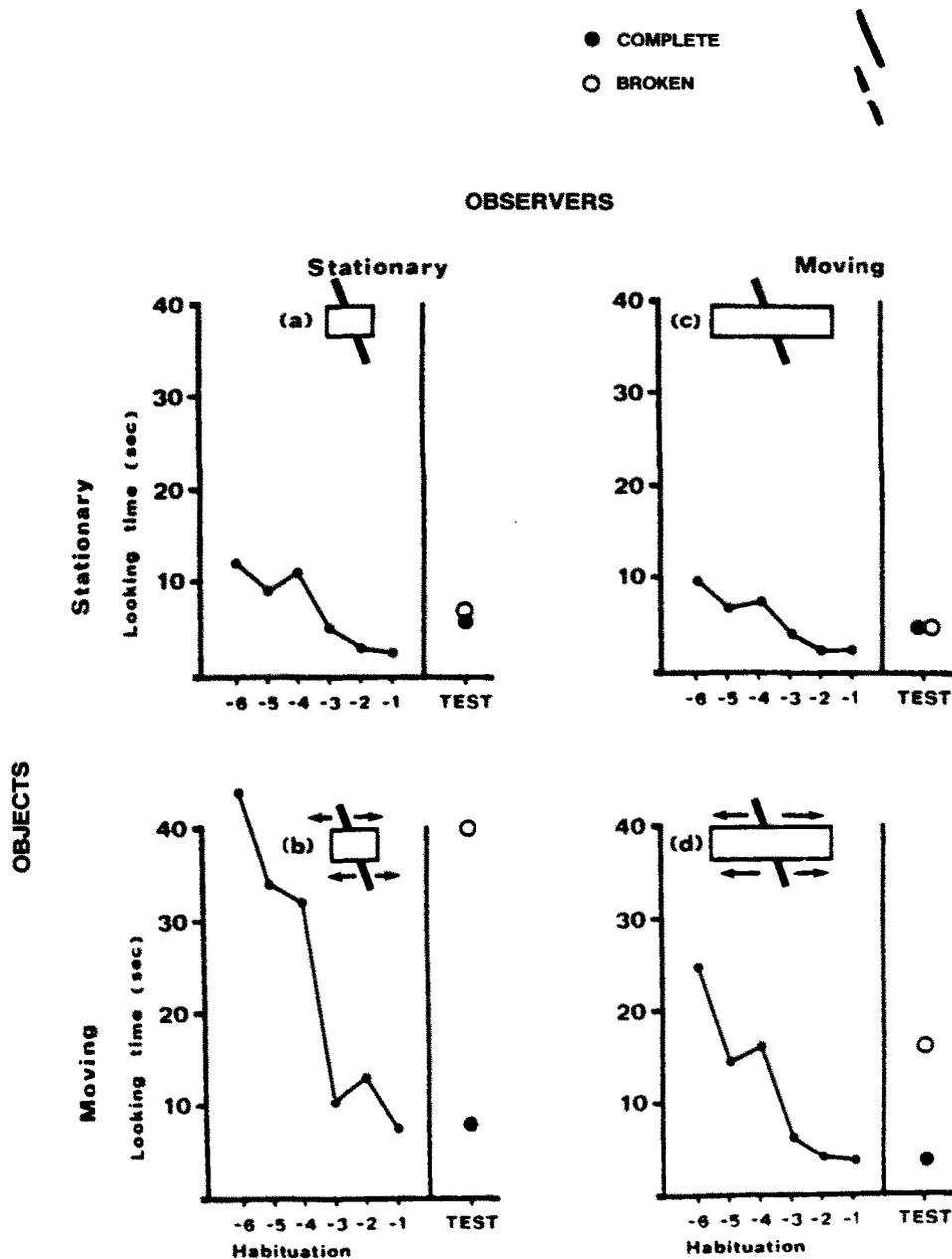


Figure 3. Looking times during the habituation and test periods. Panel a: stationary object and observer, data from Kellman & Spelke (1983). Panel b: stationary observer, moving object, data from Kellman & Spelke (1983). Panel c: observer movement condition (moving observer, stationary object). Panel d: conjoint movement condition (moving observer, moving object). (Backward habituation curves are displayed, showing looking times on the final six habituation trials. Test trials consisted of alternate presentations of broken and complete rod displays that had the same movement characteristics as the rod parts visible during the habituation period.)

ject motion during self-movement. Looking times were much higher in the conjoint movement condition than in the observer movement condition and higher than those found in previous studies with stationary displays and observers. Motion seems to have been detected in the conjoint movement condition, despite the absence of any subject-relative motion. This finding adds to

the evidence that young infants perceive object motion under a variety of stimulus conditions (Kellman et al., 1986).

Both the evidence for position constancy and the evidence for motion perception during self-movement indicate that young infants are sensitive to relations in optical flow patterns. Because the subject's movement was not self-produced, position

constancy here seems likely to have been based on optical information specifying movement of the self (Gibson, 1979), although vestibular information could have played a role.

Detection of both the stationary and the moving rod in the two conditions may also implicate accurate distance perception (cf. Gogel, 1981, 1982) because the extent of retinal displacement of a stationary object during observer movement depends on the object's distance. It remains possible, however, that motion and stability were detected in some other way, not requiring registration of distance and self-motion.² Further research to address these issues would be desirable.

Most important, the experiment provides evidence that infants perceive the unity of a partly hidden object by detecting the object's real motion, not by detecting changes in its retinal projection due to movement of the infant. The infants in the conjoint movement condition dishabituated to a broken rod after viewing the partly hidden rod, despite the absence of subject-relative motion in that condition, suggesting that subject-relative optical changes are not necessary for complete object perception. In contrast, the infants in the observer movement condition showed no differential dishabituation, suggesting that such optical changes are not sufficient for complete object perception. The absence of complete object perception in the observer movement group is not explainable as a failure to attend to relevant information. At the levels of looking time observed in this study, infants have been shown to attend to the visible surfaces of a partly occluded object and to discriminate changes in those surfaces (Kellman & Spelke, 1983). It appears that for infants at this age, perception of the unity of an object depends on registration of the perceived motions of surfaces through the layout.

Perception of the unity of partly occluded objects thus seems not to depend on a particular stimulus variable such as retinal displacement or even differential displacements relative to the projections of other objects and surfaces.³ Perception of object unity would appear to be at least a two-step process, in which infants first detect the objective arrangements and motions of surfaces and then group together surfaces undergoing a common objective motion. The organization of the visual world into objects would seem, at least in some situations, to depend on the results of other visual processing (cf. Epstein, 1982; Hochberg, 1974; Marr, 1982). Indeed, it may depend on mechanisms that are quite central (see Spelke, 1987).

It is perhaps surprising to discover that infants' perception of objects could depend on detection of relations in real motion rather than on more easily definable retinal relations. This dependence may be less surprising from the standpoint of the ecological validity of these different sources of information. Detection of correspondences in real motion may have greater ecological value as an indicator of object boundaries than do relations in retinal displacements. During movements of the head or body, parts of the visual field that are equidistant from the observer share a common retinal displacement, different from the displacements of areas at other distances. Equidistant, partly hidden surfaces may often be connected, but equidistance is neither a necessary nor a sufficient condition for unity. In contrast, a principle of unity perception based on common real motion in space usually leads to correct specification of the

unity and boundaries of objects. Visible surfaces seldom move rigidly together unless they are connected (although sometimes the connection is temporary, as when a hand holds a cup). If the full range of adult object perception abilities develops from more restricted early foundations, it would make sense for the latter to depend on information of highest ecological validity.

The present findings, and related work (e.g., Kellman, 1984; Kellman & Spelke, 1983), are inconsistent with traditional and persisting claims that the development of visual perception requires either a long learning period or information from coordinated motor activity (Harris, 1983; Helmholtz, 1885/1925; Piaget, 1954; Wallach, 1985). The infants in our study were not yet capable of crawling or of reaching for objects; thus, they could not learn to perceive objects and motion by locomoting around objects or observing the consequences of object manipulation. Nevertheless, the infants were able to perceive the motion and unity of a moving object and the stability of a stationary object during their own motion. Although it is conceivable that human infants learn, in the first few months, to interpret motion patterns, such learning would seem to presuppose considerable initial capacity for encoding complex optical transformations.

² For example, any head movements with a vertical component could in theory provide information about the objectively moving parts of the array because the combination of the horizontal and nonhorizontal components of motion for a laterally moving object could not arise from an object in any stationary position. However, scoring of videotaped records of all subjects indicated that such head movements hardly ever occurred in this apparatus. Another possibility is that in the conjoint condition, the depth ordering of the block, rod, and background indicated by occlusion differed from their ordering as indicated by optical velocities. Such a difference between these two types of ordering relations could potentially indicate that at least one object is moving, without employing information about absolute distance or any information about self-motion. We thank Martin S. Banks for raising many of these issues and pursuing them with us in subsequent discussions.

³ It remains possible that some more comprehensive stimulus variable in changing optical stimulation directly specifies unitary motion under the conditions we have studied (cf. Lee, 1974), although no such variable has yet been described. If so, perceived unity might not depend on detection of motion per se but on certain optical changes that normally occur only when objects move.

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