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Kinematic Foundations of Infant Visual Perception

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> *If asked what aspect of vision means most to them, a watchmaker may answer "acuity," a night flier "sensitivity," and an artist "color." But to animals which invented the vertebrate eye, and hold the patents on most of the features of the human model, the visual registration of motion was of the greatest importance.*
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> —Walls, 1942, p. 342

Only mobile organisms have elaborate perceptual systems, and their functions are tied to motion in multiple ways. The most obvious importance of registering motion involves the detection of moving things, which may pose danger, offer nutrition, and so on. No less important is the registration of self-motion: the use of optical information to guide locomotion and other activities. In recent years, another central role of motion has been recognized and elaborated, most clearly in visual perception: The motions of objects and observers furnish information about persisting properties of the environment, such as objects and spatial layout (J. J. Gibson, 1966, 1979; Johansson, 1970; Johansson, von Hofsten, & Jansson, 1980). Information given by spatiotemporal changes or *kinematic* information has been argued to be central in mature perception because of its greater accuracy in specifying properties of the environment, and because perceivers seem specially equipped to utilize it (Braunstein, 1976; J. J. Gibson, 1966, 1979; Johansson et al., 1980). In this chapter, I connect these notions of the primacy of kinematic information about objects and events with a conjecture about the development of visual perception: Kinematic information may be fundamental to the earliest perceptual capacities. The initial abilities of human infants to perceive objects, spatial layout, and events may depend predominantly on information carried by spatiotemporal patterns. After elaborating this thesis, I evaluate it by examining research in three areas: perception of the unity and boundaries of objects, perception of three-dimensional form, and perception of motion and stability by moving observers.

Traditionally, students of visual perception have pondered how knowledge of the world might be obtained from momentary images projected to the eyes. Changes in stimulation given by motion and events were often considered as complexities compounding the already difficult problem of interpreting images. The past two decades have witnessed something of a reversal in this characterization in perceptual theory. Some theorists, especially J. J. Gibson (1966, 1979) and Johansson (1970), have gone so far as to suggest that temporal and spatiotemporal variation in the optic array is most fundamental to perception. From this characterization of perception as *event perception,* information in static optic arrays (purely spatial variation) is considered a limiting or degenerate case.

Two related ideas are central to an event perception perspective. One is that information carried by motion has, in principle, greater power to specify properties of objects, space, and events than purely spatial (static) information. The second is that perceptual systems are specially adapted to utilize such information. Regarding the first claim, mathematical analyses have indicated the richness of optical change information about spatial layout, object structure, and particular events (Koenderink, 1986; Lee, 1974; Longuet-Higgins & Prazdny, 1980; Nakayama & Loomis, 1974). Optical transformations can specify unequivocally the rigidity or non-rigidity of a scene, the three-dimensional (3-D) layout of surfaces and the forms of objects. Events, such as the motion of an observer through an environment or the approach of an object, are also specified by information available in transforming optic arrays. Although the linkages between available information and aspects of spatial layout and events depend in every analysis upon certain assumptions, these assumptions are often satisfied in ordinary perception and, moreover, can in some cases be verified by other available optic flow information (e.g., Lee, 1974; Longuet-Higgins & Prazdny, 1980). Brunswik (1956) used the phrase *ecological validity* to refer to the accuracy, in ordinary circumstances, of the relation between perceptual information and facts about the environment. In terms of ecological validity, a strong case has been made that spatiotemporal information is generally superior to information available in momentary projections (Braunstein, 1976; J. J. Gibson, 1966; Hochberg, 1974). J. J. Gibson's use of the term *ecological* (1966, 1979), as in *ecological optics,* is both different and related. It refers to the ways in which the physical world structures energy; such structured energy (e.g., the optic array) carries information specific to the environment producing it. Brunswik's notion, a grading of the value of various information sources, is more neutral with regard to the origins of information. Much of the importance claimed for kinematic information in perception depends on the connection between Gibson's and Brunswik's notions of ecology. If spatiotemporal patterning in the optic array carries information specific to the structure of the environment, this information is part of ecological optics in Gibson's sense and has high ecological validity in Brunswik's sense.

Evidence that kinematic information about the environment is not only available in principle but actually utilized in ordinary perception has also accumulated rapidly, both in psychophysical and psychobiological investigations. The study of perception of structure from motion (SFM) has become a central area of research in visual perception (Braunstein, 1976; Johansson, 1970; Rogers & Graham, 1982; Ullman, 1979). Kinematic information comprises some of the most effective bases for structural properties of the environment, such as relative depth and surface layout (Braunstein, 1976; J. J. Gibson, Kaplan, Reynolds, & Wheeler, 1969; Rogers & Graham, 1982) and perception of 3-D form (e.g., Todd, 1982; Wallach & O'Connell, 1953). Information in optic flow has also been shown to be effective and precise in specifying events, such as an observer's motion through the environment (Warren, 1976) and the time to contact between an observer and an object (Lee, 1974).

Evidence for physiological specialization has also emerged. The possibility of neural circuits specifically designed to detect properties of optical change has been suggested by both psychophysical experiments in humans and receptive field mapping in other species (Regan & Beverly, 1978; Regan & Cynader, 1979). Results reported by Allman, Miezin, and McGuinness (1985) raise the possibility that a large number of cortical cells previously thought to have classical (local) receptive fields actually respond better to relative motions involving both local and more remote regions of the retina. Such findings may ultimately lead to the positing of certain optical transformations, as opposed to static dots, edges, and corners, as the basic neurological "vocabulary" of visual perception.

Event Perception and Early Perceptual Competence

A number of theorists have suggested a relation between spatiotemporal information and the evolution of perceptual systems (E. J. Gibson, 1984; J. J. Gibson, 1966; Johansson, 1970; Marr, 1982; Shepard, 1984). The linkages between objects, spatial layout, and events in the world on one hand, and spatiotemporal changes in optic array on the other, depend on the basic geometry of space and time. For example, the projective changes given by a rigid, rotating 3-D object are determined by projective geometry, along with some basic physical constraints (e.g., light moves in straight lines; objects tend to be opaque). The specificity of this relationship is such that, given a few ecologically plausible constraints, the 3-D form of an object is recoverable from the information in optical transformations (Ullman, 1979). Because such relationships are rooted in basic aspects of the ecology, it is plausible that they have been exploited in the evolution of perceptual systems. For example, Johansson (1970) suggested that the visual system might have evolved to be a "perspective decoder," detecting objects from optical transformations by the rules of projective geometry.

Compatible with such evolutionary hypotheses is a developmental one. Kinematic information—information given over time by motion—may be fundamental in perceptual development. An evolutionary origin already suggests that such perceptual abilities, subserved by specialized perceptual mechanisms, might operate without learning. The developmental hypothesis intended here goes further in suggesting that kinematically based abilities appear earliest in development and constitute the primary source of meaningful contact with the environment in the early months of life. An evolutionary origin need not imply developmental primacy; mechanisms sensitive to kinematic information might arise by maturation after others already operate. The developmental hypothesis that kinematic information is fundamental requires an additional rationale.

Ecological Validity and Risk Aversion

Adult perceivers use information from a variety of sources, each having different informational validity. As Berkeley (1709/1963) made clear, information about 3-D space that is present in a single, momentary image is ambiguous. Yet it can hardly be denied that monocular spatial information plays some role in perception. Pictorial cues, such as the depth indicated by two converging lines (linear perspective), might sometimes be misleading (as when the lines are not really parallel in 3-D space) but can be shown to operate in the absence of other information. The Ames room and Ames window (Ames, 1951) are dramatic examples. Wallach (1985) has argued that any stimulus variable that correlates to some degree with depth will come to function as a depth cue, and he has documented some surprising examples of this hypothesis.

These cues, which generally have lesser ecological validity, are in most cases readily overridden by kinematic or stereoscopic information (Braunstein, 1976; J. J. Gibson, 1966; Wallach & O'Connell, 1953). The existence of multiple information sources in adult perception differing in their conditions of availability and their ecological validity might be viewed in terms of optimization. When the most reliable information is not available, it is better to have information of some validity than no information at all. This would be especially true in situations demanding prompt responses; obtaining the best possible description of the environment under a given set of perceptual circumstances may be preferable to perceiving an indeterminate reality.

For perceivers in the early months of life, the situation may differ radically. Relative to adult perceivers, infants' perception might serve best by being *risk-averse*. This conjecture would make sense if the functional role(s) of perception in early development differ from that later in life. During the earliest months of life, an infant's perceptual capacities may serve mostly to underwrite his or her

cognitive development. Learning about the properties of the environment, about the objects and people it contains, developing conceptual categories, and so forth, may be primary (cf., Mandler, 1988). Perceptual abilities initially serve at most a modest role in helping a person avert danger, acquire nutrition, and move safely through the environment, because early locomotor abilities are minimal. To use a somewhat non-ecological example, compare an infant lying in a crib and an adult driving a car. When something moves in the visual periphery, it is less important for the infant's perceptual system to deliver a plausible description of it than it is for the adult's, because there is little the infant can do to react. For the adult, the need for rapid reaction or further exploration may be urgent. Moreover, errors would have different significance. The momentary classification by an adult of a moving blur in the periphery as an oncoming car rather than a fly, may be relatively insignificant (and easily corrected). Correcting an error may be easier for adults because further perceptual-motor activity can reveal (or repeal) a misperception. Infants are less mobile, have shorter attention spans, have inferior sensory resolution, and are capable of using only a subset of the information sources available to adults. As a result, infants' errors may often go uncorrected. Even in cases where additional information becomes available, an error might be relatively more consequential for an infant, who may not know whether or not cars ever turn into houseflies. Misperceptions might have deeper implications in infancy.

This line of reasoning suggests that the basic perceptual capacities of infants should be those with the least possibility to mislead, that is, those with the highest ecological validity. The fact that much of the world may appear indeterminate or ambiguous early in life is not of primary importance. More crucial is that those aspects of the world that *are* perceived be perceived with high accuracy. It is in this sense that infant perception may be risk-averse.

As noted earlier, information defined by spatiotemporal changes is in general a more valid indicator of environmental circumstances than information in static arrays. Thus, risk aversion in early perception leads to the hypothesis that kinematic information might underlie the earliest perception of objects and spatial layout.

Although plausible, there are reasons why this hypothesis could be false. First, very young infants do not move through environments as much as adults, and they do not produce coordinated, self-initiated movements in the earliest months. Perceptual systems dependent on kinematics might lie dormant during too many of an infant's waking hours. Second, although the importance of kinematic information in adult perception has been amply demonstrated, the relevant perceptual abilities might be due to learning. Helmholtz (1909/1962), for example, was well aware of the importance of motion parallax in mature perception, and of differing consequences of observer motion and object motion. Yet, his view was that the use of optical changes to specify properties of the world required extensive learning, probably the connecting of visual experience with tactile experience. Piaget (1954) argued that the interpretation of visual stimulation depends on associating visual changes with self-initiated movement or action (cf. Held & Hein, 1963). The existence of basic physical and geometric regularities that could have been exploited by evolution does not guarantee that they are, in fact, built into perceptual systems.

The question of kinematic foundations of visual perception is, then, an empirical one. But it is one about which we are learning a great deal. Research over the past two decades suggests that kinematic information may underlie much of perceptual development. In this chapter I describe some of this research in several areas of object and space perception. Beyond describing these kinematic foundations of perception, there are several more specific goals. First, the role of kinematic information appears to differ in various perceptual domains. It is useful to consider these differences (e.g., the equivalence or non-equivalence of object and observer motion) in understanding particular perceptual abilities. Second, we show that the category of kinematic information may itself include information sources of differing ecological validity. Considerations of validity may help us to understand developmental patterns even within this category of information. Finally, these varieties of kinematic information have important consequences for perceptual theory. Some, but not all, cases are compatible with the idea from direct theories of perception that optical information is directly linked to perceptual outcomes, without mediation by inference or intermediate levels of representation.

PERCEPTION OF OBJECTS: UNITY AND BOUNDARIES

One of the most crucial aspects of the descriptions of our environment delivered by perceptual processes is the division of the perceived world into objects. The most basic, even defining, aspect of object perception is determining object unity and boundaries. The world perceived visually is neither an unbroken canvas of sensory qualities nor a 2-D array of millions of separate points at minimally distinguishable locations. It is instead a world of objects and surfaces. Within any one such object or surface, there is internal connectedness. Each is also bounded or separated from other objects and surfaces. Segmentation of the visual world is successful insofar as perceived units correspond to functional units in the world; that is, areas seen as unified tend to persist as physical units, to move together, and to maintain their shape, size, and other properties.

A basic problem in determining object unity and boundaries in the 3-D world is the problem of occlusion. In ordinary environments, most objects are partly hidden behind other objects. How can the visual system determine in occluded arrays which visible areas are connected?

Principles of organization, proposed by the Gestalt psychologists, have long been considered to be an approximate answer to this question (Kellman & Spelke, 1983; Michotte, Thines, & Crabbe, 1964; Wertheimer, 1912). Objects may be perceived in accordance with similarity, continuity, and overall symmetry or "good form." A principle of ***common fate***, or common motion, holds that visible areas that move in the same ways are connected (Wertheimer, 1912). Although these principles are vague, probably redundant, and may to some extent confuse outcomes with causes (see Kellman & Shipley, 1991), they have pointed to important aspects of stimulus relations that underlie object perception. Further on I consider some recent efforts to obtain a more precise account of unit formation.

Even in advance of refinement of these principles, however, it is obvious that their ecological validities differ. A principle of common fate appears to be the strongest. When visible areas share identical motions in space (or rigid motions in general), it is highly likely that they are connected. The sensitivity of this principle is nearly perfect: The parts of connected entities will almost invariably move in connected ways. Specificity is also high. Connected motion will rarely occur for separate entities. Even separate objects falling under the influence of gravity, or flocks of birds headed in the same direction will ordinarily be detectably inconsistent with a rigid unity (although such cases may occasionally appear non-rigidly connected). The ecological root of a common fate principle is that object motions ordinarily result from the application of forces. The likelihood of forces being applied by chance to separate objects so that their motion paths are rigidly related must be vanishingly small. Not only would the direction of force have to be identical, but the magnitudes of forces applied to objects of differing mass would have to be exactly adjusted to result in the same velocity and acceleration patterns. (Those who have attempted to arrange common motion of visible objects by hidden mechanical means, e.g., in perception laboratories, can attest that it is a painstaking process.) Of course, this assessment of the validity of a common fate principle rests on the assumption that the visible parts actually move in space. Common fate in optical projections may also arise from observer motion through a stationary environment. During translation perpendicular to the line of sight, for example, many visible areas at roughly the same distance from the observer will undergo the same optical changes. Such areas may have little likelihood of being connected, beyond the basic probability that nearby areas are more often connected than are areas far apart. This difference between object and observer motion turns out to have important consequences, as we will see.

The situation is different for principles pertaining to spatial variables in stationary arrays. A principle of good form depends on the regularity that objects are regular or symmetrical. A principle of good continuation depends on the smoothness of object boundaries. A principle of similarity depends on the homogeneity of an object's surface qualities. In all of these cases, the regularity is a probabilistic one; objects in normal environments may fit these descriptions to varying degrees. There are obviously cases in which objects are not symmetrical, edges are jagged, and surfaces are varied in quality. The actual levels of ecological validity of such principles are not known. Brunswik (1956) proposed a program of ecological surveys to assess such principles, but such a program has never been carried out. As a preliminary assessment, however, one might expect that principles based on object regularities are somewhat less secure than those rooted in physical dynamics and kinematics (J. J. Gibson, 1966; Shepard, 1984; Spelke, 1985). We will return to this issue.

A number of years ago, my colleagues and I began to study the perception of partly occluded objects in early infancy, using Gestalt descriptive principles as a guide (Kellman & Spelke, 1983). The general method in each experiment was to habituate 16-week-old infants to an occlusion display in which the center of an object was hidden behind a nearer object. After habituation to such a display, we recorded looking times to two types of unoccluded displays. The complete test display contained a single, connected object joining the previously visible parts. The broken test display contained only the two separate pieces visible in habituation. Figure 5.1 shows the general scheme of the experiment. Generalization of habituation to the complete test display and dishabituation to the broken test display were taken to indicate perception of the original display as containing a unified, partly occluded object. This general method was used to test a variety of relationships between the two visible parts. These included a number of relationships available in stationary arrays, such as the alignment of edges on either side of an occluding object, the possibility of a symmetrically shaped object uniting the visible parts, similarity of color and lightness, and so on. Additional studies by Schmidt and Spelke (1984) addressed these static variables using a wider range of objects and including subjects up to 24 weeks of age. In these and other studies (Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986), a variety of motion relationships were tested, including common lateral translation of visible parts, translation in other dimensions (vertical and in-depth), and rotation (Kellman & Short, 1985).

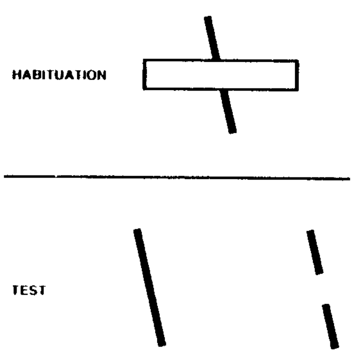

FIG. 5.1. Schematic of habituation method used to test perceived unity. The upper portion of the figure depicts the partly occluded object shown during habituation; the lower portion depicts the complete and broken test displays shown on alternating trials after habituation.

The results of these studies have been remarkably consistent in supporting two generalizations about early object perception. First, kinematic information, specifically, common translation in space of an object's visible parts, supports perception of object unity. Second, information available in static optic arrays does not support unit formation under occlusion in the first 6 months of life. Each of these conclusions is elaborated in turn.

Kinematic Information for Object Unity

In his classic paper, "Laws of Organization in Perceptual Forms," Wertheimer (1912) devoted a mere two paragraphs to the principle of common fate. A version of this principle, however, has turned out to be fundamental to early object perception. In occlusion cases, certain motion relationships of separate visible areas result in their being perceived as a single, unitary object. Data from one such condition, involving 16-week-old infants, are shown in Fig. 5.2. After habituation to a display in which the visible parts undergo the same translation, infants dishabituate markedly to an unoccluded broken display, but generalize

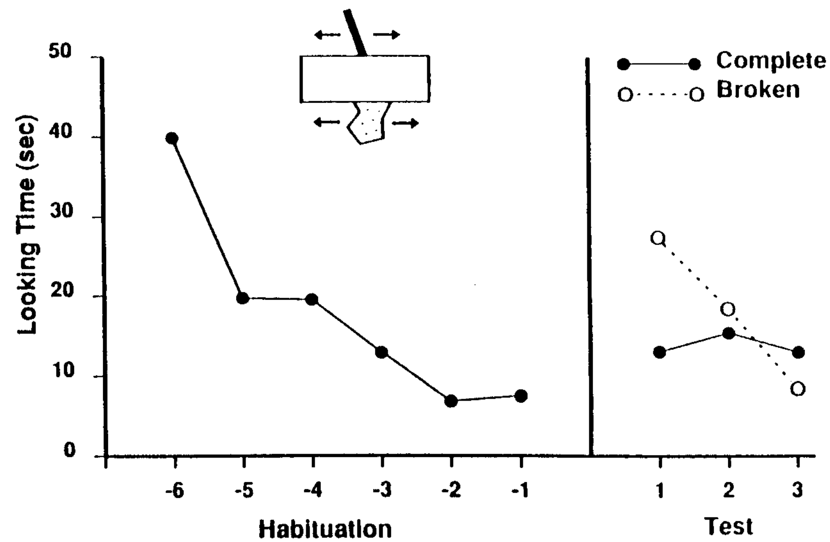

FIG. 5.2. Results of an experiment testing unity perception from common motion of visible areas. Infants were habituated to two dissimilar, misaligned visible areas that shared a common lateral translation (pictured at top). Looking times are shown for the last six habituation trials (with the final one labeled −1) and the test trials. Test trials consisted of successive presentations of unoccluded, complete and broken displays, with half of the subjects seeing the complete test display first. From Kellman and Spelke (1983).

habituation to an unoccluded complete display. A control group shown the two test displays without prior habituation to an occluded display shows no such difference in visual attention to the two test displays. This type of result occurs for translations in the plane, both lateral and vertical (Kellman & Spelke, 1983; Kellman et al., 1986). The results for vertical translation suggest that common fate relates to rigid translation of visible areas rather than to similar optical changes shared by visible areas, because in vertical translation one visible area is progressively revealed while the other is concealed. Perception of unity also occurs from translation in depth (Kellman et al., 1986). The latter result is interesting because the information for translatory motion in depth is considerably different from that specifying planar translation. Translation in depth may be specified by optical expansion/contraction, changes in convergence or disparity, or some combination. Planar translation is based on image displacement. These results suggest that common translatory motion in three-dimensional space underlies perceived unity, regardless of how that motion is specified.

A limitation on the role of kinematic information in unity perception was found by Kellman and Short (1985). When the visible parts of a partly occluded object were related by a rigid rotation (around a stationary center) or by a combination of rotation and translation (see Fig. 5.3), 16-week-old infants did not, in general, perceive the unity of the object. The difficulty in these cases appears to be the

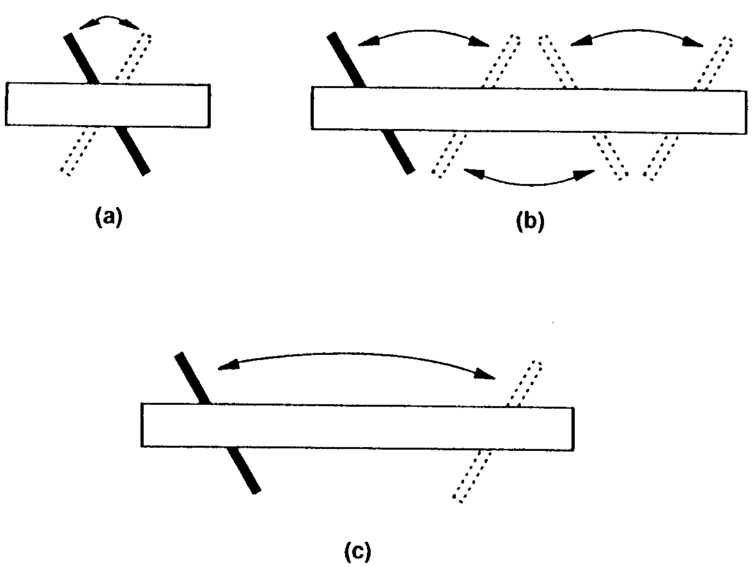

FIG. 5.3. Occlusion display with visible areas of partly occluded object related by (a) rotation, (b) rotation and translation with 3 cycles of rotary oscillation per cycle of translation, and (c) rotation and translation with 1 cycle of rotary oscillation per cycle of translation.

simultaneous motion of visible parts in opposite directions. When translation was combined with a rotary motion of the same period and phase (Fig. 5.3c), infants did respond as if they perceived a unified object. In this case, which looks something like a windshield wiper, the visible parts of the object always move in the same direction, although the velocity of the two visible areas differs. Other combinations of rotation and translation, all of which contained clear opposite directions of motion by the visible areas, produced no evidence of complete object perception.

These results suggest that the kinematic basis of early unity perception does not include the complete class of rigid motions: translations, rotations, and their combinations. Rather, a more restricted principle, based primarily on common translation, applies. One possibility is that accurate registration of rotation, or combinations of rotation and translation, present difficulties. Such combinations are known to pose problems in adult perception (e.g., Todd, 1982).

Object and Observer Motion in Perception of Object Unity

The findings reviewed so far, showing that certain motion relationships can indicate the unity of partly occluded objects, may be subject to two very different interpretations. The common motion of object parts in our experiments produces common changes in the optical projections of those parts (e.g., common retinal displacements). Does infant perception of unity depend on the real motions of objects in space or on commonalities in optical change? The latter can occur without the former when optical changes are produced by an observer moving through a stationary environment. The two possible characterizations of the relevant information—real motion vs. common projective change—require a test in which optical changes from the two sources are compared. Such a comparison raises two important issues.

First, the two possibilities would seem to differ in ecological validity. I have already noted that the common fate principle has perhaps the strongest validity of any information about unity under occlusion, when the principle is defined in terms of real object motion. The possibility of visible areas moving in certain related ways without being unitary is remote. By comparison, a common fate principle defined over optical changes would dilute ecological validity considerably. When an observer moves, common optical displacements can occur for visible areas that are not connected but happen to be at roughly the same distance from the observer. Thus, from the standpoint of ecological validity, one might predict that a common fate principle, especially one operating early in life, would be based on relationships in real motion rather than optical change. On the other hand, a principle defined over real motion in space might be more difficult to implement. It is straightforward to imagine mechanisms that respond to spatiotemporal relationships at the retina. Perceived motion, however, arises from a variety of stimulus conditions; if perceived unity depended on relationships in real motion, it would suggest a somewhat intricate computation whereby the motions of visible areas were first detected and then used to determine unity.

Second, the question of whether real or optical displacements govern unity perception raises another, somewhat prior, set of questions. Can infants tell the difference between optical consequences of their own motion and those produced by moving objects? If so, do they perceive object motion only in the latter case? In other words, do they have *position constancy*, the ability to detect the stationary position of objects whose optical projections are undergoing change due to observer movement?

Kellman, Gleitman, and Spelke (1987) explored both questions. There were two groups in their experiment, diagrammed in Fig. 5.4. Seated in a movable chair, infants were moved back and forth in an arc while viewing arrays of objects. In both groups, infants were habituated to a partly occluded rod, whose center was hidden by a nearer rectangular object. After habituation, they were tested for generalization/dishabituation to alternating presentations of an unoccluded complete rod and an unoccluded display with two separated rod pieces, as in earlier studies (Kellman & Spelke, 1983; Kellman et al., 1986).

The difference between groups involved the motion characteristics of the rods. In the observer motion group, the rod displays were stationary throughout the entire experiment (see Fig. 5.4a). However, the occluding block, the rod, and the background were separated in depth so that during the observer's motion, the visible parts of the rod underwent a unique optical displacement. The difference in optical displacement between the rod and the occluder, and also between the rod and the background, were designed to be the same as in earlier studies when stationary observers viewed a moving rod. Thus, if specification of object unity depends on differences between the optical displacement of the object's visible parts and other visible surfaces, unity should be specified in this case. If, however, perceived unity depends on real motion of the occluded object in space, and infants can accurately perceive the object as stationary, unity would not be perceived.

The other group (the conjoint motion group) was designed to be the logical converse of the first, having real motion of the occluded object in space, but no subject-relative movement. This was achieved by linking the moving infant chair and the partly occluded rod mechanically, out of sight beneath the chair and display (see Fig. 5.4b). The observer and object were rigidly connected, moving around a fixed pivot point in between. (When the infant's chair moved to the left, the object moved to the right, and vice versa.) Because the pivot point was close to the front of the block, there was little relative displacement between the occluded object and the occluder.

Perceived unity and perceived motion were assessed in different ways. As in previous studies, dishabituation patterns to unoccluded complete and broken rod displays were used to determine perception of unity. Motion perception was

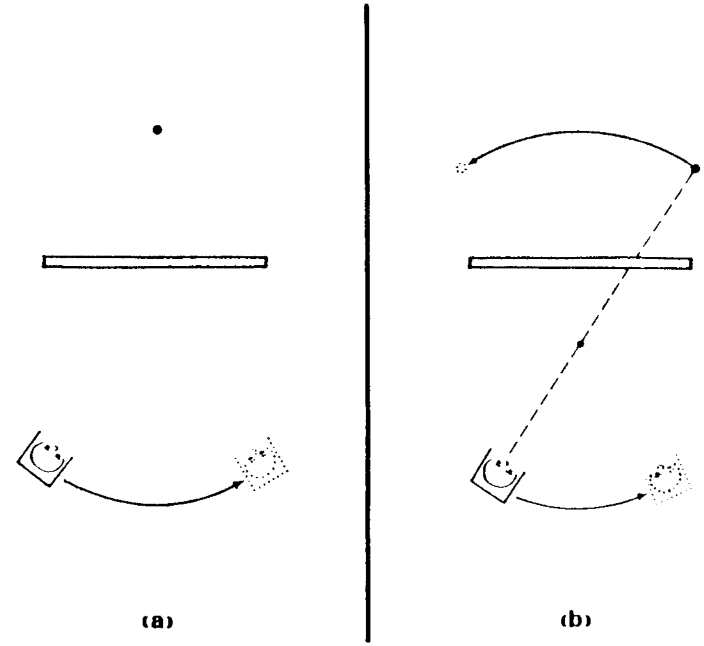

FIG. 5.4. Conditions in the experiment of Kellman, Gleitman, and Spelke (1987). Top views are shown, with solid and dotted figures indicating endpoints of motion: (a) observer motion condition, (b) conjoint motion condition.

assessed by comparing the absolute levels of looking time to those in previous studies in which stationary infants viewed moving or stationary displays. In those studies, looking times were consistently two to three times higher to moving displays than to stationary ones.

Results for the two conditions are shown in Fig. 5.5. There were three important findings. First, infants did distinguish optical changes given by their own motion from those given by moving objects. Looking times to stationary objects were on the same order as those in prior studies in which stationary observers viewed stationary displays. Second, moving infants showed evidence of motion detection. Looking times to the moving rods (conjoint motion group) were markedly higher than those in the observer motion group, and they were more similar to looking times shown in prior studies by stationary observers viewing moving objects. Finally, perception of unity depended on real motion. Infants in the conjoint motion group dishabituated to the broken test display while generalizing habituation to the complete test display. This result was remarkably strong and consistent across subjects; 15 of 16 subjects looked more than twice as long at the broken than the complete test display on the first test trial.

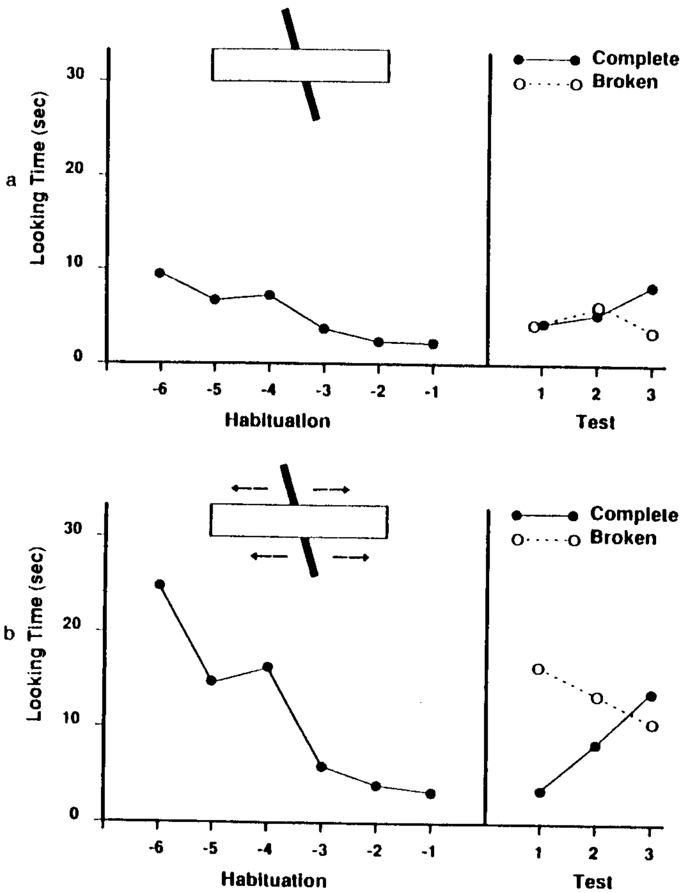

FIG. 5.5. Results of the Kellman, Gleitman, and Spelke (1987) experiment: (a) observer motion condition, (b) conjoint motion condition.

(As is typical in these studies, the effect diminished after the first set of test trials, although it was also reliable for the three test trials taken together.) In contrast, the observer motion condition showed no reliable differences in looking time to the complete and broken test displays, indicating that the subjects had not previously detected the unity of the partly occluded rod.

These findings have several interesting implications for perception of motion and stability. First, it appears that young infants have position constancy under at least some circumstances. Infants did not respond to optical displacements produced solely by their own motion as they respond to moving objects. Second, it appears that infants were able to detect the moving object in the conjoint condition during their own motion. This is noteworthy given the absence of subject-relative motion by the object.

Most important for object perception, the common fate principle in infant perception appears to be defined over real motions of objects' visible areas. Commonalities in optical change that were not based on real motion did not produce perceived unity. This outcome has implications for our hypothesis about ecological validity in perceptual development and also for accounts of the process of perception. Regarding the former, it appears that the more valid principle, defined over actual motions of objects, guides infant perception. Common optical displacement, produced solely by observer motion, does not specify a unitary object to infants. The common fate principle, as we find it in infancy, ensures high accuracy in early perception of connectedness, and accordingly furnishes a sound basis for learning about objects' properties.

From the standpoint of general theories of perception, these results have diverse implications. The findings confirm several tenets of ecological theories of perception (J. J. Gibson, 1979) and their application to perceptual development (E. J. Gibson, 1969, 1984). The primacy of kinematic information and the possibility that perceptual systems detect properties of objects and events from such information without learning are consistent with the data.[1] The evidence suggests, however, that the *process* involved is not readily explicable from the standpoint of direct perception. The dependence of perceived unity upon perceived motion appears to be an example of dependent variable coupling in perception (Epstein, 1982; Hochberg, 1974). That is, perceived unity cannot be directly ascribed to stimulus relationships (independent variables) but depends in part on another perceptual variable: perceived motion. Rather, it appears to depend on registration of visible areas undergoing certain motions in space. From our current vantage point, the process of unity detection appears most compatible with computational views of perception involving multiple levels of representation (Hochberg, 1974; Marr, 1982; Rock, 1977).

Static Spatial Information for Unity

I noted earlier that spatial relationships alone (and relations based on surface quality, such as similarity) do not seem to specify unity to infants. This leads

[1]A recent paper by Slater et al. (1990) suggests that common motion does not specify unity to newborn infants, but begins to do so some time between birth and 16 weeks. Although the investigators carefully considered (and ruled out) some alternative explanations, lack of competence is not the only plausible way to account for their results. Until these issues are studied further, the origins of the "primitive process" are clouded somewhat. If the primitive process turns out not to be strictly innate, from the ecological perspective advanced here, maturation would be its likely origin. At minimum, an alternative account in terms of learning would have to differ from classical ones based on correlations of visual sensations with touch and action, because these are disconfirmed by results from 16-week-olds. For discussion, see Kellman and Spelke (1983).

to an interesting question. In the absence of object motion, what do infants see when objects are occluded? Kellman and Spelke (1983) argued that such displays are perceived as containing occlusion, but the occluded areas are seen as indeterminate. This argument was based on evidence that occlusion boundaries (e.g., where a rod is interrupted by a block) are not responded to in the same way as non-occlusion boundaries (e.g., where the end of a rod is visible). In an habituation paradigm, the test trial response pattern to the former is dishabituation to a complete object, indicating that the initial display was perceived as containing unconnected pieces (Kellman and Spelke, 1983, Experiments 2, 3, and 4). In the case of occlusion boundaries, however, test trial responses indicate roughly equal looking times to complete and broken test displays (Kellman & Short, 1985; Kellman & Spelke, 1983), ordinarily with modest, but reliable dishabituation to both. Thus, occlusion boundaries do not seem to be mistaken for object boundaries; if such a perceptual error did exist, it would be a considerable handicap for early perceptual knowledge.

It is not known at what age nonkinematic information becomes able to specify object unity. Studies by Schmidt and Spelke (1984) indicate that static variables do not specify object unity even at 6 months of age. On other grounds, there is reason to expect that these abilities might arise at around 7 to 9 months of age. During this period, infants appear to begin to utilize pictorial depth cues (Yonas & Granrud, 1984), including interposition. Moreover, at least one study has found evidence of illusory contour perception at about 7 months of age, but not earlier (Bertenthal, Campos, & Haith, 1980). Recent work in adult perception (Kellman & Shipley, in press) suggests a close relationship between perception of partly occluded objects, perception of illusory figures, and the depth cue of interposition. In fact, it has been proposed that a single boundary interpolation process underlies perception of partly occluded objects and perception of illusory or subjective figures (Kellman & Shipley, 1991; Shipley & Kellman, 1990). This emerging understanding of interpolation processes in adult perception may shed some light on the developmental patterns appearing in research over the past 10 years. Thus, a brief overview may be useful.

A Reformulation of Information for Unity: The Primitive Process and the Rich Process

In studies of infant object perception, as in many previous studies with adults, the information available for perceiving object unity was considered in terms of Gestalt organizational principles, such as common fate, good form, good continuation, and so on. Although it was clear that these principles were vague and perhaps unduly numerous (Helson, 1933), they provided the only serviceable account at hand. Recently, a new account of perception of interpolative processes in object perception has been proposed (Kellman & Shipley, 1991). This account emphasizes local variables, such as the tangents of edges at points of

occlusion. The theory provides a unified account of boundary interpolation processes in occlusion cases, illusory figures, and other unit formation phenomena, both static and kinematic, in which boundaries are perceived in the absence of local specification. Some of the Gestalt influences are held to be outcomes, not causes, of perceptual processes; the tendency to see simple, regular forms—good form—is one example.

Briefly, the theory posits that unit formation is initiated by first-derivative discontinuities (sharp corners) in projected edges. The usefulness of first-order discontinuities derives from the fact that all cases of occlusion will give rise to projected discontinuities. Interpolation occurs when edges leading into discontinuities are *relatable* to other edges leading into discontinuities in the optic array. Relatability is defined mathematically, but embodies the requirements that two surface edges may be connected by a surface boundary that is smooth (i.e., that contains no first-order discontinuities) and monotonic. More precisely, referring to the construction in Fig. 5.6, if *E1* and *E2* are the edges of surfaces, and *R* and *r* are perpendiculars to the tangents at the ends of the edges, with *R* assigned to the longer of the two, then *E1* and *E2* are relatable if $0 \leq R \cos \Phi \leq r$. It can be shown that whenever two edges meet the relatability criteria, they can be joined by a smooth, monotonic curve (Kellman & Shipley, 1991). Figure 5.7 gives some examples of edges that are and are not relatable. Figure 5.8 shows examples of unit formation in equivalent occlusion, illusory figure, and transparency cases, based on the same discontinuities and relatable physically specified edges in all cases.

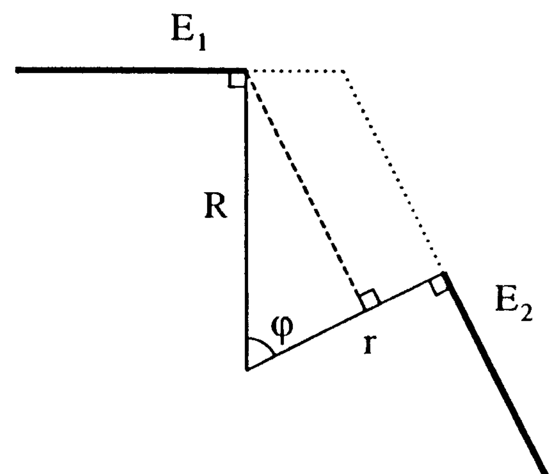

FIG. 5.6. Illustration of relatability criteria proposed by Kellman and Shipley (1991). *E1* and *E2* are edges of projected regions. *R* and *r* are perpendiculars to the tangents of *E1* and *E2*, assigned so that *R* is the longer; Φ is the angle of intersection of *R* and *r*. Edges are relatable if $0 \leq R \cos \Phi \leq r$.

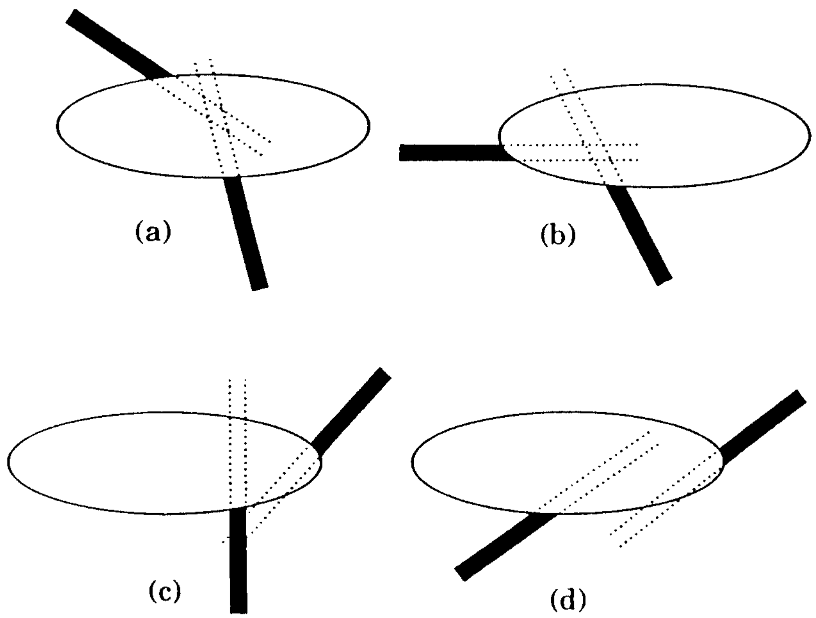

FIG. 5.7. Examples of relatable and nonrelatable edges. The visible rod parts in (a) and (b) are relatable; those in (c) and (d) are not. After Kellman and Shipley (1991).

The theory embodies the central notion of the Gestalt idea of good continuation, while giving it a more precise form. Other Gestalt notions, such as good form and closure, do not figure in the computations required by the theory, but characterize the outcomes of the process to some extent. The effect of the relatability criteria is that some projected discontinuities end up being classified as due to occlusion rather than as due to sharp corners in object boundaries. Thus, the overall smoothness and simplicity of perceived objects derives in this theory from more local, computationally tractable processes.

Most important for the present discussion is the separation of unit formation under occlusion into two putative processes what Kellman and Shipley (1991) label the ***primitive process*** and the ***rich process***. The primitive process refers to the perception of unity from certain motion relations of visible parts of objects, that is, the Gestalt idea of common fate. It might also be called the ***edge-insensitive process***, because projected orientations and arrangements of edges are inconsequential to it. The process is labeled ***primitive*** because, when acting alone, it leads to perception of unity, but not specific form. That is, two very different-looking visible parts, whose edges cannot be connected in a smooth manner, can still be seen as unified if they share a common motion in space.

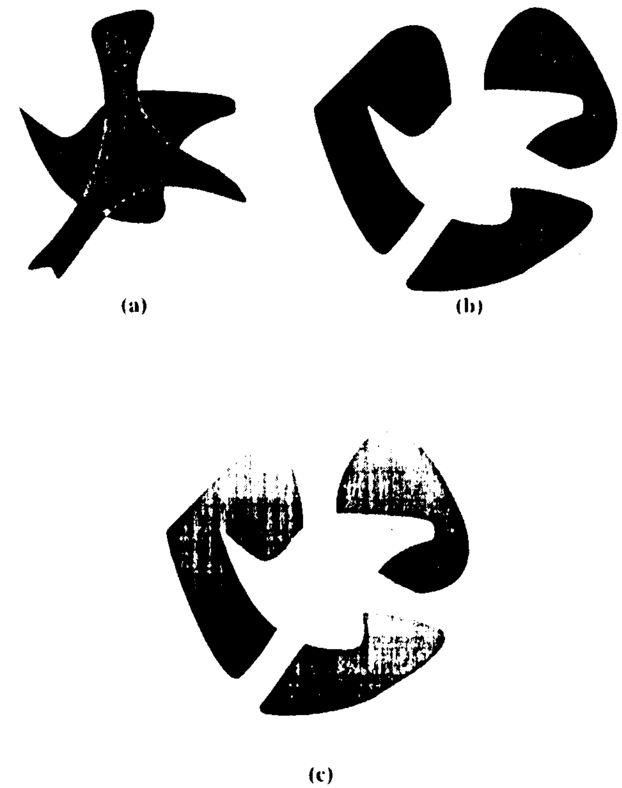

FIG. 5.8. Examples of equivalent unit formation cases: (a) partly occluded object, (b) illusory figure, (c) transparent figure.

The rich process, however, leads to both unity and form perception. It might equally well be termed the ***edge-sensitive*** process, because it is crucially dependent on the spatial and temporal relations of physically specified parts of objects. In the Kellman and Shipley account (see also Kellman & Loukides, 1987), the rich process is characterized in a way that accounts for both interpolation of object edges under occlusion and subjective or illusory contours. A series of experiments with adults by Shipley and Kellman (1990) provides confirming evidence that a single underlying process is at work in both types of unit formation.

The rich process may involve either kinematic information or information in static arrays. One crucial difference between motion information in the two processes is that the rich process works equally well from real motion of the partially specified object or relative motions, that is, of occluding and occluded objects.

The characterization of a rich, or edge-sensitive, process and a primitive, or edge-insensitive, process allows some useful reconsideration of findings in infant perception. Specifically, the division (between abilities present early and those achieved later) is not strictly between kinematic and static information. Infants seem to lack the edge-sensitive process during at least the first half year of life. Thus, unit formation that involves motion but does not depend on relations of edge orientations appears early. In such cases unity is perceived without specific form being determined. Other unit formation phenomena depend on both motion and edge relations; two such (related) phenomena are shown schematically in Fig. 5.9. In both kinetic occlusion and kinetic illusory figures, optical changes given sequentially over time carry information about both unity and edge relations. There is some evidence that young infants do not perceive specific form from kinetic illusory figure displays (Kaufmann-Hayoz, Kaufmann, & Walther, 1988). From the foregoing analysis, we would expect that the perception of stationary illusory figures, of stationary, partly occluded objects from edge relations and form (as opposed to amorphous unity) in kinetic illusory figures should appear at the same time in perceptual development. Systematic studies to test this prediction would be extremely useful.

How does the breakdown of unit formation into the rich and primitive processes fit with our earlier conjectures about the superior ecological validity of kinematic information? At a superficial level, our generalization requires some qualification. Not all information carried by motion appears early in life; moreover,

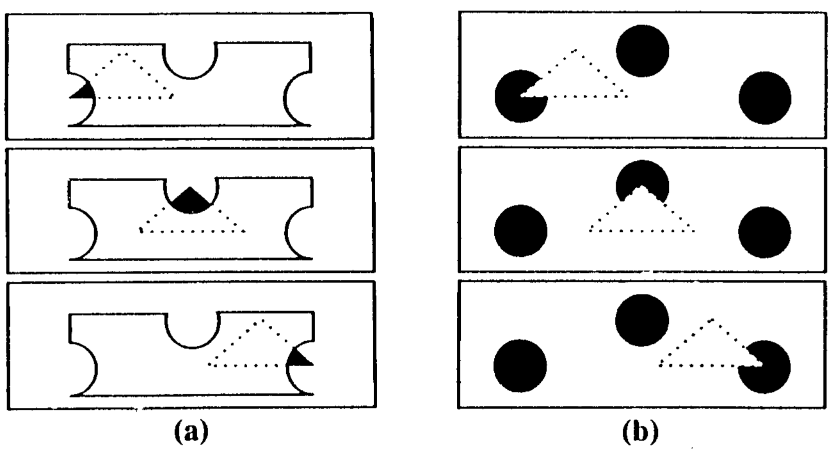

FIG. 5.9. Examples of the rich (edge-sensitive) process involving motion. Equivalent kinetic subjective figure and kinetic occlusion cases are shown: (a) Kinetic occlusion: The object moves behind the occluder projecting parts sequentially as shown in the three views; (b) Kinetic subjective figure: Background (inducing) elements are sequentially occluded by a moving form of the same color as the background.

the relevant divisions between early- and late-appearing abilities may depend on other factors. On closer examination, however, our guiding conjectures still serve well. The primitive process provides a good example of the ecological validity of kinematic information. It requires actual motion of objects, not simply sameness of optical change as might be given by observer motion. Accordingly, false-alarms—mistaken assignments of unity—are minimized, because forces acting on separate objects so as to give them common translations in space are improbable.

Compared to the primitive process, the rich or edge-sensitive process is less fundamental. Our (adult) perception and effective functioning with objects would scarcely be possible without edge interpolation given by the rich process, but its roots in ecological optics are nevertheless not as secure as the primitive process. The validity of the rich process ultimately depends on the ecological constraint that objects tend to be smooth (Hoffman & Richards, 1984; Kellman & Shipley, 1991; Marr, 1982). Certain relations between pairs of edges support visual interpolation, whereas others do not; the simplest characterization of those in the former class is that they can be connected by smooth (first-order continuous) monotonic curves. Smoothness, however, is at best only a rough, probabilistic characterization of objects (Spelke, 1985). When objects or parts of objects are not smooth, the rich process may fail to unite visible parts of an occluded object; there may also be cases (probably rare) in which parts of separate objects spuriously meet the criteria for interpolation.

Returning to the case of kinetic occlusion and kinetic illusory figures, these phenomena involve motion but also involve edge relations necessary to the rich process. The specification over time of spatial edge relations really has no greater ecological validity than simultaneous specification of such edge relations. The information about objects in kinetic occlusion and kinetic illusory figures depends as fully on a smoothness constraint as do stationary cases of the rich process.

Perception of object unity under occlusion, then, rests initially on information given exclusively by motion relationships. Of the information sources usable by adults, it is this information that appears to have the most secure roots in the physics and geometry of objects and their projections to observers. Perception based on further constraints, such as relations in edge orientations, appear to be secondary from a developmental standpoint.

PERCEPTION OF THREE-DIMENSIONAL FORM

Next to unity, the property of objects perhaps most important to our transactions with them is 3-D form. As in the case of unity, 3-D form may be given perceptually to adults by a variety of sources of information, including both static and kinematic sources.

One account of 3-D form perception—that objects are constructed out of more elementary sensory experience—has a long tradition of supporters, including British empiricist philosophers (Berkeley, 1709/1910; Mill, 1865/1965), the structuralist psychologists who dominated early experimental psychology (Titchener, 1924), as well as more contemporary advocates (Harris, 1983; Piaget, 1954). On this general account, 3-D form, perceived visually, is a construction from momentary 2-D images of an object, associated together in memory along with other sensory experiences, such as the feel of an object or the actions one performs on it. Mill's (1865/1965) formulation is perhaps most elegant: An object ject is "the permanent possibilities of sensation." Taking sensations to be the only directly given data, what a 3-D object must logically be is the set of possible sensory images one might obtain by seeing or otherwise sensing the object from various vantage points.

A more general and abstract notion of form perception was proposed by the Gestalt psychologists (Koffka, 1935). The 2-D projection of an object was claimed to activate dynamic forces in the nervous system that would cause perception of objects that were as simple and regular as possible. That objects are perceived in accordance with principles of regularity and simplicity was also suggested by Brunswik (1956), although he suggested that such principles arise from learning about the probable characteristics of objects.

Kinematic information has a more recent history, often dated from Wallach and O'Connell's classic (1953) paper, *the kinetic depth effect*. Wallach and O'Connell cast shadows of 3-D wire figures onto a translucent screen, and observers viewed the shadows from the other side. When stationary views were projected, observers reported planar figures on the surface of the viewing screen. When the wire figures were made to rotate in depth, however, observers quickly and effortlessly perceived accurately the objects' 3-D forms. Later analyses placed this "effect" into a more systematic context: Three-dimensional form may be recovered by the laws of projective geometry from optical transformations given by object or observer motion (J. J. Gibson, 1966; Johansson, 1970; Ullman, 1979). Perception of "structure from motion" has subsequently become one of the most active areas in contemporary visual perception research.

Each of the various approaches to form perception implies or readily coexists with certain ideas about development. From the constructivist standpoint, 3-D form must be learned from accumulated 2-D views and associations with touch and/or action. From the Gestalt view, 3-D organization should occur without learning, whereas a Brunswikian would expect the same organizational principles to govern perception only after a long process of learning. Finally, from kinematic analyses comes the possibility that projective geometric information given by optical transformations might be utilized by perceptual mechanisms that are products of evolution (Fodor, 1983; J. J. Gibson, 1966; Shepard, 1984).

In the first two decades of active infant perception research, beginning in the late 1950s and early 1960s, most research related to form perception em-

ployed static, 2-D displays (for reviews, see Bond, 1972; Fantz, Fagan, & Miranda, 1975; Salapatek, 1975). Implicit in much of this early research was the empiricist assumption that the perception of stationary, 2-D arrays was logically or psychologically prior to the perception of 3-D form.

A different expectation derives from an event perception perspective. In terms of the validity of information, perspective transformations given by relative motion between an observer and an object offer the most accurate information about form. In static optic arrays, when a stationary observer views a 3-D object from a single vantage point, its whole form may be predicted on the basis of considerations of simplicity, symmetry, or similarity to previously viewed objects. The accuracy of such predictions rests on probabilistic facts about the sorts of objects that exist, the likelihood of vantage points that give misleading symmetry information, and so on. In contrast, under conditions easily satisfied when a moving observer views a 3-D object, the perspective transformations provably contain sufficient information to specify 3-D form (Ullman, 1979). Illusory specification of a given object is possible only if an object deforms or the optic array is otherwise manipulated to present misleading transformations. This sort of event, however, requires a high degree of skilled manipulation (or incredible coincidence). It is true that the separation of optic flow components due to observer motion and object change (i.e., motion, deformation) is a complex task with certain limitations (discussed further on). In general, however, when an observer moves and a viewed object also moves or deforms, the transformations will not be consistent with some other rigid object. This constraint does not derive from the particular types of objects that tend to be viewed, such as symmetrical or nonsymmetrical ones, although it is related to the facts that objects tend to be rigid, or nonrigid in characteristic ways.

The ecological validity of kinematic information about 3-D form leads naturally to the possibility that it may be primary in development. Assumptions about the symmetry of objects, or inferences from past experiences, might be less reliable and later-appearing. Interestingly, one of the major motivations for their study, according to Wallach and O'Connell (1953) was to shed light on the development of 3-D form perception. They reasoned that knowledge of 3-D form seems to be available to monocular observers; yet, in development, congenitally monocular observers would not have had access to stereoscopic information about 3-D form. It is clear that with adequate learning about objects, adults can perceive 3-D form even from pictorial information. But where might the initial notion of 3-D form come from? Wallach and O'Connell hypothesized that there might be an unlearned process of detecting 3-D form from optical changes given by motion.

Experiments by several investigators have given us a relatively clear picture of early 3-D form perception (Kellman, 1984; Kellman & Short, 1987; Owsley, 1983; Yonas, Arterberry, & Granrud, 1988), and it is consistent with the conjecture of Wallach and O'Connell (1953). The evidence suggests that the earliest competence for perceiving overall form appears to be based on kinematic information. To illustrate this claim and to understand further the nature of early 3-D form perception, we consider some of this evidence in detail.

Testing 3-D form perception is challenging. When we perceive a 3-D object, we ordinarily do so from a particular station point, or a changing sequence of station points. At these station points, particular projections of the object reach the eyes. To test perception of 3-D form, one must somehow exclude particular 2-D projections as an adequate basis of response. For example, suppose infants were habituated to a stationary 3-D object from a particular vantage point. Suppose also that after habituation, infants generalized habituation to continued presentations of the same display, but dishabituated to a novel 3-D object. This pattern of response might indicate that infants detected the 3-D form of the original object, and discriminated it from the novel 3-D form. However, the observed responses could instead be based on differences in the 2-D projections; 3-D form may not have been perceived at all.

The method we developed to counter this problem is based on the geometry of the kinetic depth effect. Information about a given 3-D form can be provided by rotation around various axes, provided there is some component of rotation in depth. If objects are chosen that are not too symmetrical, one can test for recognition of an object with rotation sequences that have not been shown before.

The earliest experiment of this type (Kellman, 1984) used two objects of the sort shown in Fig. 5.10. Kinematic information for form was tested by habituating infants to videotaped displays of a single object rotating in depth. Two different axes of rotation in depth were used in habituation on alternate trials, so that the only constant from trial to trial was the 3-D form of the object—if

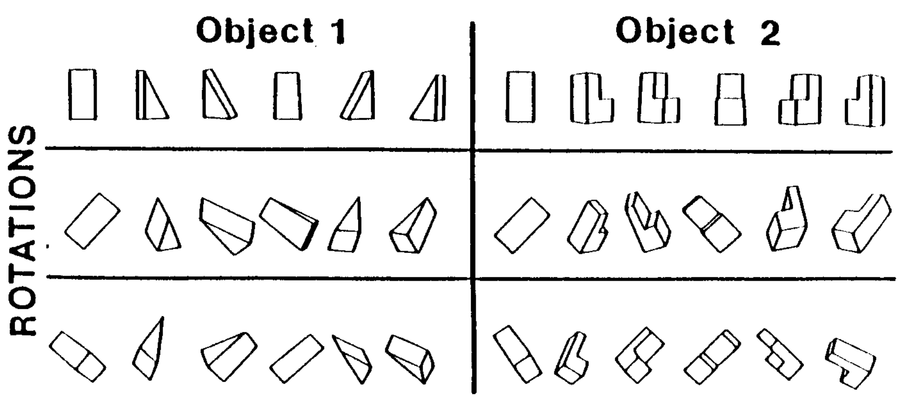

FIG. 5.10. Schematic views of objects and axes of rotation used in an experiment on 3-D form perception (Kellman, 1984). Successive views 60° apart are shown. All views in the same column are of a single 3-D object; views in the same row are from a single axis of rotation.

it could be recovered from the transforming projections. After habituation, subjects were tested on alternating trials with presentations of the same object, now moving around a new (third) axis of rotation and the different object, also rotating around the same new axis. The change to a new axis of rotation in the test period ensured that the particular proximal views and transforming patterns were novel for both the object shown previously and the new object. Thus, generalization of habituation to the same object could not be based on matching the particular views shown in the test period with particular views seen earlier.

Besides the kinematic condition, two groups viewed sequential stationary views (photographic slides) taken from the rotation sequences. The two groups differed in the number and spacing of the views (see Kellman, 1984); successive views were taken from the rotation sequences at 60° intervals for one group and at 15° intervals in the other. There were two reasons for testing infants' perception from stationary views. First, it was possible that infants could detect the 3-D forms of these objects from single views, or sequences of views. Adults can certainly do this; even the line drawings in Fig. 5.10 allow overall form to be perceived from most of the views. The slides used allowed adults to perceive overall form even more readily; besides contour information, the images contained shading information. If infants detected overall form from single views or sequences of static views, successful performance in the kinematic condition might not indicate use of optical change information; rather, it might indicate that transforming arrays are processed as sequences of static views.

The second reason for testing performance from static views was to obtain a check on the method. Although the changes of rotation axis introduced large changes in the proximal stimuli, it remained possible that views of a given object from different axes of rotation bore enough similarities to each other to allow them to be distinguished from views of the other object. In such a case, infants might show dishabituation to views of a new object without having any perception of 3-D form.

The results were unequivocal. Infants in the kinematic condition (Fig. 5.11a) generalized habituation to the same object in a new rotation, and dishabituated robustly to the new object. This result held regardless of the object and the particular axes of rotation used in the habituation and test trials. In contrast, infants habituated to sequential static views of one object showed no reliable difference in response to new views of that object versus views of a new object. Data from one of the two static conditions (successive views 15° apart, shown for 1 sec each) are shown in Fig. 5.11b.

The results suggested that young infants have the ability to perceive 3-D form, but only from continuous optical transformations. This conclusion is consistent with the work of other investigators (Owsley, 1983; Yonas et al., 1987). These results are compatible with an ecological view of the perception of structure from motion (J. J. Gibson, 1966, 1979; Shepard, 1984). Evolution of perceptual mechanisms may reflect the basic geometry of space and time, allowing

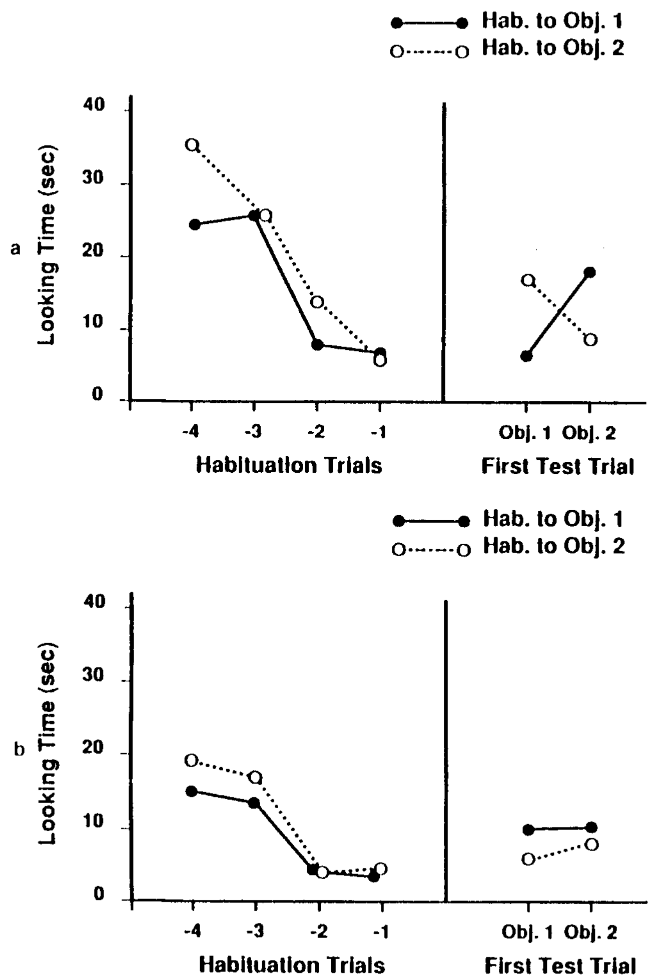

FIG. 5.11. Results from 3-D form perception experiment. Looking times are shown for the last four habituation trials and the test trials. Solid and dotted lines show data for subgroups who viewed different objects during the habituation period: (a) kinematic condition, (b) static condition (successive views spaced 15° apart).

recovery of object structure from optical transformations. Although studies with younger infants would be desirable, to determine whether such mechanisms operate from birth, existing data suggest that kinematically based 3-D form perception depends on mechanisms that are innate or early-maturing. Those learning accounts of 3-D form perception that have been proposed seem implausible given the developmental order in which kinematic and static information sources be-

come useful. The reason parallels the question posed by Wallach and O'Connell (1953). Where might information about 3-D form come from initially? Suppose young infants were able to encode optical transformations, but that these initially did not specify 3-D form. The meanings of particular optical changes would have to be supplied from other information. J. J. Gibson and E. J. Gibson (1955) termed this general type of account of perceptual development *enrichment*. Yet it is currently hard to see how enrichment might operate. Because 3-D form is apparently not apprehended from single or multiple static views of objects, and because infants even at 16 weeks are not skilled haptic explorers, it is unclear how the "meanings" of optical transformations might be found out.

Motion Perspective in Perception of 3-D Form

The idea that initial perception of 3-D form depends on mechanisms sensitive to kinematic information leads to an interesting prediction. In considering the ecological validity of kinematic information for object unity, I noted that optical changes produced by observer motion were not equivalent to those given by object motion; only the latter specify object unity. The ecological basis of 3-D form perception is different. Optical transformations that specify a particular form may be given in principle by either object or observer motion. The specificity of the motion patterns, insofar as 3-D form is concerned, is the same in both cases. Thus, an observer walking in an arc around a stationary object receives the same optical transformations, relevant to that object's form, as if the object rotated while the observer was stationary. The kinematic information about form and spatial layout given to a moving observer has been termed *motion perspective* (J. J. Gibson, 1966).

Kellman and Short (1987) tested whether motion perspective could specify the 3-D forms of stationary objects. A sketch of that apparatus is shown in Fig. 5.12. The experiment served an additional purpose as well. Suppose the superiority of kinematic information arises not from the nature of the information available but from the fact that moving displays attract more attention. Perhaps with enhanced attention, or with a certain critical amount of fixation time, infants can detect 3-D form from static views. Kellman (1984) offered several arguments and some data against this view. However, assessing 3-D form perception from motion perspective information provides a more direct test. If the presence of object motion, rather than certain optical changes, is crucial, 3-D form perception should not occur when a moving infant observer views a stationary object.

The procedure in this study was the same as in Kellman (1984), except that the different axes of rotation used in the habituation and test periods were given by attaching a vertical axis into the display objects at different places. A stationary control group was also tested in which successive static views of the ob-

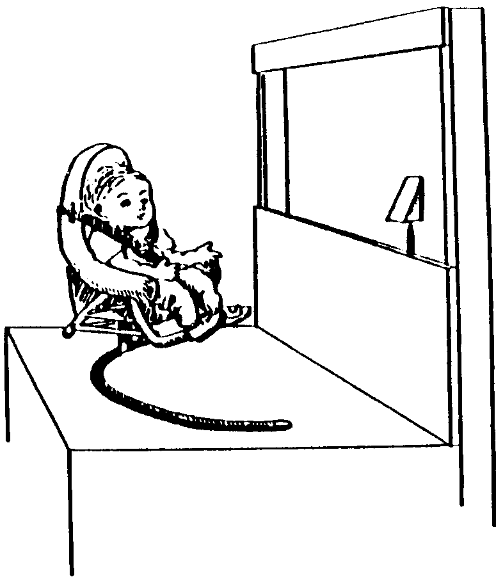

FIG. 5.12. Apparatus used in testing form perception from motion perspective. Observers were passively moved in an arc while viewing 3-D objects. From Kellman and Short (1987).

jects were presented. This was achieved by covering the display object on any trial momentarily during movement of the subject. Thus, the subject saw the stationary object from numerous vantage points, but continuous transformations of the object's projection were not available.

The results (shown in Fig. 5.13) indicated that 16-week-old infants did perceive objects' 3-D forms from motion perspective. They generalized habituation to the same object presented in a new rotation, but not to a novel object. As in the previous study with moving objects, continuous transformations are crucial to the effect. A comparison group, shown multiple, successive, static views of the objects from the same rotation sequences, showed no evidence of 3-D form perception. Those data are discussed further on.

Perspective Transformations and Early Form Perception

So far the findings I have discussed indicate an early ability to perceive 3-D form from kinematic information, but I have not specified more explicitly the nature of the information that makes form perception possible. Most analyses of adult perception of structure from motion have emphasized perspective transformations of object edges (J. J. Gibson, 1979; Ullman, 1979; Wallach & O'Connell, 1953). However, the transforming optical projection of a rotating (solid) object

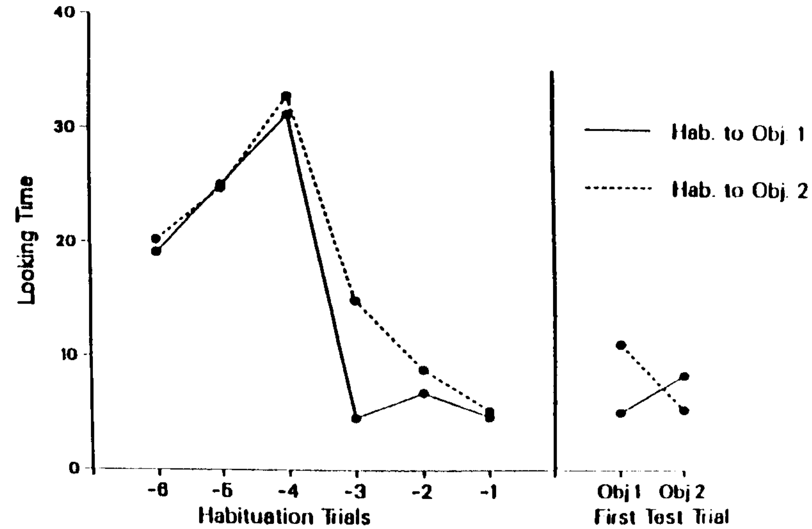

FIG. 5.13. Looking times during habituation and test trials in the motion perspective experiment.

also contains changes in brightness and texture gradients. Recently, Pentland (1990) has emphasized the potential usefulness of this sort of information about form. Regarding infant 3-D form perception, Shaw, Roder, and Bushnell (1986) argued that changes in brightness and texture are necessary for infants younger than 24 weeks of age to detect form. In the experiments described earlier, by Kellman (1984) and Kellman and Short (1987), solid objects were illuminated primarily from one direction. Thus, brightness changes were available along with transformations involving projected edges.

To disentangle the contributions of perspective transformations from brightness changes during motion, we carried out a study using wire figures similar to those introduced by Wallach and O'Connell (1953). Such figures contain thin edges but no surfaces connecting them; when such figures rotate, they provide the same geometric transformations of surface boundaries as do solid objects, but unlike solid objects, transformations of surface brightness and texture are virtually absent. In our experiment, the lighting was directionally balanced to eliminate detachable shading changes even along the thin edges of the figures. The figures used in the study are shown in Fig. 5.14.

Both figures resembled the "parallelogram" figure used by Wallach and O'Connell (1953). Each consisted of two triangles, in different planes, that shared a common edge. In one figure, the triangles were oriented at 95° to each other, whereas in the other figure, the triangles formed an angle of 165°.

Besides eliminating transformational shading information, these figures were

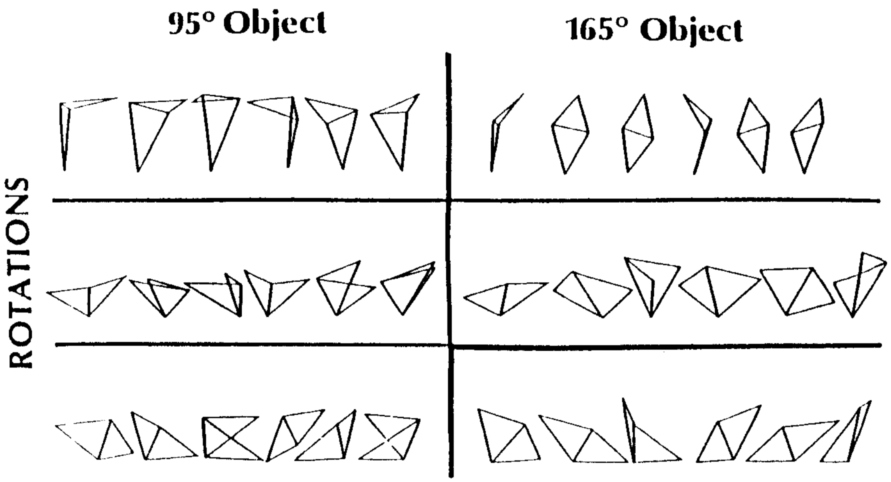

FIG. 5.14. Objects and rotations used to test 3-D form perception from perspective transformations alone. Successive views 60° apart are shown.

designed to accomplish another purpose. The method used in our prior studies of form assessed perception of 3-D form, apart from 2-D projections, by changing the rotation axes between habituation and test periods. Thus, generalization of habituation to the same 3-D form always required infants to remain habituated despite being shown particular transforming projections that had not previously been seen. Despite these changes, it was possible that varying rotations of a given object bore some similarities to one another. Data from control groups were reassuring in this respect, indicating that stationary views taken from the rotation sequences did not support 3-D form perception.

The experiment with wire figures, however, allowed an additional way of ruling out contributions from 2-D similarities across axes of rotation. Not only were the two test objects designed to be very similar to each other, but their structure added an even greater safeguard. A theorem of projective geometry states that all triangles are projectively equivalent; that is, any 2-D projection of one triangle could be the projection of any other triangle in some 3-D orientation and distance. By constructing each 3-D figure in our experiment from two triangles, the overall structure of the object was minimized. As a check on this manipulation, we tested adults' ability to sort static, 2-D views of the two objects, taken from the three rotation axes used for each, into two separate groups. Accuracy of sorting views of the two 3-D objects did not differ from chance (Kellman & Short, 1987, Experiment 3b).

When continuous optical transformations were shown (on videotape), however, adults readily discriminated the two objects from each other, and effortlessly perceived the identity of each object across the three axes of rotation

used in the experiment. If our interpretation of earlier experiments was correct, and if perspective transformations alone are sufficient, 3-D form perception by infant subjects (16-week-olds) was expected as well.

This expectation was confirmed. Infants showed robust evidence of 3-D form perception, generalizing habituation to the same object in a new axis of rotation, and dishabituating to a new 3-D object, shown in the same, new rotation. Figure 5.15a shows the data from this group. Infants in a static control group, who viewed successive stationary views of the objects, showed no evidence of discrimination based on 3-D form. As shown in Fig. 5.15b, viewing of one object or the other during the habituation period did not differentially affect subsequent looking at the two test objects.

This experiment shows that perspective transformations of the bounding con-

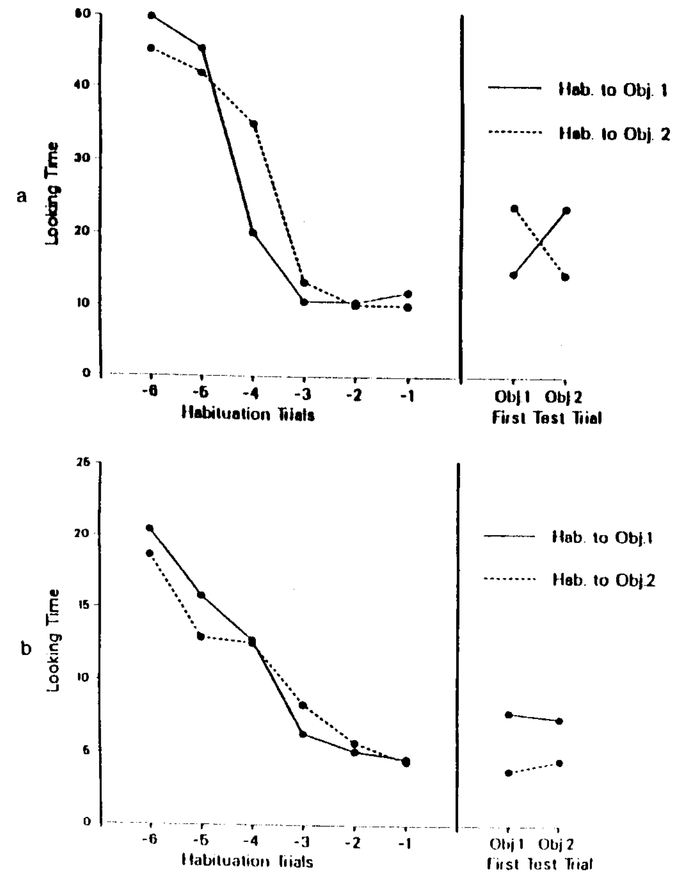

FIG. 5.15. Looking times during habituation and test trials in perspective transformation experiment: (a) kinematic condition, (b) static condition.

tours of objects contain sufficient information to specify 3-D form perception to young perceivers. The results with these stimuli, which provided little in the way of shading or brightness change information, were as robust as those in prior work with solid objects (Kellman, 1984). Although these findings do not rule out the possible informativeness of transformations of shading and texture, these are clearly not necessary for early 3-D form perception.

Static 3-D Form Perception

Adults perceive the 3-D forms of objects not only from kinematic information but from single or multiple static views of objects. For example, in Fig. 5.10, the overall shapes of the objects are evident from most of the individual views. In the course of our research on 3-D form, my colleagues and I have accumulated a good deal of evidence that these abilities arise relatively late in development. In Kellman (1984), subjects in two static conditions viewed multiple, sequential static views taken from the rotation sequences used in the kinematic condition. One group viewed six 2-sec views per rotation, spaced 60° apart. The other group viewed twenty-four 1-sec views from each rotation sequence, spaced 15° apart. Neither group showed any differential responding in the test period as a function of the habituation object presented previously. This initial failure of static views was interpreted with caution, because the views were given as photographic slides. Perceiving 3-D form from static views may be more difficult when using photographs, which may present depth cue conflicts, than from real scenes.

The failure of static information, however, is not unique to 2-D stimuli. Ruff (1978) found that 6-month-old infants failed to apprehend 3-D forms from stationary views of 3-D objects. The objects used were rather complex, however. Kellman and Short (1987, Exp. 2) tested multiple, stationary views of the objects pictured in Fig. 5.10 with infants aged 4 and 6 months. The general method was the same as in earlier form studies, except for the mode of presentation. On a given trial, multiple, stationary views of a 3-D object were presented, but the movements of the object through successive positions was blocked from the subjects' view by an occluder that hid the object momentarily during each position change. During test trials, again with sequences of static views, neither group dishabituated differentially to views of the two objects based on the object presented in habituation. Figure 5.16 shows the results of this experiment.

The difficulty of deriving 3-D form perception from static information is not limited to 16-week-olds. In recent experiments, we have obtained the same results at 24 and 32 weeks. At both of these later ages, infants still show no reliable differential responding to static views of the two test objects as a function of the object whose views were given in the habituation period.

Because adults perceive 3-D form so readily even from single views of ob-

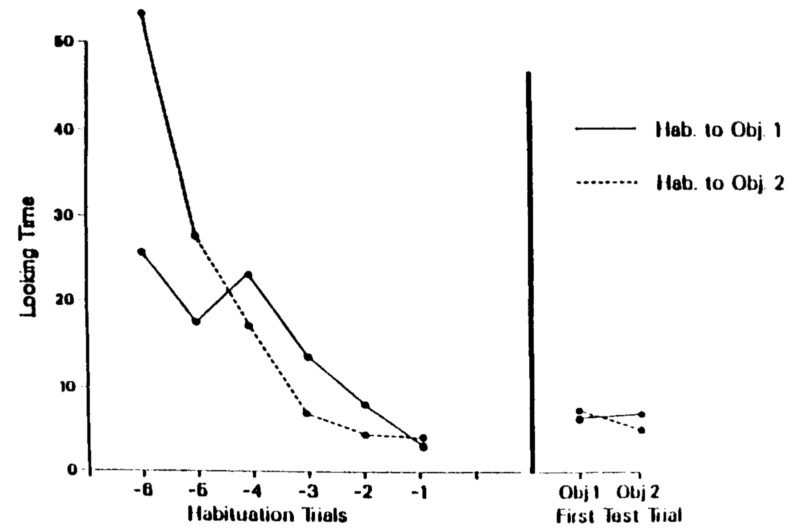

FIG. 5.16. Looking times during habituation and test trials by 16-week-olds in experiment with static views of 3-D objects.

jects, it is surprising that even at 8 months of age, there is no evidence that infants do. The unexpectedness of this result led us to consider whether some aspect of our method was obscuring infants' competence. We entertained several possibilities. First, in our method successive static views were given by hiding the object momentarily; while occluded, the object was moved to a new position. Despite the fact that each shift in position was only 15°, it was possible that infants have some ability to perceive 3-D form from multiple static views but that the changing of the object's position in space while occluded disrupts integration of the views into a coherent representation. A second possibility is that attentional factors limit static form perception. Only a subtle version of an attentional explanation would fit the data, however. Attention, to the successive static views in these studies, as indexed by fixation times at least, is not low. Initial trial looking times on the order of 40 or 50 seconds were not uncommon, as can be seen in Fig. 5.16. Many infant perception experiments have demonstrated habituation and novelty responses to aspects of static patterns with per-trial looking times of one fifth or even one tenth of these levels. Nevertheless, any inference about the inability of infants to perceive 3-D form from static information rests on negative results and leaves open the possible roles of attentional or other extraneous factors.

To pursue these issues further, we modified our approach. Concerning the first problem—that unseen movements of the object may have been disruptive—we altered the situation so that the position of the observer, not the object, changed. During each trial, successive static views were presented by displaying the object, occluding it momentarily, and moving the observer to a new position (15° around an arc). The display situation contained ample stationary references, potentially allowing the observer to detect the constant position of the object. To check for some attentional problem in the test trials, we followed the normal test trials with an additional test. In the additional test, we changed a characteristic of the habituation object that we are certain infants are capable of detecting: the color of the object. Whereas the normal display objects were red-orange, the final test object was yellow. If attention has dwindled by the time infants reached the test trials, we might expect infants to fail to respond to any change, including color. On the other hand, if infants' difficulty is not attentional, but has to do with the inability to detect the invariant 3-D form from multiple static views, then we might expect to find a novelty response to a color change, despite the absence of such a response to form change.

Figure 5.17 shows the results of this experiment at 16 weeks of age. The final habituation trial, the first test trial with each test object, and the final (yellow) trial are shown. Two aspects of the data are salient. First, as in the earlier studies at 4, 6, and 8 months of age, there is no differential responding to the test objects as a function of habituation exposure. Second, there is a reliable novelty preference to the yellow object, presented at the very end of the experiment, indicating that subjects had not suffered some overall attentional lapse.

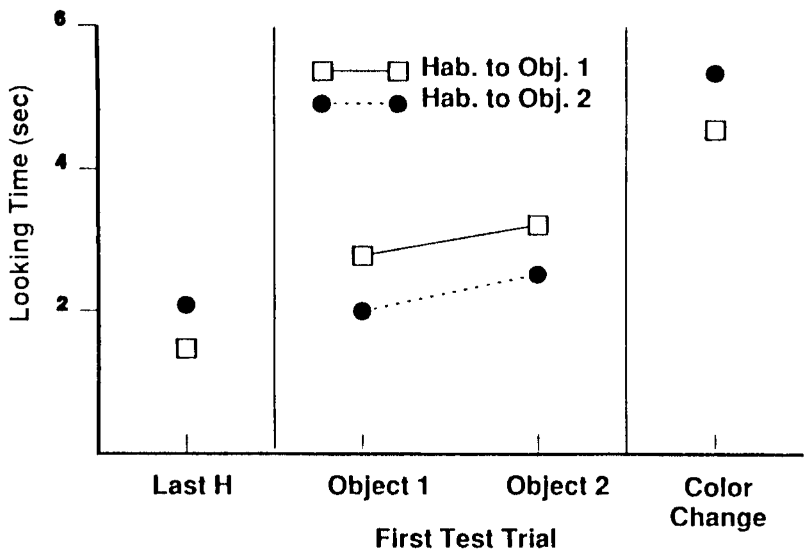

FIG. 5.17. Results in the modified static-view experiment. Looking times on the final trial of habituation, the first test trial with each test object, and the attentional probe trial (color change) are shown.

These results give further indication that static information does not furnish infants with 3-D form information.

There is some evidence that binocular, static views of objects can allow recognition of 3-D forms that have previously been perceived from kinematic information (Owsley, 1983; Yonas et al., 1987). This suggests that some aspects of 3-D structure can be apprehended from stationary, binocular viewing and compared to an overall representation of form given by motion information. There is no evidence that the overall form of the object can be given initially from static views, even multiple and sequential ones.

What is the limitation on 3-D form perception from static information? An abundance of evidence indicates that infants from the earliest months of life can detect and distinguish 2-D patterns, colors, and orientations (e.g., Cohen, DeLoache, & Strauss, 1979). By 6 months of age, virtually all infants have stereoscopic depth perception, which should accurately indicate the slants of surfaces in the studies using real objects. The problem seems to be extrapolating beyond the information in a single view to the whole form. The process is not well understood in adult perception, either, but such extrapolations seem to invoke considerations of symmetry or simplicity (Buffart, Leeuwenberg, & Restle, 1981). Such assumptions may be products of learning. Whether they arise from learning or maturation, the late appearance of such heuristic processes fits our general view about ecological validity in perceptual development. The conformity of unseen parts of objects with predictions made from symmetry or simplicity may be likely but is nowhere near certain. Such extrapolations may form part of the adult perceiver's optimization in perceiving, but they are poor candidates for the repertoire of the risk-averse infant perceiver.

Summary: Perception of 3-D Form

In sum, 3-D form appears to be first perceived visually from perspective transformations given over time. This ability is unlikely to be dependent on learning, because no other source of information about 3-D form is readily available in the early months of life. As one might predict from an ecological analysis of the information, perception of 3-D form occurs from optical changes given by both object and observer motion. In many respects, perception of 3-D form provides developmental evidence for Johansson's (1970) description of the visual system as a *perspective decoder*, using the rules of projective geometry to extract spatial arrangement from optical change. Our studies of form perception are also consistent with an event perception perspective in that static sources of information about form seem to be inoperative through much of the first year of life. Their later appearance parallels their lesser validity from an ecological perspective. It is likely that the 3-D forms of stationary objects viewed from a stationary position are, to a young infant, indeterminate. The overall picture of early 3-D form perception fits closely our portrait of the risk-averse perceiver: The information usable earliest is also the soundest.

PERCEPTION OF MOTION AND STABILITY BY MOVING OBSERVERS

Perceptual theorists have long pondered the fact that motion is signaled by changes in the optical projection, but that such changes can also be produced by an observer moving in a stationary environment. Helmholtz (1909/1962) speculated that early in life, the optical changes produced by self-motion and by object motion were indistinguishable; an active perceiver might learn, however, that certain transformations of the world, such as those caused by moving one's head, can be reversed or undone, while others cannot. In Helmholtz's view, the perception of a stationary world during one's own movement develops from learning about such reversible transformations.

A contrasting view of object and observer motion perception was proposed by J. J. Gibson (1966, 1979). Gibson argued that the visual information specifying motion of objects differs from that specifying motion of the observer. For example, when only a single object moves, optical changes are confined to relatively local regions of the optic array. When the observer moves, global transformations of the optic array result. Given the availability of information distinguishing object and observer motion, and given the fundamental importance of observer motion in perception, such information might be usable by perceivers without learning.

Despite its theoretical centrality, there has not been much research on the development of perception of motion and stability during observer motion in early infancy. Besides its theoretical interest, it would appear to have important practical interest. The Helmholtzian infant would live in a dramatic kaleidoscopic world in which every head or eye movement would set the world into motion. Developing an understanding of both the physical and social worlds would be far more challenging from this starting point than from a more stable representation of the environment. Consider, for example, the task of comprehending the principles governing moving bodies, under conditions in which many, perhaps most, cases of perceived object motion are spurious.

Understanding early abilities for perceiving motion and stability is, thus, a high priority in the study of cognitive development. Although a detailed consideration of the various types of active and passive movements, eye and head movements around various axes, and so forth, is beyond the scope of this chapter (see Kellman & Hofsten, in press), I describe here some initial research into the perception of motion and stability by moving observers.

Motion and Distance Perception

This work focuses on cases in which perceiving motion and stability is related to distance perception. When an observer translates orthogonally to the line of sight, perceived objects undergo optical changes that depend on their distances from the observer. Figure 5.18 depicts this situation. Specifically, if D is the (perpendicular) distance from the observer's motion path to the object and M is the extent of motion, the optical change, Θ, in visual angle is given by:

$$\Theta = 2 \arctan (M/2D) \qquad (1)$$

For small Θ, this can be approximated by the simpler expression:

$$\Theta = M/D, \qquad (2)$$

where Θ is expressed in radians. The same optical change can be given by a moving object at distance $D + d$, if it moves parallel to the observer's motion. The extent of motion x that gives this optical change at distance $D + d$ is given by:

$$x = -dM/D \qquad (3)$$

Note that when d is negative, that is, the moving object is closer than D, x is positive, and the object motion is in the same direction as the observer's.[2] Without referring to a stationary reference point D and an additional increment of distance d, the motion of the target can be determined from the total distance T (equal to $D + d$), the observer's motion (M) and the angular change (Θ) by:

$$x = M - \Theta T \qquad (4)$$

A more revealing form of equation 4 is:

$$x = M - (M/D)(D + d) \qquad (5)$$

in which M/D has been substituted for Θ, and $D + d$ has been substituted for T. In the case in which there is no target movement ($x = 0$), $d = 0$ and $T = D$. Thus, D in general gives the position at which a *stationary* object would give rise to a particular optical displacement given a particular extent of observer motion (the "pivot point" in Gogel's, 1980, terminology). All other combinations of target motion and distance giving the same optical change are pairs (x, d) such that $-x/d = M/D = \Theta$. Perceptually, discriminating a stationary object from one moving parallel to the observer presents a difficult perceptual task because of the ambiguity of optical change alone. Additional information

[2]For simplicity, this analysis is presented for the case in which the stationary target is straight ahead, that is, the line of sight is perpendicular to the direction of motion. The more general analysis would include a correction for the eccentricity of the target; the more eccentric the target (at a given distance from the observer) the smaller the angular change produced by a given observer motion.

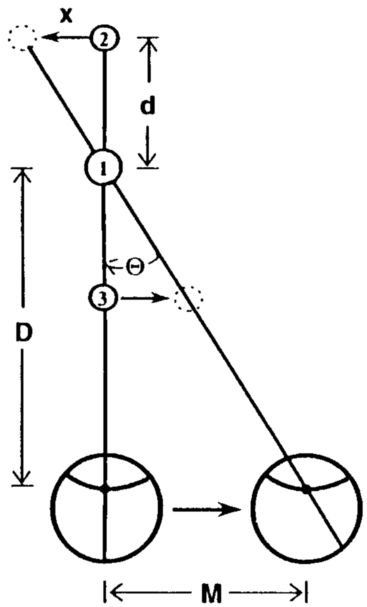

FIG. 5.18. Geometry of parallel object and observer motions. *M* is the extent of lateral observer motion; *D* is the initial distance from the object of the nodal point of the eye; Θ is the angular change for an object at position 1 given by motion *M*. For an object at distance *D* + *d* (labeled 2), object motion *x* gives the same optical change.

(e.g., distance information) is needed to determine whether a given optical change arises from observer or object motion.

Gogel (1980, 1982) has shown that this geometry of distance and motion is utilized in adult perception. That is, perceived movement depends in some circumstances upon perceived distance. Can infants also detect the moving and stationary parts of their environment based on these relations?

To explore these questions, we developed a new method (Kellman, Hofsten, Condry, & O'Halloran, 1991). Infants are passively moved laterally back and forth in a moving chair while viewing arrays of objects. On each trial, one object in the array also moves, parallel to the infant's path of motion. The motions of object and observer are always either in-phase or in opposite-phase (180° out of phase); moments of acceleration/deceleration always coincide. These connections are achieved by mechanically linking the infant's chair and the moving object in a way not visible to the subjects (Fig. 5.19). On each trial, an object moved, either on the right or left side of the array. To control for the particular optical displacement, a stationary object at a different distance is always placed on the other side of the display to give the same extent of optical displacement

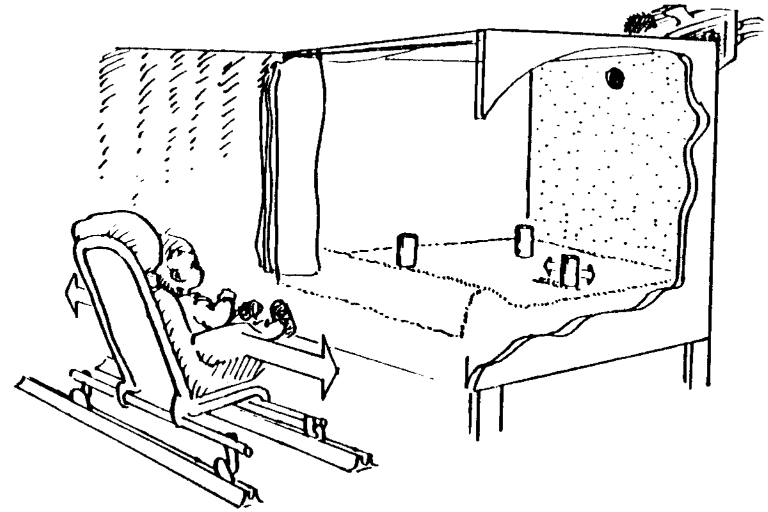

FIG. 5.19. The object-observer motion apparatus.

as the moving object. For in-phase motion, the control object was placed further away; in the opposite-phase condition, the control object is nearer. Examples are given in Figs. 5.20a and b. Additional stationary objects in the displays controlled for possible tendencies of subjects to fixate preferentially the nearest object in the array, the largest object, and so on.

We assumed that if the infants detected one moving object in an array of stationary ones, they would tend to fixate that object preferentially. Infants ordinarily devote greater visual attention to moving objects (Carpenter, 1974; Volkmann & Dobson, 1976). Preferential looking in the direction of the moving object was thus taken to indicate motion detection.

We excluded information about the relation of the objects to the ground surface at their points of tangency by placing a hump at the near edge of the surface, which occluded the bottoms of all objects. Object visual angle was also not a clue to distance: It varied in the arrays between 2.7° diameter × 5.5° height to 4° diameter × 8° height in a way that was uncorrelated with distance.

There were several additional controls for response tendencies that might have biased the results. For example, infants might always prefer to fixate the closest object in an array. This possibility was controlled in opposite-phase conditions because the stationary object with equivalent optical change was always nearer than the moving object. When motion was in-phase, an additional stationary object, closer than the moving one and on the opposite side, was always present. A second possibility is that subjects might attend to the locus of maximum optic flow. In its simplest form, this possibility was controlled for by the

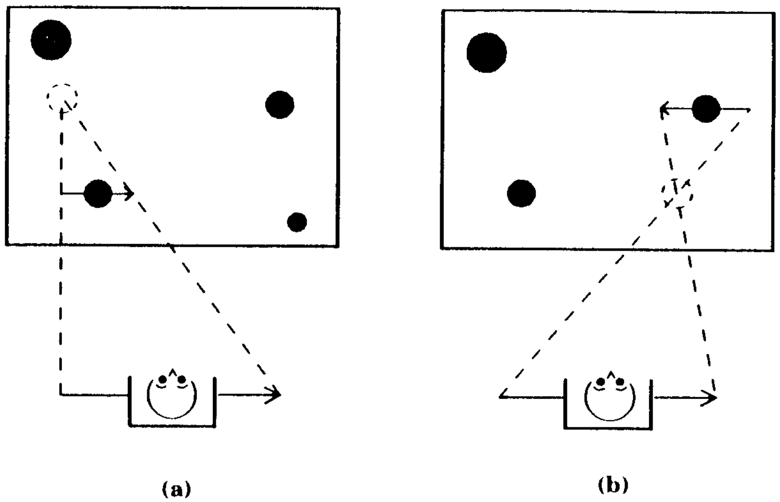

FIG. 5.20. Examples of arrays used in object-observer motion experiments. Top views are shown. Solid circles are cylindrical objects; arrows indicate motion. The dotted object represents the position a stationary object must occupy to produce an optical change identical to the moving object. Such a stationary object is placed in the corresponding position on the other side of the display: (a) in-phase condition, (b) opposite-phase condition. From Kellman, Hofsten, Condry, and O'Halloran (1991).

front edge of the hump, which always had the fastest optical velocity in all conditions. However, a more complex version of this concern is that subjects might attend to the locus of greatest optical shear, that is discontinuities in the optic flow (cf., Nakayama & Loomis, 1974). The hump, which obscured the bottoms of objects, ensured that the shear relations between the moving object and other surfaces were equivalent for the moving and stationary control objects.

Under these conditions, determination of the motion or stability of objects required the combining of distance information with registered optical change. Information given by optical (angular) change and registered extent of self-motion is not sufficient because of the geometric relations already described. In the absence of distance information, an object in this array could be located at one particular position and be stationary, or it could be located at some other distance and moving.

The dependent variable in the experiments was looking time to the left or right halves of the array, as a function of the presence of the moving object on the left or right. With the moving object presented half of the time on the left and half on the right, subjects were presented with a series of 15-sec trials. A session continued until the subject became fussy or a maximum of 25 trials was reached. Certain criteria were established in advance for including subjects

and trials in the analyses. A trial was considered valid if the infant looked at least 1.5 sec at an object. This criterion was used to weed out random, nonattentive glances. Subjects were disqualified if they did not have at least one valid trial of looking to the right and one to the left during the experiment (without regard to the position of the moving object). This criterion eliminated infants whose position bias was so strong that they never looked to one side. To assess motion perception, we compared looking times to the left and right sides of the display as a function of the placement of the moving object. To control for side preferences, the following comparison was used: For all trials, the measure L – R (looking time to the left minus looking time to the right) was calculated. Then, for each subject, mean L – R was calculated separately for trials with the moving object on the left $(L-R)_L$ and right $(L-R)_R$ sides of the display. Finally, $(L-R)_R$ was subtracted from $(L-R)_L$. This gave a single number for each subject, thus ensuring that each subject counted equally in the overall analysis, regardless of differences across subjects in the number of valid trials. This measure—$(L-R)_L$ minus $(L-R)_R$—was then tested against the null hypothesis of 0. That is, if looking times are the same regardless of the position of the moving object, then this derived measure will not differ from 0. The measure will be more positive the more looking time differs with the position of the moving object.

In our first experiments, 16-week-olds viewed the arrays binocularly. Separate groups were tested with in-phase and opposite-phase motion. Results are shown in Figs. 5.21a and b.

Overall looking times in this paradigm are not high. Infants' fixation tendencies, however, were reliably influenced by the position of the moving object. Subjects fixated more to the left when the moving object was on the left, and vice versa. No differences in this pattern were found between the in-phase and opposite-phase conditions. The effect of position of the moving object on the patterns of looking was highly reliable ($p < .01$).

Moving infants can apparently distinguish optical changes resulting from their own motion from those resulting from object motion. Infants seemed both to detect real motion and to attend preferentially to it. Because perceiving position constancy and motion in this situation required distance information apart from optic flow, the results indicate an early ability to combine optical change information with non-flow distance information.

What distance information could this be? Distance and depth information are commonly viewed as falling into four classes: Kinematic, stereoscopic, oculomotor, and pictorial information (e.g., Kaufman, 1974). Pictorial cues do not seem to operate in the first half year of life (Yonas & Granrud, 1984). Many sources of depth information, including stereopsis and most pictorial cues, provide only relative depth information (i.e., depth order). Metrical information about distance would be needed to determine motion or stability. A number of cues were intentionally excluded from the situation. Among cues with the potential

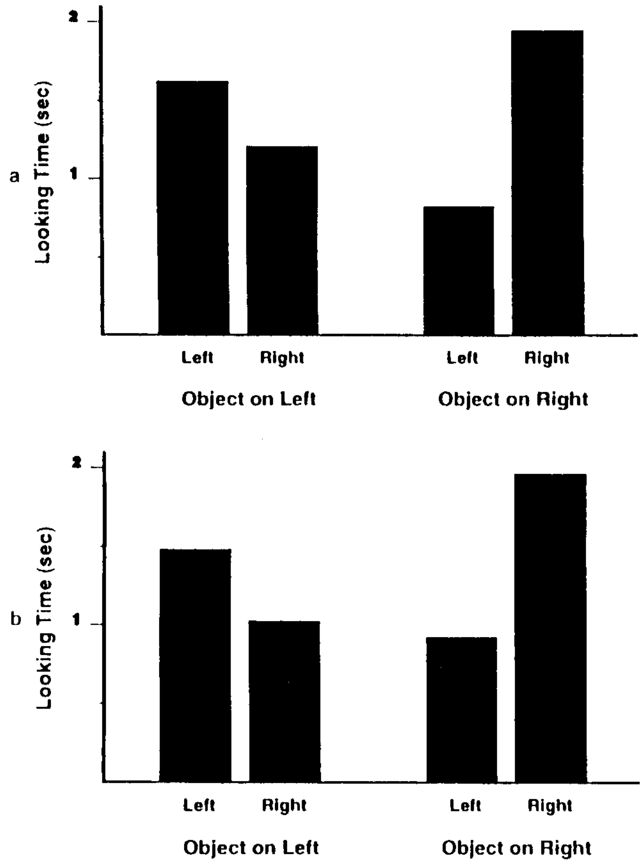

FIG. 5.21. Results of object-observer motion experiment with 16-week-olds, viewing the arrays binocularly. Looking times are shown to the left and right sides of the array when the moving object was on the left or right: (a) in-phase condition, (b) opposite-phase condition. From Kellman, Hofsten, Condry, and O'Halloran (1991).

to indicate absolute distance, a number were explicitly excluded from providing useful information in our set-up. Relative size was excluded by approximately equating the visual angle of relevant objects in the array and randomizing others (i.e., there was no correlation between visual angle and distance). I noted earlier that certain kinematic variables (e.g., optical shear) between the object and support surface at points of object tangency, were eliminated by occluding the bottoms of all objects. Another kinematic information source is motion perspective. When a moving observer views a stationary object, if the extent of observer motion is known, the absolute distance of the object is potentially re-

coverable. In our arrangement, however, motion perspective information could not determine object motion or stability. When both the motion/stability and the depth of an object is in question, the optical change cannot be used to specify both.

The remaining two classes of information offer better prospects. Oculomotor cues—accommodation and convergence—involve information from the eye muscle adjustments needed to focus or converge the eyes. The other remaining information source is ***stereopsis***, or binocular disparity. Stereopsis is perhaps the only static information source whose ecological validity and precision equals or approaches that of kinematic information. In recent years, a clear picture of the emergence of stereoscopic depth perception has emerged from a number of investigations (Braddick, Wattam-Bell, Day, & Atkinson, 1983; Fox, Aslin, Shea, & Dumais, 1980; Held, Birch, & Gwiazda, 1980). Stereoacuity seems virtually non-existent from birth to about 12 to 14 weeks, after which it reaches near-adult levels fairly rapidly. By 16 weeks, estimates are that about half of infants have stereoscopic function (Held et al., 1980). The relatively abrupt onset and increase in acuity, along with certain electrophysiological findings, suggest that stereoscopic depth perception arises from maturation of the nervous system (Braddick & Atkinson, 1988; Held et al., 1980).

Stereoscopic and oculomotor function are closely related. For instance, proper convergence of the eyes is a prerequisite for obtaining meaningful disparity information. Oculomotor information may also be used to calibrate binocular disparity (Wallach & Zuckerman, 1963). The advantage of this combination is that disparity alone provides only relative depth information, but with very high sensitivity. The oculomotor cues (especially convergence) can provide *absolute* distance information, but only in very near space (approximately 2 meters) and with modest precision.

There has been little study of convergence as a source of distance information early in life. Several studies have assessed the accuracy of convergence (Aslin, 1977; Slater & Findlay, 1975), showing vergence changes appropriate in direction, if not highly precise, from birth. One study attempted to assess perception of distance based on convergence. Hofsten (1977) altered 20-week-olds' convergence using optical devices. He found appropriate changes in the lengths of subjects' reaches for objects. Whether convergence provides useful distance information earlier than 20 weeks is unknown. Convergence appears, however, to be the best candidate for the distance information underlying motion detection in our experiments with 16-week-olds. It is also possible that a combination of convergence and binocular disparity provide the needed distance information. Convergence has also been suggested to be the distance information underlying size perception by neonates (see Granrud, this volume).

To test the hypothesis that convergence provided necessary information in our experiments, we carried out experiments under monocular viewing. Subjects were fitted with a patch over one eye. If motion detection depended on

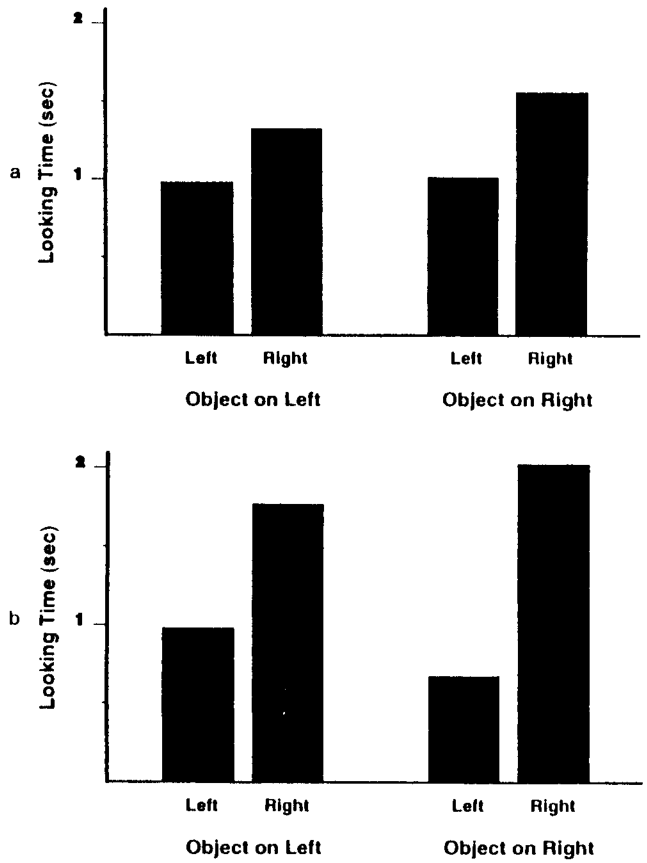

FIG. 5.22. Results of object-observer motion experiment with 16-week-olds, viewing the arrays monocularly: (a) in-phase condition, (b) opposite-phase condition. From Kellman, Hofsten, Condry, and O'Halloran (1991).

convergence or convergence plus disparity, it should have been eliminated under monocular viewing.[3] Figure 5.22 shows the results from these studies for in-phase and opposite-phase object-observer motions. As predicted, monocular viewing eliminated motion detection: Infants' looking patterns were not reliably influenced by the position of the moving object.

The results described so far suggest that moving infants detect motion and stability by using binocular distance information. There is an alternative inter-

[3]This excludes the possibility of accommodatively triggered vergence. The results disconfirm this possibility, however.

pretation, however. The eyepatch used in the monocular condition might have caused some general distress or inattention rather than reducing the ability to detect motion. An experiment carried out by Kirsten Condry tested this possibility (Condry, 1988; Kellman, Hofsten, Condry, & O'Halloran, 1991). Infants wore an eyepatch but were stationary throughout the experiment. The moving objects appeared just as in previous studies, half of the time on the left and half on the right. Detecting motion in this case requires no binocular information, because the observer is stationary. If the negative results in the previous monocular conditions resulted from general inattention or distress caused by the eyepatch (rather than from an inability to detect motion), then these infants were predicted to fail to look preferentially at the moving object. If distress or inattention was not the reason for monocular infants' difficulty in the earlier study, infants would be expected to show motion detection in this case.

Figure 5.23 shows the data from this experiment. Stationary, monocular infants clearly detected the moving objects. Fixation was greater toward the side of the array on which the moving object appeared. The eyepatch did not cause distraction sufficient to keep the infants from attending to motion. From this outcome, it appears unlikely that the failure of moving, monocular infants to detect object motion was due to general distress or inattention caused by the eyepatch. It appears that moving, monocular infants did not detect motion because they require binocular distance information to do so.

As noted already, if binocular distance information underlies infants' motion detection, this binocular information could be supplied by convergence or by a combination of convergence and binocular disparity. Can we specify further which information is at work?

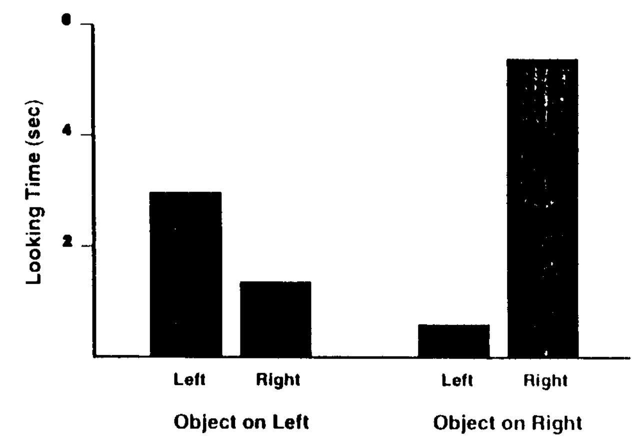

FIG. 5.23. Results of experiment with stationary viewing by monocular subjects. From Kellman, Hofsten, Condry, and O'Halloran (1991).

In our studies of 16-week-old infants, we did not pretest for stereoscopic ability. It is thus possible that some combination of binocular disparity and convergence furnished the relevant information about distance. Binocular disparity cannot specify absolute distance; however, it can provide precise absolute depth intervals in combination with a source of absolute distance information, such as convergence, that can specify the distance of at least one visible point (Wallach, Moore, & Davidson, 1963).

To assess the roles of convergence and disparity, we conducted experiments in the object–observer motion paradigm with 8-week-old infants (Kellman, Hofsten, Van de Walle, & Condry, 1991). Infants of this age, in general, show no stereoscopic depth perception, but they do show convergence. There is little or no data, however, indicating whether convergence provides usable distance information at this age.

The experiments were carried out in the same way as those with older infants. Object motion of the same phase and of opposite phase were tested in separate studies. Only binocular conditions were run; we assumed that since monocular 16-week-olds had been unable to detect motion, younger infants would be also.

Results are shown in Fig. 5.24. In contrast to earlier studies, there was a difference between the data obtained from in-phase and opposite-phase motion. When the object moved in opposite phase to the observer (Fig. 5.24a), 8-week-olds showed clear evidence of motion detection, but when the object moved in phase (Fig. 5.24b), motion detection was not observed.

From the results in the opposite-phase condition, it appears that motion detection is possible from convergence information alone. The motion preference in this condition was as strong as that of 16-week-olds in either phase condition. Such a pattern was not evident, however, in the in-phase condition. This outcome may reflect certain sensory limitations of 8-week-olds, along with finer discriminations demanded by the in-phase motion condition (in which the stationary control object was positioned further away than the moving object; for discussion, see Kellman & Hofsten, in press).

These studies suggest that at 8 weeks convergence alone can furnish the absolute distance information that underlies motion detection. Subjects' difficulty with in-phase motion indicates that these younger infants are not as well-equipped to use distance-motion relations as their older counterparts; nevertheless, the basic perceptual capacity appears to be present. Stereoscopic depth perception, which 8-week-olds lack, does not appear to be a prerequisite. Still, it is likely that the later onset of depth perception from disparity increases the specificity of detection of motion and stability.

The possibility that convergence is a primary source of distance information is consistent with recent studies of size constancy in newborns (Granrud, 1987; Slater, Mattock, & Brown, 1990). Evidence from these studies suggests that newborns are sensitive to the real sizes of objects across changes in their project-

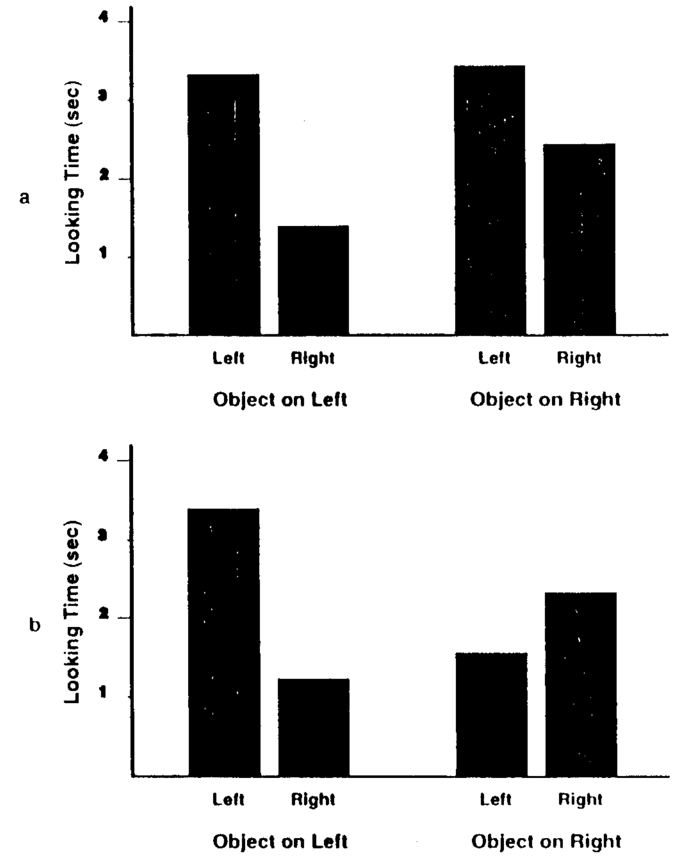

FIG. 5.24. Results of object-observer motion experiment with 8-week-olds, viewing the arrays binocularly: (a) in-phase condition, (b) opposite-phase condition. From Kellman, Hofsten, Van de Walle, and Condry (1991).

ed size and distance. Although size constancy may sometimes be achieved in other ways, such as in connection with optical texture gradients (J. J. Gibson, 1950, 1979), Granrud's situation is one in which distance information, implicit or explicit, appears to be required. Hence, his experiments suggest that some form of absolute distance perception is innate.

Motion and the "Blooming, Buzzing Confusion"

In discussing perception of object unity and 3-D form, we were concerned with persisting properties of the environment. In this section, I have considered some of the kinematic foundations of perceiving *events* or changes in the environment, such as the motions of objects and observers. Our findings suggest an early capacity for perceiving a coherent environment, in which stationary objects remain perceptually at rest when the observer moves, and moving objects may be detected. The basis of these early abilities seems to be a combination of optic flow information with nonflow distance information. This combination successfully grapples with the geometry of object–observer motion, in which an optical change alone may be produced in more than one way.

Taken at face value, the present results constitute another example of linkages in perception among dependent variables. Perceived motion is not strictly a function of some optical change, but results from a computation involving distance as well (Gogel, 1982). This characterization, however accurate, may have limited generality. Recall that we have restricted our test conditions intentionally to cases in which detection of motion required distance information. Although these cases form an important subset of naturally occurring cases, in many, perhaps most, ordinary circumstances additional information is available. Perception of the moving and stationary parts of the environment may often be accomplished directly from optic flow variables, such as optical shearing or relations between optical velocity and occlusion (Lee, 1974). Thus, it would be incorrect to claim from our results to date that moving infants' motion detection generally requires distance information. What can be said is that infants display such dependent variable coupling in cases that require it.

The role of kinematic information in motion detection fits our general view of ecological validity and risk aversion. Information in spatiotemporal change is crucial, but its specific status depends on its ecological roots. In some cases when objects and observers move, the geometry of the situation requires information in addition to optic flow; when information sources are combined, the movements and positions of parts of the environment are well-specified. Perhaps because of its ecological validity, perceptual systems capable of utilizing this spacetime geometry are present early in life.

CONCLUSION

Perception of persisting properties, such as object unity and form, and events, such as object or observer motion, comprise some of the most fundamental tasks of development. I have argued that spatiotemporal information, because of its ecological status and the evolution of perceptual systems, plays a preeminent role in the achievement of these tasks. As a closing example, we might contrast this perspective with a different one on the initial perception of motion. The notion that optical changes due to observer and object motion are not distinguishable early in life has a long history (Helmholtz, 1909/1962; James, 1890; cf., Piaget, 1954). On such a view, the world would appear to move whenever objects or observers do. The resulting chaos would surely contribute greatly

to the "blooming, buzzing confusion," as James (1890, p. 173) characterized the world of the newborn.

Such a view could hardly be at greater variance with our conjecture of risk aversion in perceptual development. To a newborn, the mistaken assignment of motion to objects in the world would be a severe handicap to learning about the physical world. The learning process suggested by Helmholtz—that perceivers come to notice and discount observer-contingent motions—might be of little consolation. Infants might just as well learn that when they move, some objects also move, instead of learning that the world remains at rest during observer motion. Although imaginable, misassignment of motion to external objects would require an unlearning process of considerable sophistication.

The results we have considered, in motion as well as object perception, are consistent with a wholly different view: Perceptual systems have evolved to furnish useful descriptions of the environment. At no time in human development is the soundness of information of greater import than during infancy; consequently, infant perception may be risk-averse. Risk aversion is best served by early perceptual capacities that utilize the most ecologically secure information. From such a perspective, it is not surprising that the geometry of observer and object motion seems to be appropriately utilized to perceive motion and stability in the early weeks of life.

We have seen that the particulars of kinematic information differ in different domains. The motions of objects through the environment are crucial to the primitive process of unity perception. For 3-D form perception, on the other hand, either object or observer motion alone can furnish the crucial information. Where perception of motion is itself the issue, the geometry of distance and motion requires combining kinematic information with other sources of spatial information. The invariant theme is not that early perceptual competence is tied to one sort of motion or optical change, but that in each domain it appears to be tied to the kinematic information possessing the highest ecological validity.

The conjecture that kinematic information dominates early perception because of its superior ecological validity is consistent with the evidence I have discussed about early perception of objects, space, and motion. It is, however, a broad characterization not subject to a single empirical test. My examples and arguments have been selective. At least, however, the conjecture is heuristically useful for summarizing current knowledge about early perceptual development. At most, it may be much more. The young perceiver seems to be able to extract meaningful information about objects, the spatial layout, and events. The means to achieve these feats do not comprise the full complement of adult abilities, but a clear subset. That subset seems to be dominated by spatiotemporal information sources that not only are usable by the perceptual systems of inexperienced perceivers, but are apparently the very sources of information most securely rooted in the basic physics and geometry of space and time.

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REFERENCES

Allman, J., Miezin, F., & McGuinness, E. (1985). Direction- and velocity-specific responses from beyond the classical receptive field in the middle temporal visual area. *Perception, 14,* 105-126.

Ames, A. (1951). Visual perception and the rotating trapezoidal window. *Psychological Monographs, 67* (7, Whole No. 324).

Aslin, R. N. (1977). Development of binocular fixation in human infants. *Journal of Experimental Child Psychology, 23,* 133-150.

Aslin, R. N. (1988). Anatomical constraints on oculomotor development: Implications for infant perception. In A. Yonas (Ed.), *The Minnesota symposia on child psychology: Vol. 20. Perceptual development in infancy* (pp. 67-104). Hillsdale, NJ: Lawrence Erlbaum Associates.

Berkeley, G. (1910). *Essay toward a new theory of vision.* London: Dutton. (Original work published 1709)

Bertenthal, B. I., Campos, J. J., & Haith, M. M. (1980). Development of visual organization: The perception of subjective contours. *Child Development, 51,* 1072-1080.

Bond, E. (1972). Perception of form by the human infant. *Psychological Bulletin, 77,* 225-245.

Braddick, O., & Atkinson, J. (1988). Sensory selectivity, attentional control, and cross-channel integration in early visual development. In A. Yonas (Ed.), *The Minnesota symposia on child psychology: Vol. 20. Perceptual development in infancy* (pp. 105-144). Hillsdale, NJ: Lawrence Erlbaum Associates.

Braddick, O., Wattam-Bell, J., Day, J., & Atkinson, J. (1983). The onset of binocular function in human infants. *Human Neurobiology, 2,* 65-69.

Braunstein, M. (1976). *Depth perception through motion.* New York: Academic Press.

Brunswik, E. (1956). *Perception and the representative design of psychological experiments.* Berkeley: University of California Press.

Buffart, H., Leeuwenberg, E., & Restle, F. (1981). Coding theory of visual pattern completion. *Journal of Experimental Psychology, 7,* 241-274.

Carpenter, G. C. (1974). Visual regard of moving and stationary faces in early infancy. *Merrill-Palmer Quarterly, 11,* 182-193.

Cohen, L., DeLoache, J., & Strauss, M. (1979). Infant visual perception. In J. Osofsky (Ed.), *Handbook of infant development* (pp. 393-438). New York: Wiley.

Condry, K. (1988). *Four-month-old infants' perception of moving objects during observer motion.* Unpublished manuscript.

Epstein, W. (1982). Percept-percept couplings. *Perception, 11,* 75-83.

Fantz, R. L., Fagan, J. F., III, & Miranda, S. B. (1975). Early visual selectivity as a function of pattern variables, previous exposure, age from birth and conception, and expected cognitive deficit. In L. B. Cohen & P. Salapatek (Eds.), *Infant perception: From sensation to cognition* (Vol. 1, pp. 241-345). New York: Academic Press.

Fodor, J. (1983). *The modularity of mind.* Cambridge, MA: MIT Press.

Fox, R., Aslin, R., Shea, S., & Dumais, S. (1980). Stereopsis in human infants. *Science, 207,* 323-324.

Gibson, E. J. (1969). *Principles of perceptual learning and development.* New York: Appleton-Century-Crofts.

Gibson, E. J. (1984). Perceptual development from the ecological approach. In M. Lamb, A. Brown, & B. Rogoff (Eds.), *Advances in developmental psychology* (Vol. 3, pp. 243-285). Hillsdale, NJ: Lawrence Erlbaum Associates.

Gibson, J. J. (1950). *The perception of the visual world.* Boston: Houghton-Mifflin.

Gibson, J. J. (1966). *The senses considered as perceptual systems.* Boston: Houghton-Mifflin.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston: Houghton-Mifflin.

Gibson, J. J., & Gibson, E. J. (1955). Perceptual learning: Differentiation or enrichment? *Psychological Review, 62,* 32-41.

Gibson, J. J., Kaplan, G., Reynolds, H. N., & Wheeler, K. (1969). The change from visible to invisible: A study of optical transitions. *Perception and Psychophysics, 5,* 113-116.

Gogel, W. (1980). The sensing of retinal motion. *Perception & Psychophysics, 28*(2), 155-163.

Gogel, W. (1982). Analysis of the perception of motion concomitant with a lateral motion of the head. *Perception & Psychophysics, 32*(3), 241-250.

Granrud, C. E. (1987). Size constancy in newborn human infants. *Investigative Ophthalmology and Visual Science, 28,* (Supplement), 5.

Harris, P. (1983). Infant cognition. In M. M. Haith & J. J. Campos (Eds.), *Cognitive development* (pp. 689-782). New York: Wiley.

Held, R., Birch, E. E., & Gwiazda, J. (1980). Stereoacuity of human infants. *Proceedings of the National Academy of Sciences (USA), 77,* 5572-5574.

Held, R., & Hein, A. (1963). Movement-produced stimulation in the development of visually-guided behavior. *Journal of Comparative and Physiological Psychology, 56,* 872-876.

Helmholtz, H. von (1962). *Treatise on physiological optics* (3rd ed.; J. P. C. Southall, Ed.). New York: Dover. (Original work published 1909)

Helson, H. (1933). The fundamental propositions of Gestalt psychology. *Psychological Review, 40,* 13-32.

Hering, E. (1861). *Beitrage zur Physiologie* (Heft 1) [Introduction to physiology, Vol. 1]. Leipzig: Englemann.

Hochberg, J. (1974). Higher-order stimuli and inter-response coupling in the perception of the visual world. In R. B. McLeod & H. L. Pick, Jr. (Eds.), *Perception: Essays in honor of J. J. Gibson* (pp. 17-39). Ithaca, NY: Cornell University Press.

Hoffman, D. D., & Richards, W. A. (1984). Parts of recognition. *Cognition, 18,* 65-96.

Hofsten, C. von (1977). Binocular convergence as a determinant of reaching behavior in infancy. *Perception, 6,* 139-144.

James, W. (1890). *The principles of psychology* (Vol. 2). New York: Holt.

Johansson, G. (1970). On theories for visual space perception. *Scandinavian Journal of Psychology, 11,* 67-74.

Johansson, G., Hofsten, C. von, & Jansson, G. (1980). Event perception. *Annual Review of Psychology, 31,* 27-63.

Kaufman, L. (1974). *Sight and mind.* New York: Oxford University Press.

Kaufmann-Hayoz, R., Kaufmann, F., & Walther, D. (1988, April). *Perception of kinetic subjective contours at 5 and 8 months.* Paper presented at the Sixth International Conference on Infant Studies, Washington, DC.

Kellman, P. J. (1984). Perception of three-dimensional form in infancy. *Perception and Psychophysics, 36,* 353–358.
Kellman, P. J., Gleitman, H., & Spelke, E. S. (1987). Object and observer motion in the perception of objects by infants. *Journal of Experimental Psychology: Perception and Performance, 13*(4), 586–593.
Kellman, P. J., & Hofsten, C. von (in press). The world of the moving infant: Perception of objects, motion and space. In C. Rovee-Collier & L. Lipsitt (Eds.), *Advances in infancy research.* Norwood, NJ: Ablex.
Kellman, P. J., Hofsten, C. von, Condry, K., & O'Halloran, R. (1991). *Motion and stability in the world of the (moving) infant.* Unpublished manuscript.
Kellman, P. J., Hofsten, C. von, Van de Walle, G., & Condry, K. (1991). *Perception of motion and stability during observer motion by pre-stereoscopic infants.* Unpublished manuscript.
Kellman, P. J., & Loukides, M. G. (1987). An object perception approach to static and kinetic subjective contours. In G. Meyer & G. Petry (Eds.), *The perception of illusory contours* (pp. 151–164). New York: Springer-Verlag.
Kellman, P. J., & Shipley, T. F. (1991). A theory of visual interpolation in object perception. *Cognitive Psychology, 23,* 141–221.
Kellman, P. J., & Short, K. R. (1985, April). *Infant form perception from perspective transformations.* Paper presented at the meeting of the Society for Research in Child Development, Toronto, Canada.
Kellman, P. J., & Short, K. R. (1987, June). *Infant perception of partly occluded objects: The problem of rotation.* Paper presented at the Third International Conference on Event Perception and Action, Uppsala, Sweden.
Kellman, P. J., & Spelke, E. (1983). Perception of partly occluded objects in infancy. *Cognitive Psychology, 15,* 483–524.
Kellman, P. J., Spelke, E., & Short, K. R. (1986). Infant perception of object unity from translatory motion in depth and vertical translation. *Child Development, 57,* 72–76.
Koenderink, J. J. (1986). Optic flow. *Vision Research, 26,* 161–180.
Koffka, K. (1935). *Principles of Gestalt psychology.* New York: Harcourt Brace Jovanovich.
Lee, D. N. (1974). Visual information during locomotion. In R. B. McLeod & H. L. Pick (Eds.), *Perception: Essays in honor of J. J. Gibson* (pp. 239–252). Ithaca, NY: Cornell University Press.
Longuet-Higgins, H. C., & Prazdny, K. (1980). The interpretation of moving retinal images. *Proceedings of the Royal Society, London B, 208,* 385–397.
Mandler, J. (1988). How to build a baby: On the development of an accessible representational system. *Cognitive Development, 3,* 113–136.
Marr, D. (1982). *Vision.* San Francisco: W. H. Freeman.
Michotte, A., Thines, G., & Crabbe, G. (1964). Les complements amodaux des structures perceptives. *Studia Psycologica.* Louvain: Publications Universitaires de Louvain.
Mill, J. S. (1965). Examination of Sir William Hamilton's philosophy. In R. Herrnstein & E. G. Boring (Eds.), *A source book in the history of psychology* (pp. 182–188). Cambridge, MA: Harvard University Press. (Original work published 1865)
Nakayama, K., & Loomis, J. M. (1974). Optical velocity patterns, velocity-sensitive neurons, and space perception: A hypothesis. *Perception, 3,* 63–80.
Owsley, C. (1983). The role of motion in infants' perception of solid shape. *Perception, 12,* 707–718.
Pentland, A. (1990). Photometric motion. *Investigative Ophthalmology and Visual Science Supplements, 31,* 172.
Piaget, J. (1954). *The construction of reality in the child.* New York: Basic Books.
Regan, D., & Beverly, K. I. (1978). Looming detectors in the human visual pathway. *Vision Research, 18,* 415–421.
Regan, D., & Cynader, M. (1979). Neurons in area 18 of cat visual cortex selectively sensitive to changing size: Non-linear interactions between responses to two edges. *Vision Research, 19,* 699–711.

Rock, I. (1977). In defense of unconscious inference. In W. Epstein (Ed.), *Stability and constancy in visual perception* (pp. 321–373). New York: Wiley.
Rogers, B., & Graham, M. (1979). Motion parallax as an independent cue for depth perception. *Perception, 8,* 125–134.
Ruff, H. A. (1978). Infant recognition of the invariant form of objects. *Child Development, 49,* 293–306.
Salapatek, P. (1975). Pattern perception in early infancy. In L. B. Cohen & P. Salapatek (Eds.), *Infant perception: From sensation to cognition* (pp. 133–248). New York: Academic Press.
Schmidt, H., & Spelke, E. S. (1984, April). *Gestalt relations and object perception in infancy.* Paper presented at the International Conference on Infant Studies, New York.
Shaw, L., Roder, B., & Bushnell, E. (1986). Infants' identification of three-dimensional form from transformations of linear perspective. *Perception and Psychophysics, 40,* 301–310.
Shepard, R. N. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving imaging, thinking, and dreaming. *Psychological Review, 91,* 417–447.
Shipley, T. F., & Kellman, P. J. (1990). Perception of partly occluded objects and subjective figures: Evidence for a common process. *Investigative Ophthalmology and Visual Science Supplements, 31,* 106.
Slater, A. M., & Findlay, J. M. (1975). Binocular fixation in the newborn baby. *Journal of Experimental Child Psychology, 20,* 248–273.
Slater, A., Mattock, A., & Brown, E. (1990). Size constancy at birth: Newborn infants' responses to retinal and real size. *Journal of Experimental Child Psychology, 49,* 314–322.
Slater, A., Morison, V., Somers, M., Mattock, A., Brown, E., & Taylor, D. (1990). Newborn and older infants' perception of partly occluded objects. *Infant Behavior and Development, 13,* 33–49.
Spelke, E. S. (1985). Perception of unity, persistence and identity: Thoughts on infants' conceptions of objects. In J. Mehler & R. Fox (Eds.), *Neonate cognition* (pp. 89–113). Hillsdale, NJ: Lawrence Erlbaum Associates.
Titchener, E. B. (1924). *A textbook of psychology.* New York: Macmillan.
Todd, J. T. (1982). Visual information about rigid and nonrigid motion: A geometric analysis. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 238–252.
Ullman, S. (1979). *The interpretation of visual motion.* Cambridge, MA: MIT Press.
Volkmann, F. C., & Dobson, M. V. (1976). Infants responses of ocular fixation to moving visual stimuli. *Journal of Experimental Child Psychology, 22,* 86–89.
Wallach, H. (1985). Learned stimulation in space and motion perception. *American Psychologist, 40,* 399–404.
Wallach, H., & O'Connell, D. N. (1953). The kinetic depth effect. *Journal of Experimental Psychology, 45,* 205–217.
Wallach, H., & Zuckerman, C. (1963). The constancy of stereoscopic depth. *American Journal of Psychology, 76,* 404–412.
Walls, G. (1942). *The vertebrate eye and its adaptive radiation.* New York: Hafner.
Warren, R. (1976). The perception of egomotion. *Journal of Experimental Psychology: Human Perception and Perfeormance, 2,* 448–456.
Wertheimer, M. (1912). Experimentelle studien uber das sehen von bewengung. *Zeitschrift fur Psychologie, 61,* 161–265.
Yonas, A., Arterberry, M., & Granrud, C. (1987). Four-month-old infants' sensitivity to binocular and kinetic information for three-dimensional object shape. *Child Development, 58,* 910–917.
Yonas, A., & Granrud, C. (1984). The development of sensitivity to kinetic, binocular, and pictorial depth information in human infants. In D. Ingle, D. Lee, & M. Jeannerod (Eds.), *Brain mechanisms and spatial vision.* Amsterdam: Martines Nijoff.