

# *Ontogenesis of Space and Motion Perception*

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## I. INTRODUCTION

Thirty years ago, a discussion of the origins and development of visual space and motion perception would have been an exercise in speculation. At best, such a discussion might have included weak inferences from studies of adult performance, some philosophical conjectures, and some inconclusive reports of tests on visually impaired subjects whose sight had surgically been restored. Perhaps most noteworthy at that time were early reports of possible ways to study perception in early infancy (e.g., Bridger, 1961; Fantz, 1958, 1964; E. J. Gibson & Walk, 1960). The ensuing three decades have delivered on the promise of those early reports to produce a scientific understanding of the origins of perception. Although there is more to be learned, and new kinds of questions have replaced those answered, we can now present a reasonably detailed picture of early perceptual abilities.

In this chapter we examine what has been learned about the development of perception of space and motion. In the first part of the chapter, we address space, and in the second, motion. We also find important connections between the two along the way. There are several tasks not undertaken in this chapter. We review little data about developmental neuroanatomy or neurophysiology and consider only selectively the large body of research

characterizing sensory discrimination abilities of the infant's visual system. We include findings in which the relation between sensory capacities and perceptual function is fairly clear. This strategy derives only from considerations of space and direct utility. For more comprehensive reviews of basic visual sensitivities, the reader is referred to Banks and Salapatek (1983) or Banks and Dannemiller (1987).

We also confine our attention to *visual* perception of space and motion. Vision is primary in guiding our movements and spatially oriented activity; it provides the most detailed information about objects, spatial layout, and events. Vision has also been a primary focus of research on the development of space and motion perception. Important aspects of spatial and kinematic perception involving auditory space perception, vestibular influences, and intermodal perception are beyond our scope in this chapter.

## II. SPACE: THE FIRST FRONTIER

Space is the first frontier in human perceptual and cognitive development. It is the stage on which all objects reside and in which all events unfold. To understand early spatial perception abilities is to understand many of the limits on what else can be perceived, what parts of the world can be comprehended, and what can be learned.

The study of the origins of spatial perception also occupies a central place in perceptual theory. The nature of mature perception may be revealed by understanding what competencies are part of humans' innate endowment and what and how others arise. A classical and persistent view holds that space is a construction from more primitive elements, achieved by experience (Berkeley, 1709/1910; Harris, 1983; Helmholtz, 1867/1925; Piaget, 1954). Originally, this view was advanced on logical grounds (Berkeley, 1709/1910): Vision was held to be inherently ambiguous because of the loss of information in projecting a three-dimensional (3-D)-world onto a two-dimensional (2-D) retina. Assuming this ambiguity, visual perception of the outside world can only be achieved by combining visual sensations with extra-visual information. On most accounts this combination occurred through extensive learning (Berkeley, 1709/1910; Helmholtz, 1867/1925; Piaget, 1954; for a recent revival of this type of account, see Nakayama & Shimojo, 1992). An alternative, ecological view places spatial perception in an evolutionary context: Perceptual systems evolved to deliver useful information about the physical world (Gibson, 1966; Johansson, 1970). Underlying this proposal is a revised analysis of the information available to vision. Kinematic and stereoscopic information can remove many of the ambiguities inherent in the interpretation of single, static, 2-D images. Thus, the logical arguments regarding early visual competence may be dismissed; moreover, the existence of visually guided, spatially oriented behavior in

newborns of some other species (E. J. Gibson & Walk, 1960; Hess, 1956) provides at least an existence proof for the possibility of unlearned perceptual mechanisms. None of these considerations settle the issues of perception's origins in human beings, however. In the absence of prevailing logical arguments, these issues must be settled by empirical study. Although investigators have tried to settle them indirectly by making inferences from adult abilities (Gottschaldt, 1926; Senden, 1960; Wallach, 1985), real progress on these issues awaited the development of techniques, over the past few decades, for studying human infants.

### A. The Task of Early Space Perception

Before examining specific spatial abilities, it is useful to place them in a functional context. For animate organisms, the functions of space and motion perception are obvious. They guide locomoting through the environment, avoiding hazards, reproducing, acquiring nutrition, and so on. A striking fact for understanding early perceptual ability in *homo sapiens* is that human infants do virtually none of these things. On average, a human infant does not crawl until 6–7 months, does not walk until about 1 year, and does not even reach effectively until 4–5 months. On attaining these milestones, the infant still remains relatively incompetent in finding its own nutrition or escaping danger. Yet by 1 year, the infant's perceptual abilities are adultlike in many, perhaps most, respects, and from the earliest months, infants are engaged in earnest attention to spatial and kinematic features of their environments.

It has been argued (Kellman, 1993; Mandler, 1988) that the function of perception early in life is to underwrite cognitive development. Despite the lack of motor skill, the infant is actively engaged in learning about the physical and social worlds. The perceptual skills available in this period dictate the pace and content of that learning.

The study of the constraints spatial perception places on early learning about the physical and social environments is not far advanced. The foundation of such an analysis must be a clear characterization of early space perception abilities: What spatial properties are perceivable, how, and how well? These questions are our focus.

Besides facilitating early learning, another task of early spatial perception might be learning new perceptual skills. These might be of at least two varieties. One is the more precise extraction and differentiation of information resulting from experience (E. J. Gibson, 1969). The other is that certain detectable stimulus variables might come to specify spatial properties of the environment due to learning. This latter idea has a long history of fervent advocates, although there is little evidence for it in early development. One possible explanation is that the idea is misconceived (Gibson &

Gibson, 1955), but other explanations are possible. Some evidence in adult perception is consistent with the idea that new depth cues can be learned by correlation with old ones (Wallach & O'Leary, 1982). Our profile of early spatial abilities helps make clear which sources of spatial information usable by adults might be products of learning, and those that almost certainly are not.

Sources of information about depth and distance are remarkably numerous. For convenience, we organize them into classes based on similarities in their physical foundations and somewhat by the mechanisms by which they are processed. The four classes are motion-carried information, stereoscopic information, oculomotor information, and pictorial information. This organization differs slightly from some other groupings (e.g., Yonas & Owsley, 1987).

## B. Motion-Carried Information about Space

Motion-carried information is arguably the most important source of spatial information for adults, given its precision and informativeness for spatial layout, guidance of locomotion, and skilled action. Motion-carried information is also noteworthy in being unambiguous under very reasonable constraints (e.g., Lee, 1974). For example, the depth ordering of viewed objects given by motion perspective when an observer moves her head back and forth is unequivocal, assuming only that the objects do not move contingent on the observer's movement. Infants do not self-locomote until the second half of their first year, so one might conjecture that motion-carried information would not have developmental priority. The ecological validity of motion information, however, might suggest the opposite. Early learning about the environment might be best served by reliance on only the most accurate sources of information, even if this means that some perceptual situations will be indeterminate (Kellman, 1993).

Spatial information carried by motion is multifaceted. Diverse sources of information reveal diverse aspects of the environment. We consider four: (1) *Optical expansion-contraction* can indicate relative motion between a target and the observer. (2) *Motion parallax or motion perspective* can indicate relative and possibly absolute distance from the observer under some conditions. (3) *Accretion-deletion of texture* can indicate depth ordering of surfaces. (4) The continuously changing optical projection of an object, given by object or observer motion, carries information about its 3-D form, allowing perception of *structure-from-motion* (SFM).

### 1. Kinematic Information for Approach

The optical projection of an approaching object expands symmetrically as the object comes closer to colliding with the observer. The *time-to-contact* of

an object is derivable from the projected boundary's retinal eccentricity and its time derivative (Lee, 1974), and there is some evidence that this information indicates time to contact in adult perception (Lee, Lishman, Roly, & Thomson, 1982). Studies with other species indicate that optical expansion patterns elicit unlearned defensive responses (Schiff, 1965). Early studies of human infants 1–2 months old suggested that optical expansion triggers head retraction, raising of the arms, and blinking (Ball & Tronick, 1971; Bower, Broughton, & Moore, 1970). Later work questioned the interpretation of head and arm movements (Yonas et al., 1977). Infants may move their heads because they track visually the top contour of the pattern, and their relatively undifferentiated motor behavior may lead to the arms following along. To test this hypothesis, Yonas et al. presented a display in which only the top contour moved. Such a display does not specify approach of an object. At 1–2 and 3–4 months of age, infants showed as much or more head and arm movements to the single contour movement display as to the expansion display. It appears that tracking behavior may explain much or all of the apparent “defensive” movements by infants.

Paradoxically, however, it appears that both the tracking hypothesis and the original hypothesis are correct. Yonas et al. (1977) also measured eye blinking to their displays. In contrast to the head and arm movement results, infants blinked reliably more to a display specifying approach than to a single contour. Reliable effects of blinking to approach displays, more than to control displays, have been found in several studies with infants from about 1 month on (Yonas, 1981; Yonas & Granrud, 1985; Yonas, Pettersen & Lockman, 1979).

## 2. Motion Perspective

Motion perspective is the phantom of perceptual development research to date. A number of investigators have suggested that it may be an innate foundation of spatial perception (E. J. Gibson & Walk, 1960; Yonas & Owsley, 1987). However, evidence specifically implicating or testing motion perspective is thin. E. J. Gibson and Walk (1960) noted lateral head movements by the newborns of certain species in the visual cliff situation that probably indicated use of motion perspective. If such behavior characterizes human infants on the visual cliff, it is less pronounced. Also, human infants cannot even be tested in the standard visual cliff situation until they develop locomotor abilities (around 6 months of age).

Hofsten, Kellman, and Putaansuu (1992) recently reported experimental results related to the development of motion perspective. They presented an array of three vertical bars in a horizontal row, perpendicular to the line of sight, to 14-week-old infants. The infant was placed in a chair that moved laterally back and forth, and the middle bar moved a small amount parallel and in tandem with the chair. In Experiment 1, infants habituated to such an

array in which the middle rod moved  $.32^\circ/\text{s}$  in phase with the moving infant chair. Afterward they were tested with two displays. One was spatially similar in that it consisted of three aligned, stationary rods. The other had three stationary rods, but the middle one was displaced backward 15 cm; this gave the moving infant the same optical change patterns as in habituation. Infants generalized habituation more to the spatially different display having the same optical change as in habituation. Experiment 2 showed that the effect disappeared if the contingent motion was reduced to  $.16^\circ/\text{s}$ . Experiment 3 tested whether infants in Experiment 1 responded simply on the basis of similarity of optical change patterns or if they were sensitive to the contingency between the optical changes and their own movement, as would be predicted if the optical changes were used as motion parallax information. After habituation, infants saw two test displays differing by whether the center, stationary rod was displaced backward from the flanking rods or forward. Both test displays gave the same magnitude of contingent motion, but only one matched the phase relations used in habituation. Results indicated that infants dishabituated to the changed motion contingency.

The results are consistent with the idea that young infants utilize small contingent optical changes as information about object depth. In the experiments, the dishabituation patterns all fit predictions that were based on sameness or difference of depth position as indicated by motion parallax. However, the results do not uniquely imply this interpretation. The dishabituation patterns also correspond to what would be expected if infants registered and responded to particular optical changes and the contingency (including direction) of these optical changes on the observer's movement. In other words, it is not clear whether the optical changes were taken to indicate depth. One suggestion that these contingent optical changes are special in some way is that infants proved sensitive to velocities well below those found in studies of motion thresholds that used noncontingent motion and stationary observers (see section III. B. 2 below). Although this contrast would fit neatly with the idea that small, contingent motions are encoded as depth, not motion, information, further research will be necessary to bear out, or disprove, this conjecture.

### 3. Accretion and Deletion of Texture

Accretion and deletion of texture is a source of kinematic information for edges and depth discovered in recent times (Gibson, Kaplan, Reynolds, & Wheeler, 1969; Kaplan, 1969). During relative motion of two opaque surfaces at different depths, texture elements on the further surface will become visible (accretion) or hidden (deletion) at the edges of the nearer surface. In random-dot surfaces in which no other information is available, accretion-

deletion of texture effectively specifies edges, form, and depth ordering of surfaces to adult observers (Andersen & Cortese, 1989; Kaplan, 1969; Shipley & Kellman, 1994).

Kaufmann-Hayoz, Kaufmann, and Stucki (1986) studied shape perception from this kind of information. Three-month-olds who habituated to one shape specified by accretion–deletion dishabituated to a different shape, and vice versa. The result suggests that accretion–deletion effectively specified edges and shape at this early age, although no inferences can be made about depth ordering from the data. Granrud et al. (1984) studied perception of depth ordering by using a reaching procedure. Assuming that infants would reach preferentially to the nearer of two surfaces, they presented moving displays of computer-generated random-dot surfaces with vertical accretion–deletion boundaries specifying nearer and farther surfaces. Infants at both 5 and 7 months of age reached about 50% of the time to areas specified as nearer and 35% to areas specified as farther. (The remaining reaches were to edges or to two or more display regions.)

These results suggest that sensitivity to accretion–deletion information arises early. Later, Yonas and his colleagues raised questions about the basis of infants' responding. They pointed out that ordinary accretion–deletion displays might contain two kinds of information. Besides the actual appearance and disappearance of texture elements, there are different relations between moving texture elements and the boundary between two regions. On one side elements remain in a fixed position relative to the boundary; this side is nearer than the other. In the other region, elements move closer to or further from the boundary over time; this surface is further. Tests with adult subjects show that the latter information (termed *boundary flow*) is usable as depth information when no accretion–deletion of elements at the boundary is present (Craton & Yonas, 1990). Craton and Yonas (1988) reported that 5-month-olds responded to boundary flow information when no accretion–deletion was present. Further work may be needed to indicate whether accretion–deletion alone can specify depth order. The data do suggest that at minimum, accretion and deletion enables infant perceivers to locate the boundaries between regions since the boundaries (required to compute boundary flow) were not given in any other way in the Granrud et al. (1984) and Kaufmann-Hayoz et al. (1986) studies.

#### 4. Structure from Motion

A number of studies indicate an early capacity for detection of 3-D structure from motion (Kellman, 1984; Kellman & Short, 1987a; Yonas, Arterberry, & Granrud, 1987; Arterberry & Yonas, 1988). Infants 14–18 weeks old generalize habituation and dishabituate on the basis of sameness or difference in 3-D form, even when the specific information indicating that form changes

between habituation and test periods. Such changes are accomplished by using a new axis of rotation (Kellman, 1984; Arterberry & Yonas, 1988) or by testing transfer from kinematically specified to stationary stereoscopically specified form (Yonas et al., 1987). Since the projective geometric information underlying SFM is equivalent whether the object moves or the observer moves, one might predict that infants would be able to perceive 3-D form from either. This prediction has been shown to be correct (Kellman & Short, 1987a). A more detailed discussion of perception of 3-D form from motion-carried information may be found in the chapter by Kellman in *Perceptual and Cognitive Development*, this series.

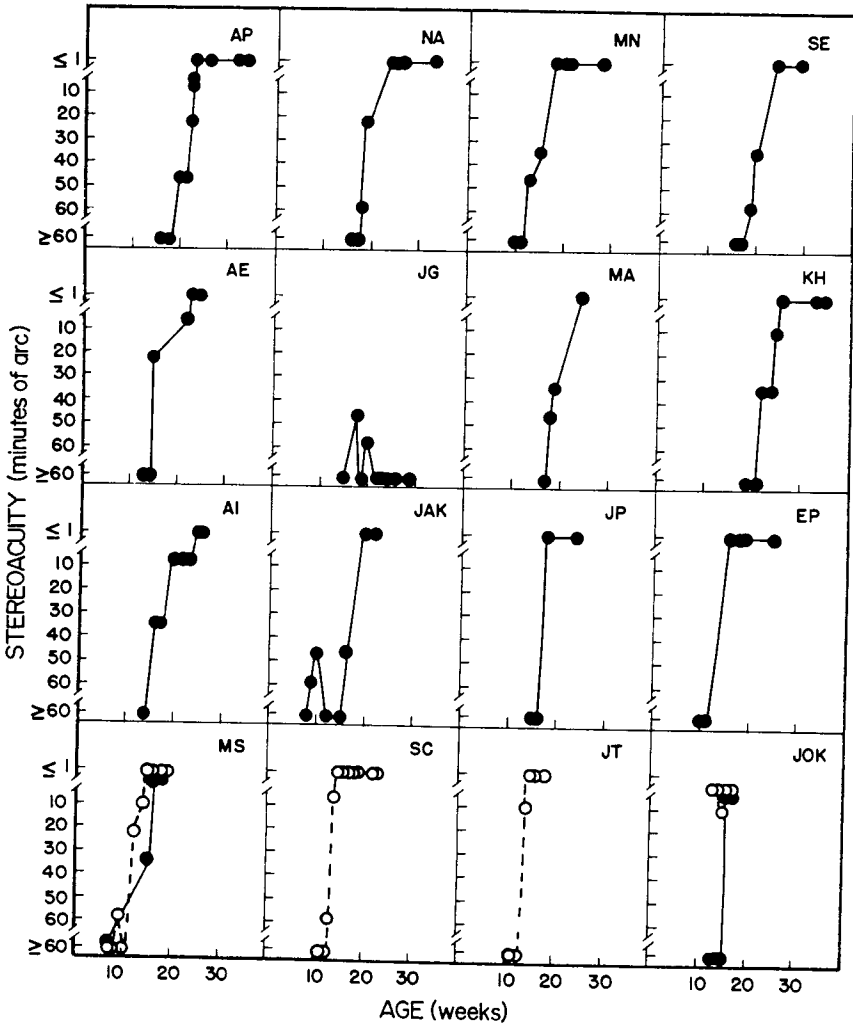
### C. Stereoscopic Information

Perception of depth from stereoscopic disparity is among the most precise forms of depth information available to adults. In combination with some information about the absolute distance of at least one visible point, it also allows perception of precise metric depth intervals between objects (Wallach & Zuckerman, 1963). Several facts point to innate foundations for this form of depth perception, including the existence of cortical cells sensitive to particular disparities at birth or after minimal visual experience in several species (Hubel & Wiesel, 1970; Pettigrew, 1974; Ramachandran, Clarke, & Whitteridge, 1977).

Evidence suggests that perception of depth from disparity arises by maturation in the early months of life. A number of studies have reported disparity sensitivity in some infants as young as 2–3 months, with most infants first showing sensitivity around the 4th month of life. These studies have used preferential looking methods with stationary displays (Atkinson & Braddick, 1981; Held, Birch, & Gwiazda, 1980) or with random-dot kinematograms (Fox, Aslin, Shea, & Dumais, 1980). These methods are based on the hypothesis that detection of depth specified by disparity leads to greater attention than a comparable flat display. Petrig, Julesz, Kropfl, Baumgartner, & Anliker (1981) found a similar onset of sensitivity by using recordings of visual-evoked potentials (VEPs).

Systematic studies of disparity thresholds have been carried out by Held and his colleagues (Held et al., 1980; Birch, Gwiazda & Held, 1982). In longitudinal studies using a visual preference procedure it was assumed that a striped display containing perceptible depth differences would attract more attention than a comparable flat display. The average ages at which reliable preferences appear are 12 weeks for crossed disparities and 17 weeks for uncrossed. A striking feature of the data is that improvement in stereoscopic sensitivity once it appears is rapid. (see Figure 1) In 3–4 weeks, thresholds change from greater than 60 min to less than 1 min of disparity, the latter measured value limited by the apparatus (Held et al., 1980) and comparable to adult sensitivity under some conditions.





**FIGURE 1** Stereoacuity as a function of age. Each data point indicates the smallest disparity for which the infant showed a preference on at least 80% of trials. Filled circles indicate data for uncrossed disparities; open circles indicate data from crossed disparities. From Held, Birch, and Gwiazda (1980); reprinted with permission.

There is some question whether studies of early binocular function indicate use of disparity as depth information or merely sensitivity to disparity. This issue is difficult to resolve with certainty; however, control conditions used in several studies all tend to support the interpretation that preferences for displays containing disparity depend on stereopsis. Held et al. (1980), for example, found that subjects who showed clear preferences for vertical line displays containing horizontal disparity showed no such preferences when

the displays were rotated  $90^\circ$  to give 34 min of vertical disparity (a condition that produces rivalry for adults). Fox et al., (1980) reported that infants who preferentially fixated disparities that would have indicated depth to adults did not do so for very large disparities that do not signal depth to adults. In fact, they found a reliable tendency for infants to look away from the latter displays. This result is worrisome in one sense; it suggests that disparities apart from stereopsis might affect infants' fixation. The most straightforward interpretation of the overall pattern of results, however, is that preferential looking found in studies using horizontal disparity depends on stereopsis.

### 1. Mechanisms Underlying the Onset of Stereopsis

The abrupt onset and rapid rise in stereoscopic acuity seen in longitudinal studies seem consistent with a maturational explanation. Some possibilities include maturation of disparity-sensitive cortical cells, fine tuning of convergence, or changes in visual acuity that might constrain disparity sensitivity. Some evidence suggests that the onset of stereopsis is not dependent on improvements of basic visual acuity (grating acuity). In a longitudinal study measuring both in the same subjects, little or no change in grating acuity is evident during the period in which stereopsis shows its sudden onset (Held, 1993). The same conclusion is supported by Westheimer and McKee (1980). They tested adult stereoacuity under conditions that reduced their acuity and contrast sensitivity to approximately those of a 2-month-old infant. Although these manipulations markedly reduced stereoacuity, they were not adequate to explain the absence of early sensitivity to large disparities. Likewise, development of convergence is an unlikely basis because it would not explain differences in the onset of crossed and uncrossed disparity (Held et al., 1980). In fact, past a certain point, development of precise convergence may await improvements in disparity sensitivity, rather than vice versa (Aslin, 1981; Held et al., 1980). The most likely mechanism for the onset of stereoscopic vision is some maturational change in cortical disparity-sensitive units themselves. Such a dependence of stereoscopic discrimination performance on changes in binocularly sensitive cortical cells has been observed in kittens (Timney, 1981; Pettigrew, 1974). Held (1985, 1988) suggested that cortical changes underly the onset of stereopsis and binocular rivalry; specifically, these changes might reflect development in the segregation of ocular dominance columns in layer four of the visual cortex. In the early months of life, cells in layer four generally receive projections from both eyes. Between birth and 6 months, inputs from the two eyes separate into alternating columns receiving input from the right and left eyes (Hickey & Peduzzi, 1987). Since eye-of-origin information is required for extracting disparity information, this neurological development may be a prerequisite for disparity sensitivity.

## D. Oculomotor Information

### 1. Accommodation

Accommodation is often considered a weak depth cue in adult perception (Hochberg, 1971). There is evidence, however, that it can act as a source of distance information in near space (within 2 m), especially when measured by using an indirect method, for example, via effects on perceived size (Gogel, 1977; Leibowitz, Shiina, & Hennessy, 1972; Wallach & Floor, 1971).

No research has directly addressed accommodation as a source of depth information in human infants. There have been several studies of the development of accommodation, however. An early study (Haynes, White, & Held, 1965) suggested that infants in the first few weeks of life do not adjust accommodation for target distance, maintaining accommodation appropriate for a target at about 19 cm. Accommodative responses improved steadily over the first several months, nearing adultlike responses by 3–4 months. It is probable that the target stimulus used by Haynes et al. was not optimal for testing accommodation, given the visual acuity of the youngest infants (Banks, 1980). Subsequent research indicated that the accommodative responses of 1-month-olds do vary appropriately with target distance, although their accommodative errors are substantially greater than older infants (Banks, 1980; Brookman, 1980; Braddick, Atkinson, French & Howland, 1979; Hainline, Riddell, Grose-Fifer, & Abramov, 1992). The research showing the early presence of accommodative function opens the possibility that accommodation could act as a depth cue from early on. Further research is needed to test this possibility.

### 2. Convergence

Aslin (1988) discusses some of the reasons that precise assessment of early convergence is difficult. Despite these difficulties, research on the development of vergence has proved to be possible (Aslin, 1977; Slater & Findlay, 1975). Early results indicated that from the first weeks of life, infants make vergence changes appropriate for changes in the distance of viewed targets. Although their convergence is often appropriate for target distance, there is substantial variability across trials and subjects in younger infants. Average accuracy improves steadily through at least 5 months of age. A recent study reported more consistent results (Hainline et al., 1992). Using paraxial photorefractive techniques and targets placed at distances between 25 and 200 cm, they found that most infants even at the youngest age tested (26–45 days) showed appropriate slopes relating convergence to target position. The authors characterized convergence as essentially adultlike, even in the youngest group.

If newborn convergence is reasonably accurate, an important question is what visual information might drive it (Aslin, 1988). What could be the

stimulus for eye movements leading to accurate convergence? Given the data on the development of stereopsis, binocular disparity does not seem to be a reasonable candidate before 3–4 months of age. Nor does accommodatively triggered vergence seem plausible since accommodation is much less accurate in the early weeks of life than is convergence. Hainline et al., (1992) suggest two possibilities. First, when targets are sparse or unique, convergence may derive from foveating the target in each eye. Second, correlations in firing of cortical units sensitive to similar retinal positions, but driven by different eyes, could drive convergence. Currently there is little evidence bearing on these hypotheses.

The studies described so far have been concerned with the accuracy of infants' convergence, not with its relevance to depth perception. One study took up the latter issue directly. Hofsten (1977) studied 5-month-olds' reaching behavior under normal viewing and while wearing convergence-altering glasses. He found that reaches were altered appropriately toward positions consistent with convergence information. This result suggests that convergence can provide absolute distance information.

An array of indirect evidence supports the idea that convergence provides distance information much earlier, perhaps from birth. Kellman, Hofsten, Condry, & O'Halloran (1991; Kellman & Hofsten, 1992) studied 8- and 16-week-olds in a situation in which moving observers were tested for motion detection. The visible arrays contained several stationary objects and one moving object that was linked to the observer's moving chair and moved along a path parallel to it. Detection of motion in this situation requires distance information (Gogel, 1982). Infants showed evidence of accurate motion detection when they viewed the displays binocularly, but not monocularly. Although motion detection in the 16-week-old group may have been based on convergence, disparity, or a combination of the two, it is unlikely that disparity is present in many 8-week-olds (Held et al., 1980). The best explanation of 8-week-olds' motion sensitivity in this situation is that it is based on distance information furnished by convergence.

Other results may also plausibly be explained by early availability of distance information from convergence (Granrud, 1987; Slater, Mattock, & Brown, 1990). These studies are discussed in the sections on size and shape constancy.

### **E. Pictorial Depth Information**

A programmatic approach to the development of pictorial depth perception has been carried out by Yonas and his colleagues (see Yonas et al., 1987b, for a review). Many of these studies used reaching as a dependent measure. Paired displays in which pictorial information specified that one object was nearer to the subject than the other were presented to monocular infants.

Preferential reaching to the nearer display was taken to indicate the effectiveness of the pictorial cue.

### 1. Perspective

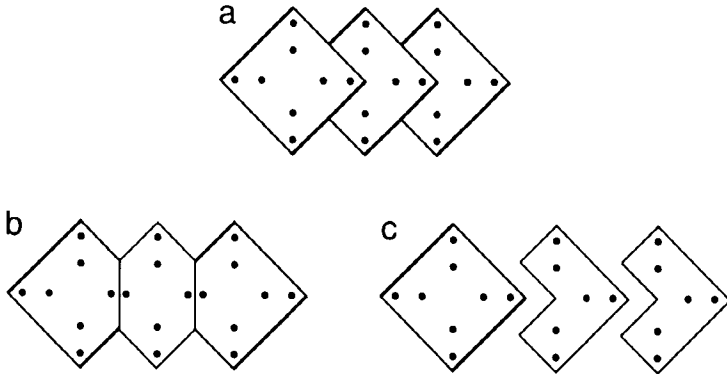
A study by Yonas, Cleaves, and Pettersen (1978) used an Ames trapezoidal window (Ames, 1951) to test linear perspective. Five- and 7-month-old infants viewed the trapezoidal window monocularly and binocularly on different trials. Equal reaching to the two sides was observed in the binocular condition, suggesting that binocular information overrode any depth differences signaled by other cues (as would occur for adults in near viewing of such a display). Under monocular viewing, 7-month-olds reached significantly more to the larger side of the window, but 5-month-olds did not. A subsequent study (Oross, Francis, Mauk, & Fox, 1987) provided evidence that infants 7.5 and 9.5 months of age, but not 5.5 months, perceive the illusory oscillation of a rotating Ames window display. These results suggest that perspective signals relative depth to infants by 7 months.

### 2. Familiar Size

One cue of special importance in evaluating learning effects in space perception is the cue of familiar size. From the geometry of size and distance relations, the combination of a known object size and the projected size can be used to derive the distance from observer to object. Infants' use of familiar size was investigated by Yonas, Pettersen, and Granrud (1982) and Granrud, Haake, and Yonas (1985). As with perspective, 7-month-olds showed evidence of using familiar size, whereas 5-month-olds did not. This is a fascinating outcome because it provides an existence proof for learned information in infant space perception. Perception of distance from familiar size would seem to require accessing memory representations by means of shape and retrieving stored information about object size.

### 3. Interposition

Granrud and Yonas (1984) studied the effectiveness of interposition information by using displays like those shown in Figure 2. According to this cue, when contours intersect, the one that continues through the intersection is the edge of a surface in front, whereas the contour ending is the edge of a surface going behind the other surface. Thus, in Figure 2a, the left-most part of the display is signaled to be nearer than the middle, which is nearer than the right-most display. In Figure 2b, all contours change direction at the intersections, and no depth order is specified. Finally, Figure 3c provides a control display in which the three panels are separated but have areas identical to those visible in Figure 2a.



**FIGURE 2** Displays used to study depth perception from interposition. (a) Interposition display. (b) Control display, with no interposition information. (c) Control display, with no interposition information and visible areas comparable to (a). Redrawn from Granrud and Yonas (1984).

In their experiments, Granrud and Yonas (1984) tested 5- and 7-month-olds with one eye covered (to remove conflicting binocular information) and all parts of the displays coplanar and equidistant from the subjects. Infants' reaches to different parts of the displays were recorded. In Experiment 1, both 5- and 7-month-olds reached reliably more often to the left-most part of the display in Figure 2a than to the left-most part of the control display in Figure 2b (61% vs. 50% for 7-month-olds and 56% vs. 47% for 5-month-olds). In Experiment 2, the pattern of Figure 2c was used as the control display to ensure that interposition, not relative size of visible areas, produced the patterns of data in Experiment 1. Results indicated that 7-month-olds reached reliably more to the left-most part of the interposition display than to the control display (63% vs. 54%), whereas 5-month-olds showed no reliable difference (56% vs. 54%). Granrud and Yonas interpreted their results as evidence for depth perception from interposition at 7 months but not at 5 months.

#### 4. Shading

In a study by Granrud, Yonas, and Opland (1985), 5- and 7-month-olds were presented with a surface containing a concavity and a convexity. They were also presented, under binocular and monocular viewing, with a photograph depicting a concavity and convexity. Classification of concavity and convexity from shading alone depends on the position of the light source; in some other species as well as in human adults, evidence suggests that illumination from above is assumed in perception of shaded regions (Hershberger, 1970). It was assumed that infants would reach preferentially to an

area that appeared nearer than the rest of the surface. Both age groups reached preferentially for the real convexity in both monocular and binocular conditions. Seven-month-olds viewing the photograph reached preferentially for the area specified to be convex by shading information, but only when they viewed the display monocularly. When viewing binocularly, they showed no reaching preference. Five-month-olds showed no reaching preferences to the photographic display under either monocular or binocular viewing. The results suggest that shading alone provides depth information to 7-month-olds but not to 5-month-olds. An elegant feature of this pattern of results is that the perceptual ability under study was inferred from less accurate performance: The older group, but not the younger, appeared to perceive the flat photograph as having depth.

### 5. Overview of Pictorial Depth

Taken together, the results on a variety of pictorial information sources are remarkably consistent. Sensitivity to all of these sources of information appears to be present by 7 months but not at 5 months of age. The absence of pictorial depth sensitivity in the first half year and the apparent synchrony of the onset of various cues pose an interesting explanatory challenge. The similar timing of initial sensitivity to the various cues has been cited as evidence implicating maturational processes (Yonas & Granrud, 1984). An alternative account that is based on learning might explain the timing of these developments by considering other developmental changes. For example, infants may learn to use these cues after they begin to crawl at around 6 months of age. The importance of locomotion would be consistent with evidence in other species showing connections between self-produced locomotion and sensitivity to visual information about space (Held & Hein, 1963). Analogously, Bertenthal and Campos (1990) provided evidence that crawling experience correlates with human infants' avoidance of the deep side of the visual cliff.

Specific research examining the locomotor hypothesis in relation to pictorial depth cues has been disconfirming, however. Arterberry, Yonas, and Bensen (1989) tested the relation of locomotor experience to sensitivity to linear perspective and texture gradients. Seven-month-olds at different stages of learning to crawl showed no reliable differences in sensitivity. All three groups reached reliably more to an object specified to be closer by perspective or textural information. These findings do not support the hypothesis that crawling experience leads to acquisition of pictorial depth cues.

Other learning accounts for the onset of pictorial depth perception remain possible. For example, infants might learn relationships between static-monocular patterns and depth relations given by motion or stereopsis. One experimental approach that might help to decide the roles of learn-

ing and maturation would be training studies, in which a new depth cue correlates with already usable information about depth. Likewise, a longitudinal study that included tests for several different pictorial cues could assess the hypothesis of a single maturational basis by showing how closely in time the various cues really come to operate. Such studies would be complex but useful undertakings.

## F. Effects of Distance Perception on Object Perception

Information about distance not only has direct value for perceivers but may also provide information that makes possible constancies in object perception: notably size and shape constancy. In turn, studies of infants' perception of shape and size (and motion, see below) can provide a window into early spatial perception. In this section, we review several findings of this sort, emphasizing the implications for development of space perception. (For a more complete treatment of early object perception abilities, see the chapter by Kellman in *Perceptual and Cognitive Development*, this series.)

### 1. Size Constancy

Slater, Mattock, and Brown (1990) performed two experiments to assess newborns' size perception abilities. In Experiment 1 they used a visual preference procedure with pairs of objects having identical shapes but differing in distance (23–69 cm) and real size (cubes with 5.1 cm or 10.2 cm sides). In all cases in which retinal size differed, infants showed clear preferences for the object of larger projected size. This finding documented looking preferences for larger projective sizes but did not test size constancy. In the second experiment, Slater et al. used an elegant design to test size constancy apart from the looking preferences found in the first experiment. Subjects were familiarized with either a large cube or a small cube of a constant size over six trials, with distance varying across trials. After familiarization, the large and small cubes were presented successively for two test trials. Distance of the large and small cubes differed so that they had equal projective sizes at the observer's eyes. The cube previously shown during the familiarization period was positioned at a distance that had not been used earlier. Thus, the retinal sizes of both test objects were novel. Specifically, the larger test cube (10.2 cm per side) was positioned 61 cm from the observer, and the smaller cube (5.1 cm per side) was positioned 30.5 cm from the observer.

All of the 12 subjects showed longer test–trial looking to the object whose real size was novel; mean novelty preference was about 84%. A nice feature of the design is that the test configuration in this experiment was presented in the earlier visual preference experiment, at which time it evoked no reliable preference.



These results suggest that size constancy in humans is innate, a conclusion supported by other research (Granrud, 1987; Slater & Morison, 1985). In Granrud's study, rates of habituation were examined to two kinds of sequences of objects in which retinal sizes varied identically. In one sequence, the real object size varied, whereas in the other, it remained invariant. Slower habituation was reported for the former case, suggesting that the changing object size was noticed and sustained subjects' interest.

None of these studies indicate much about the mechanism(s) by which constancy is achieved. Some inferences can be made, however, using a process of elimination. Because objects in the Slater et al. (1990) and Granrud (1987) studies were suspended in midair in front of homogeneous backgrounds, certain relationships of projective size and the area of occluded ground surface (Gibson, 1950) cannot be used as a basis of size perception. These are, therefore, cases in which projective size and viewing distance must combine to determine size accurately. Among possible sources of absolute distance information, relatively few might be available in these displays and usable by newborns. Convergence of the eyes on a viewed target, although estimates of its precision vary somewhat (Aslin, 1977; Hainline et al., 1992; Slater & Findlay, 1975) is the most likely source of information. Accommodative information could in principle be used, but there is no evidence for its use as a depth cue in infancy, and its precision in neonates is poor (Banks, 1980; Hainline et al., 1992). Another possibility is motion parallax. Newborns in the viewing situation used by Slater et al. and Granrud require substantial head support and do not commonly make the self-produced head movements that would be required to generate motion perspective information. Moreover, to maintain subjects' interest, Granrud moved the objects back and forth, a procedure that would at minimum complicate the extraction of distance by optical change contingent on the observer's movement. Thus, convergence is the most likely source of absolute distance information underlying size constancy. The precision of this distance information is not known. However, the data of Slater et al. and Granrud give some indications about precision. On the simple assumptions that projective size is correctly registered and that an object will not be seen as having changed size unless its distance changes discriminably, infants' performance implies that objects are located within an error not exceeding  $2.8^\circ$  of convergence angle in the Slater et al. experiment and about  $1.8^\circ$  in Granrud's experiment. Recent work on infants' convergence indicates that average convergence accuracy in the youngest age group tested (26–45 days) met or exceeded these standards of precision (Hainline et al., 1992).

## 2. Shape Constancy

In the absence of distance information, recovery of the shape of planar objects slanted in depth (under polar projection) should be impossible. Re-

search with newborns (mean age: 2 days, 8 hr) by Slater and Morison (1985) provides evidence for perception of constant shape despite detectable variations in slant. Earlier work by Caron, Caron, & Carlson (1979) had found such an ability with 12-week-old infants. There is little discussion in these reports of the depth information that supports shape constancy. Because the objects were stationary, motion perspective is a possibility. The requisite head movements would be unlikely in the case of newborns, however, given both their lack of neck strength and the need for head and neck support that would limit movement. A bias for perceiving a symmetric form could explain results for a rectangle at different slants whose projection is trapezoidal. Both the investigations of Caron et al. (1979) and Slater and Morison (1985) found similar effects when the true planar shape was a trapezoid or a rectangle. As in our analysis of the size constancy results, convergence appears to be the likely candidate. It would be useful to test this hypothesis with newborns viewing the displays monocularly or with optically altered convergence.

### 3. Position Constancy and Motion Perception

Another perceptual outcome that can depend on distance information is perception of objects as remaining stationary (position constancy) or moving during observer motion (Gogel, 1982). Evidence from studies of infants as young as 8 weeks of age suggests that during observer motion, distance information is used to determine which optical displacements indicate real object motion and which are consequences of observer motion (Kellman & Hofsten, 1992; Kellman, Gleitman, & Spelke, 1987). The ability to discriminate moving and stationary objects was eliminated when infants viewed the displays monocularly, suggesting that convergence may also provide the distance information underlying this ability (Kellman & Hofsten, 1992). This topic is explored further in our treatment of motion perception.

## G. Summary: Space Perception

Perception of many aspects of the 3-D layout of space, and the use of spatial information to determine other attributes such as object size, shape, and motion, appear to be part of the early competence of human beings. Contact with a 3-D world appears to be present from the beginning, as does some early responsiveness to particular events, such as the approach of an object. What information and processes accomplish this early spatial ability and allow its further development? Motion-carried information about space appears to operate from the beginning of life, although more direct evidence is needed. A variety of spatial abilities requiring some degree of metric information about space, as opposed to merely ordinal depth information,

have been unearthed, and binocular convergence is emerging as the likely source of distance information in these cases. The neural bases of stereoscopic depth perception are innate, but maturation is required to bring this system into operation around 4–5 months of age. Finally, the pictorial cues to depth appear relatively late, sometime in the second half year of life. Whether they depend on maturation, learning, or some combination is unknown.

### III. MOTION PERCEPTION

If space is the first frontier, motion is the *raison d'être* of perception. Perceptual systems exist to guide the motion of organisms, and the properties of objects and environments are important because of the events they make possible. It is therefore no surprise that motion perception is a central topic in perceptual development.

As with space perception, the role of motion perception in infancy is different from its role later in life. Infants' motion perception abilities substantially predate their abilities for skilled action. Responding to threats or foraging for food are possible only in the most limited fashion for the first several months of life. Yet infants are active perceptual explorers of their environment, and they are especially captivated by motion. Why is this the case? A plausible conjecture is that motion is an especially rich source for early learning about the physical and social worlds.

Motion may be special for more than one reason. First, it has a double role, termed by J. Gibson as *dual specification* (Gibson, 1966). Motions of objects and observers are important events to be perceived. At the same time, optical changes given by object or observer motion carry information about unchanging aspects of the environment, such as object form and spatial layout. For early learning, information carried by motion might be primary in specifying both what changes and what persists. A second consideration involves the ecological validity of information sources. The lack of knowledge and mobility makes infants less able to correct perceptual errors. Errors could severely distort early physical and social knowledge. On these grounds, it has been argued that information sources that function in early perception should be those with the highest accuracy in specifying properties of the world (Kellman, 1993). Whether or not this functional interpretation is correct, it appears that infants are sensitive to a subset of the information sources usable by adults, and this subset appears to consist of those sources with the highest ecological validity (Kellman, 1993). Much of this early repertoire involves motion-carried information, which, on mathematical and ecological grounds, has been argued to be among the least ambiguous information sources in many perceptual domains (Gibson, 1966, 1979; Lee, 1974).

## A. Motion and Attention

From the earliest ages, motion attracts attention (Fantz & Nevis, 1967), and infants orient toward moving stimuli by using head and eye movements (Haith, 1983; Kremenitzer, Vaughan, Kurtzberg & Dowling, 1979; White, Castle & Held, 1964). Infants' tendency to fixate and track moving displays has often been exploited in studies of other perceptual abilities (Atkinson, Braddick, & Moar, 1977; Fox et al., 1980; Manny & Klein, 1984; Shimojo, Birch, Gwiazda, & Held, 1984).

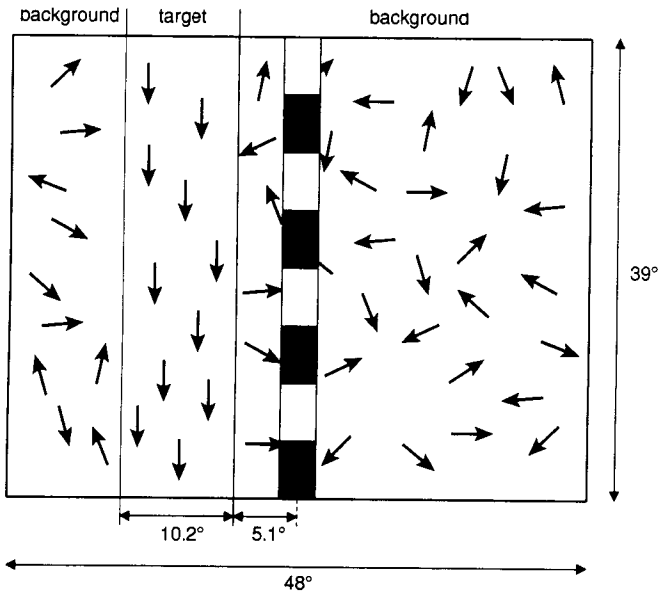
The causal direction of the connection between motion and information is not known. Infants might be hard-wired to attend to moving things—a useful adaptation for learning about objects and events. Alternatively, it may be information, not motion, that guides attention. Infants may preferentially attend to events more than static scenes because more or better information about space and objects is available to them from kinematic sources than from static ones.

## B. Motion Sensitivity

Motion characteristics can be expressed in terms of time derivatives of spatial position. Tests of motion perception ordinarily involve the first derivative, velocity. Velocity may be subdivided into direction and magnitude (speed), and it is useful to assess visual sensitivity to both of these dimensions. Finally, there are multiple possibilities for the mechanisms that might underly sensitivity to moving stimuli. Research on early motion perception has examined all of these aspects of motion and motion detection.

### 1. Directional Selectivity

Recent work by Wattam-Bell (1991, 1992) tested the development of directional sensitivity by using behavioral and electrophysiological measures. For direction reversals in oscillating checkerboard patterns, the median ages at which infants first showed detectable visual evoked potentials (VEPs) to stimulus velocities of  $5^\circ/\text{s}$  and  $20^\circ/\text{sec}$  were 74 and 90 days, respectively. In a later behavioral study, Wattam-Bell (1992) used displays in which a vertical target strip had coherent vertical motion of random dots, against a background consisting of randomly changing dot patterns or opposite direction motion. The target display was always presented simultaneously with an adjacent random or uniformly moving display in a visual preference paradigm. (See Figure 3.) Infants were expected to look longer at the target display if they could detect its motion. The studies used a modified staircase procedure to find the greatest element displacement ( $d_{\text{max}}$ ) in the target display that supported coherent motion detection. Subjects ranged from 8 to 15 weeks of age. Results indicated  $d_{\text{max}}$  for targets against noise or oppo-



**FIGURE 3** Schematic illustration of display used to study directional sensitivity. The two display panels differ by the presence of a vertical strip of coherently moving dots in the center of the left-hand panel. All other motions are random in direction. The center column of rectangles was used to attract infant's attention to the center of the display and disappeared during each trial. From Wattam-Bell (1992); reprinted with permission.

site motion and both increased substantially across the ages tested. For example, at displacement intervals of 20 ms, 8–11-week-olds showed a  $d_{\max}$  around  $0.25^\circ$ , compared with about  $0.65^\circ$  for 14–15-week-olds and nearly  $2^\circ$  for adults. However, under the smallest  $d_{\max}$  conditions, even the youngest subjects consistently showed evidence of motion detection.

These results suggest that directional selectivity may be poor, especially in the first 10 weeks of life. Wattam-Bell (1992) suggests that poorer performance of infants during this time may be due to the absence of motion detectors sensitive to larger spatial displacements at relatively short time intervals, that is, detectors sensitive to high velocities. Some support for this conjecture comes from an experiment in which the temporal interval was lengthened:  $d_{\max}$  increased under these conditions. Evidence about velocity sensitivity is also consistent with this idea.

The weakness of early directional sensitivity has been suggested as a possible explanation of results of studies of perception on the basis of motion-carried information. For example, Slater, Kellman, Spelke, and Johnson (1994; see also Slater et al., 1990) found that newborns differed from 2- to 4-month-olds in their use of common motion as information for

the unity of a partly occluded object. They argued that improvements in this ability might depend on maturation of directional selectivity required for accurate registration of the motions of visible parts.

Although directional selectivity may be poor in the early weeks of life, it would be an overstatement to claim it is absent altogether. Whereas the VEP data show no indication of sensitivity before about 10 weeks, the behavioral data indicate earlier ability. The possibility that directional sensitivity is absent at birth also seems paradoxical given that newborns show directionally appropriate responding to moving stimuli, such as saccadic tracking of slowly moving stimuli and optokinetic nystagmus (OKN) responses (Aslin, 1981; Barten, Birns, & Ronch, 1971; Dayton, Jones, Steele, & Rose, 1964). However, it has been argued that these may depend only on subcortical mechanisms (Atkinson & Braddick, 1981).

## 2. Velocity Sensitivity

Estimates of velocity thresholds in the first half year vary somewhat depending on features of the stimulus used. Volkman and Dobson (1976) presented a horizontally oscillating checkerboard pattern and a similar but stationary pattern in a preferential looking procedure to 1- to 3-month-olds. The 2- and 3-month-olds clearly preferred the moving display even at  $2^\circ/s$  (the slowest velocity tested); 1-month-olds showed a weak preference. Using rotary motion, Kaufmann, Stucki, and Kaufmann-Hayoz (1985) estimated thresholds, also assessed by a preference procedure, at about  $1.4^\circ/s$  at 1 month and  $.93^\circ/s$  at 3 months.

Somewhat higher threshold estimates have come from studies designed to distinguish different mechanisms underlying responses to moving patterns (see below). Using vertical grating stimuli and 75% correct as the threshold criterion, Aslin and Shea (1990) found velocity threshold of about  $9^\circ/s$  at 6 weeks and  $4^\circ/s$  at 12 weeks. Dannemiller and Freedland (1989) estimated threshold at about  $5^\circ/s$  for 16-week-olds and about  $2.3^\circ/s$  for 20-week-olds. However, they found no reliable motion preferences at 8 weeks. Dannemiller and Freedland (1991) studied differential velocity thresholds—the minimum difference in velocity that could evoke a reliable looking preference. They assumed that infants would preferentially fixate the display appearing to move faster. Their subjects reliably distinguished a velocity of  $3.3^\circ/s$  from  $2.0^\circ/s$  but not from  $2.5^\circ/s$ . Although it is difficult to compare stimulus conditions and measurement techniques, these threshold estimates are much higher than velocity thresholds for motion detection in adults; the latter can be as small as 1–2 min of arc/s when stationary reference points are visible (Kaufman, 1974).

Hofsten et al. (1992) suggested that these threshold estimates might understate infant motion detection abilities. As is always true with the visual

preference method, a reliable difference in attention requires both that infants can distinguish two displays and that one of the two displays is significantly more interesting or attention holding. It is possible that velocities slower than those at the estimated thresholds are perceptible but not seen as more interesting than stationary patterns.

One reason for suspecting that true thresholds are lower involves motion perspective. Although there is not much direct evidence, there are reasons to suspect that motion perspective provides depth information in infancy (see above). Yet the differential velocity thresholds suggested by Danemiller and Freedland (1991) would be too large to allow effective use of motion perspective. As Hofsten et al. (1992) calculated, if a child moved her head sideways 4 cm, she or he would be unable to distinguish a target at 69 cm ( $3.3^\circ/\text{s}$ ) from one at 92 cm ( $2.5^\circ/\text{s}$ ).

Using observer-contingent motion and 14-week-old subjects, Hofsten et al. (1992) found sensitivity to a differential velocity of only  $0.32^\circ/\text{s}$ , much lower than earlier estimates. Subjects also proved to be sensitive to the contingency of the motion with their own motion. Hofsten et al. suggested two possible reasons for the higher sensitivity they found. First, they used a habituation of looking procedure, which is likely to be a more sensitive method. Second, it is possible that the smaller, observer-contingent motions studied by Hofsten et al. are perceptually processed differently from larger, noncontingent motions. The former motions may be taken to indicate depth positioning of stationary objects, whereas the latter specify object motion.

An interesting application of infants' velocity perception is their anticipatory reaching for moving objects. Research by Hofsten (1980, 1983) indicates that infants reach in a predictive way for objects moving through their field of view. This behavior appears at about the same time (around 4 months of age) as directed reaching for stationary objects (Hofsten, 1980). In these experiments, the moving object was attached to a 74-cm rod that rotated in a horizontal plane around a fixed axis. At its closest point to the infant, the object was 14 cm away. Starting points and velocities were varied, and infants were scored for touching or grasping the object. Careful analysis of the timing and spatial properties of reaches suggested that infants reached with precision of about 0.05 s and with no systematic timing error. Accurate reaching was observed for even the fastest moving objects in the study (60 cm/s); additional observations on several subjects showed accurate reaching for objects moving at 120 cm/s. For various reasons, it is difficult to work back from these remarkable results to specific conclusions about the precision of infant velocity perception. However, the capacity to utilize spatial and motion information in this task appears impressive. Assuming that the development of reaching to stationary objects depends on maturation in the motor system (Field, 1990), the findings also support the

idea that accurate 3-D perception precedes skilled motor behavior. Given that predictive reaching and reaching for stationary objects appear at about the same time, it appears that the ability to perceive objects and events with considerable precision must already be in place.

### 3. Specifying the Effective Stimulus

The study of motion detection abilities is complicated by the fact that a moving stimulus produces multiple changes in a spatial array. Preferential attention to a moving pattern might indicate detection of motion, but there are other possibilities. Positional change of the display or some part of it might be detected. When periodic stimuli are used, such as the checkerboard pattern used by Volkman and Dobson (1976), the luminance at any point will change periodically. Demonstrated sensitivity might be based on this flicker rather than on motion per se.

Research to distinguish motion (velocity)-sensitive, position-sensitive, and flicker-sensitive mechanisms has been carried out by Aslin and Shea (1990), Freedland and Dannemiller (1987), and Dannemiller and Freedland (1989). Freedland and Dannemiller tested several combinations of temporal frequency and spatial displacement with random black- and white-check patterns. Strength of preference for moving over static displays was not a simple function of velocity. It appears that preference for a moving pattern over a static one is influenced by both spatial displacement and temporal frequency. Their experiments were not designed to distinguish perceived motion from flicker, however. Aslin and Shea (1990) used vertically moving luminance (square wave) gratings to distinguish these possibilities. By varying spatial frequency and velocity, it is possible to separate the effects of flicker and velocity. A response that varied with velocity, for example, might be expected to change if velocity were doubled and spatial frequency halved. Such changes, however, should have no effect on a flicker sensitive mechanism since the temporal frequency remains the same. The results indicated that velocity governed the motion preferences of 6- and 12-week-old infants. The design of their displays allowed Aslin and Shea to rule out some but not all versions of the hypothesis of a position-sensitive mechanism. Dannemiller and Freedland used motion of a single bar flanked by stationary reference bars. Such a display avoids ongoing flicker in any spatial position characteristic of spatially periodic stimuli. Infants' preference patterns were best explained by a velocity-sensitive mechanism. Arguing against a position-sensitive mechanism was the finding that extent of displacement did not predict responses at 16 or 20 weeks of age.

On the whole, these findings are compatible with the hypothesis that infant sensitivity to moving patterns is controlled largely by velocity-sensitive mechanisms.



### C. Object and Observer Motion

The primary stimulus for motion is often described as retinal or optical displacement, a change in an object's projected position. Such changes always have two potential causes: object motion or observer motion. The same is true of other stimuli for motion perception such as optical expansion-contraction or convergence changes given with changes in object-observer distance.

These facts have led many theorists to suspect that before extensive learning, object and observer motion should be confused with each other (Helmholtz, 1867, 1925). William James, who conjectured that the world of the newborn is a "blooming, buzzing confusion," had this problem centrally in mind. As neonates, he believed "any relative motion of object and retina both makes the object seem to move, and makes us feel ourselves in motion" (James, 1890, Vol. 2, p. 173). Only through experience can the observer come to infer that particular optical changes indicate motion of an object or of the observer. To describe this account as the prevailing view would be an understatement since until recent years an alternative view had scarcely been articulated. J. J. Gibson (1966, 1979) presented an alternative. He argued that, despite the similarity of a single object's optical change in the two cases, visual information is available to distinguish object and observer motion. The information is relational: When an object moves, its surroundings undergo no optical change. When the observer moves, however, all visible areas undergo optical change. (Any given object's optical change can of course be canceled by appropriate eye or head movements. This subtlety complicates but does not invalidate Gibson's observation of informational differences in object and observer motion.) Given that information exists to distinguish object and observer motion, one might conjecture that visual systems have evolved to be sensitive to these differences.

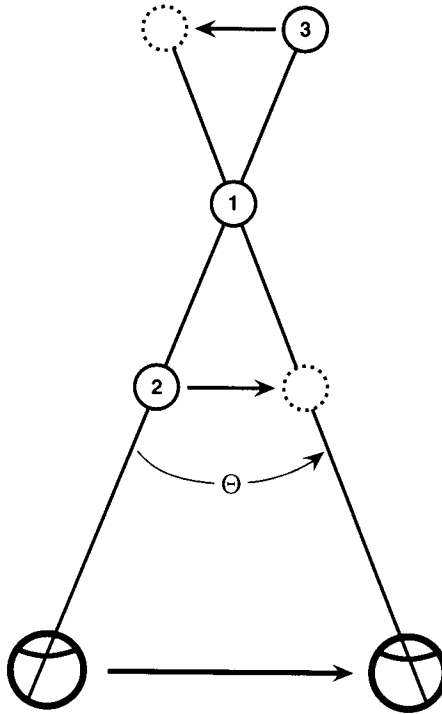
Until quite recently, there has been little research directly concerned with the origins of human capacities to distinguish object from observer motion. One study was carried out by Kellman et al. (1987). They tested the role of observer-contingent motion in 16-week-olds' perception of partly occluded objects. Earlier work showed that infants of this age perceive a center-occluded object as complete when its visible parts share certain motion relationships (Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986). In those experiments, stationary observers viewed moving displays. Kellman et al. sought to determine whether the crucial information was provided by perceived motion of objects or merely by certain optical displacements. To contrast these possibilities, they arranged two conditions in which infant observers moved back and forth. In one, subjects viewed a stationary array consisting of a partly occluded rod. In the other, the partly occluded rod was yoked to the infant chair's movement so that it moved back and forth in

opposite phase from the subject. (Both the chair and rod rotated rigidly around a fixed point between the infant and the object.)

This arrangement allowed two questions to be asked. First, do infants distinguish cases in which optical displacement arises from object motion from cases in which only the observer moves? Second, if the situations can be distinguished, do they differ in terms of their effect on perceived object unity? The two questions were assessed in different ways. Perceived unity was assessed by habituation and recovery patterns of visual attention. Infants in both groups were habituated to a partly occluded rod, stationary in one case and moving so as to maintain a fixed relationship with the observer (conjoint movement) in the other. After habituation, each subject was tested for looking time to two test displays, whose movement characteristics (stationary or conjoint) matched those of the habituation display. The test displays were an unoccluded complete rod and an unoccluded "broken" display, in which two visible pieces were separated by a gap where the occluder had previously been. If infants perceived the original occluded rod as complete, they were expected to recover attention after habituation to the broken rod but not to the complete rod (Kellman & Spelke, 1983). Perception of motion was assessed by examining overall looking levels during both habituation and test periods. Numerous studies with similar displays had shown that (stationary) infants' looking times to moving displays averaged two to three times longer than to stationary displays. If moving infant observers detected the real object motion during their own movement, they were expected to look longer than moving infants viewing stationary objects, despite the absence of subject-relative change in the conjoint motion condition.

Results suggested that moving infants viewing stationary displays (observer movement condition) did not perceive the displays to be in motion. Their looking times were on the same order as those of stationary infants viewing stationary displays. In contrast, infants in the conjoint movement case appeared to perceive motion: their looking times were two to three times higher than those in the observer motion group. These findings are especially striking in that relative to the subject, there was substantial subject-relative motion in the observer movement condition and none in the conjoint condition. These findings suggest an early capacity of infants to utilize relationships in optical change to perceive the motion and stability of objects during their own motion. In terms of object perception, it is noteworthy that perception of the occluded display as containing a complete object occurred only in the case in which real motion was perceived. (For further discussion see the chapter by Kellman in *Perceptual and Cognitive Development*, this series.)

Subsequent studies tested moving infants' perception of motion and stability more directly (Kellman & Hofsten, 1992; Kellman et al., 1991). The



**FIGURE 4** Geometry of object and observer motion. When the observer moves (depicted by the moving eye at bottom), a stationary target at (1) undergoes an angular change  $\Theta$  in visual direction. The same optical change can be given by a nearer object moving in the same direction as the observer (2) or by a more distant object moving in the opposite direction as the observer (3). In this situation, distance information may be required to detect object motion or constant position during the observer's motion.

paradigm used may be understood by reference to Figure 4, which shows some basic geometry of object and observer motion, following the analyses of Gogel (1980, 1982). When the observer moves (depicted as the moving eye in Figure 4), a stationary target at a given distance (1) produces a given optical change ( $\Theta$ ). The same optical change may be produced by a nearer object that moves in the same direction as the observer (2) or a more distant object that moves opposite to the observer (3). When appropriately arranged, detection of whether a viewed target is stationary or moving requires information about the target's distance (Gogel, 1982). In the infant experiments, the observer was laterally moved in a moving infant seat while viewing two or more objects. On any trial, one of the objects moved a short distance along a path parallel to the observer's. The moving object appeared on the left and right side of the display area equally often. Consistent with

the geometry of Figure 4, a stationary object was placed on the side opposite to the moving one, at such a distance so as to have the same optical change during the subject's motion. Object size was also adjusted so that the corresponding moving and stationary objects had the same projective size. The subject was thus faced on each trial with objects to the left and right having similar optical projections and displacements. Detecting which was moving and which was stationary required information about target distance. On the basis of other research, it was assumed that infants would preferentially attend to the moving object, if they could distinguish moving from stationary objects under these conditions.

Infants at both 16 and 8 weeks of age showed reliable preferences for the moving object when the object and observer movement were in opposite phase, whereas only 16-week-olds showed the preference when the object and observer moved in the same direction (Kellman et al., 1990; Kellman & Hofsten, 1992). It is not clear why detection of opposite motion was superior for the younger group. Subsequent tests indicated that motion preferences were eliminated under monocular viewing. These results suggest an early capacity for moving observers to perceive the motion and stability of objects. They also implicate binocular information as necessary for this achievement. In particular, the results point to binocular convergence as a source of absolute (egocentric) distance information early in life. Stereoscopic vision is ordinarily present in about half of 16-week-olds and virtually never in 8-week-olds (Held et al., 1980). Also, binocular disparity alone does not specify egocentric distance (Wallach & Zuckerman, 1963). In combination with some source of absolute distance, such as convergence, disparities can specify precise depth intervals (Wallach & Zuckerman, 1963). It is possible that the combination of convergence and disparity allows more precise determination of motion and stability at 16 weeks.

Early detection of motion during observer motion of object and observer motion is fascinating for several reasons. It indicates sophisticated integration of information in infant perception. The character of this integration may also be revealing. The evidence suggests that motion (or stability) perception depends not merely on certain stimulus variables but on perceived distance. The dependence of one perceptual outcome on another is consistent with computational views of perception. Specifically, it suggests multiple levels of representation and computations performed on them (Epstein, 1982; Hochberg, 1974; Marr, 1982).

### 1. The Bidirectional Geometry of Motion and Distance

The particular computations involving the geometry of motion and distance raise a paradoxical issue. Earlier we described the depth information called motion perspective. Optical changes given by stationary objects to a mov-

ing observer provide information about depth and distance. Extracting this information depends on the assumption that objects are stationary. Detecting whether an object is moving or not, when the observer moves, requires the same geometry with different known and unknown quantities. Here, optical changes and distance, given by some other information source, are used to determine whether the object is moving or stationary. The geometry of motion and distance can apparently be used in two ways: to extract distance assuming that the object is stationary or to extract target motion for a given object distance. An important challenge for both infant and adult vision research is to determine the conditions under which this geometry is used to determine motion from distance or distance from motion.

#### **D. Summary: Motion Perception**

During the early months of life, infants do not detect motion with the sensitivity matching that of adults. Infants' sensitivity is adequate, however, to detect all but the slowest motions of nearby people and objects, and infant attention is evoked by motion more readily than by any other stimulus dimension. Besides supporting detection of moving targets and their properties, such as direction and velocity, motion processing appears to be disproportionately involved in early perceptual competence. Motion-carried information about objects and space appears to be usable earlier than many other sources of information that operate in adult perception. Even complex interactions between motion and spatial perception, such as combining optical change and distance information to determine object stability or motion during observer motion, are part of the repertoire of infants in the early weeks of life.

### IV. CONCLUSION

#### **A. Beyond the Blooming, Buzzing Confusion**

Research over the past three decades has radically restructured our ideas about the origins of space and motion perception. An old but durable view that infant development begins with sensory systems providing meaningless, disorganized sensations no longer seems reasonable. Human infants have a smaller perceptual repertoire than do adults, but infants perceive a 3-D spatial environment and events occurring within it. Of course, clear understanding of perception in the newborn is hampered by sensory immaturities and an extremely limited behavioral repertoire. Thus, a general view of the origins of perception must draw on inferences from patterns of behavior in a few observable response systems. Moreover, in many cases the inferences involve data from infants of several weeks or months of age.

The evidence allows us to rule out certain learning hypotheses (such as “touch educates vision” in acquiring 3-D visual perception), but the possibility that there are learning processes we have not imagined is harder to rule out. What is striking about research to date is that no evidence has emerged to support the traditional empiricist view of infants’ initial state characterized by William James as a “blooming, buzzing confusion.”

Changing the starting point of knowledge has important implications for theories of human cognitive development. Influential accounts of development (e.g., Piaget, 1954; Harris, 1983) and traditional views of perception agree that the infant’s first task on the way to achieving knowledge is the interpretation and organization of sensory stimulation. One implication of infant perception research is that evolution may have done much of this work already. There is little evidence for a sensorimotor stage during which the young human being produces perceptions from sensations. Although early perceptual abilities will be refined and supplemented as time goes on, it appears that they are attuned to reality. Thus, the earliest tasks of cognitive development less likely involve constructing reality than learning about it. This changed view of the starting point of development has begun to be reflected in recent accounts of cognitive development (Fodor, 1983; Mandler, 1988; Spelke, Breinlinger, Macomber, & Jacobson, 1992).

## **B. Perceptual Development and Theories of Perception**

Research on the origins of space and motion perception has implications for arguments about the general character of perception (Kellman, 1988). We have mentioned that the constructivist idea of perceptions built from sensations through learning is untenable as an overall picture of early perception. Many findings of early competence, and the importance of motion-carried information, confirm ecological views of perception’s origins (E. J. Gibson, 1984; J. J. Gibson, 1966, 1979; Gibson & Gibson, 1955).

Regarding the *process* of perception, the evidence supports a hybrid of claims from inferential and direct theories. Some early abilities to use complex stimulus relationships are consistent with the idea that perception is a direct response of specialized mechanisms to relational variables (E. J. Gibson, 1984; J. J. Gibson, 1979). An example might be the use of accretion-deletion of texture to determine object boundaries and depth order. Yet other early-appearing perceptual abilities suggest less direct processes. The use of distance information in early size, shape, and motion perception, and use of the depth cue of familiar size, implicate processes in which some perceptual outcomes are computed from other perceptual dependent variables or prior representations (Epstein, 1982; Hochberg, 1974; Marr, 1982). A plausible, emerging view is that representations of space, objects, and events are derived from perceptual processes that are computational in char-

acter but different from the unconscious inferences that are based on learning described by Helmholtz (1867/1925) in the last century. Instead, perception achieves correspondence with reality because evolved perceptual mechanisms and processes embody constraints about the enduring physical and geometric properties of the world (Shepard, 1984; Johansson, 1970).

### **C. Kinematic Information and Ecological Foundations**

Much of the research on early perception implicates a central role of motion or change information. This is true both attentionally, in that young perceivers attend preferentially to motion, and informationally, in that most or all of the main sources of information carried by motion appear to be useful early in life. The early dependence on kinematic information sources may reflect the more secure ecological foundations of these. Other information sources of high ecological validity, such as stereoscopic depth information, also appear in the first half year. The ambiguities Berkeley (1709/1910) noted in static retinal images involve exactly the information sources that are the last to appear in infants' visual perception. This late onset of perceptual cues involving static spatial relationships applies not only to depth cues but to related perceptual domains, such as object perception (Kellman & Spelke, 1983). Early perception may be "risk averse" in that it depends only on information sources of the highest ecological validity (Kellman, 1993).

### **D. Interdependence of Space and Motion**

We have seen that motion and space are interrelated in early perception, as well as later. Two kinds of interrelations are significant. On one hand, as Gibson (1966, 1979) emphasized, properties of the persisting spatial layout can be given by information carried by motion or change. On the other hand, perception of motion depends in many cases on spatial (distance) information, most centrally in cases of observer motion. Despite the geometric complexity of some of these relationships, or perhaps because of them, there appear to be impressive early capacities to perceive accurately whether objects, the observer, or both are moving through space.

### **E. Developmental Change**

Finally, evidence of early perceptual competence should not obscure the magnitude of developmental change. It is hard to name any perceptual domain in which the precision or speed of infants' information pick-up abilities is comparable to adults. As an example, even the lowest estimates of infant velocity thresholds appear to be an order of magnitude higher than adult velocity thresholds. Moreover, there are whole categories of informa-

tion in spatial perception, such as pictorial depth information, that are not usable until the second half year of life. Perhaps even more significant are differences that are due to perceptual learning involving the skilled deployment of selective attention (Gibson, 1969). All of these differences imply profound differences in the perceptual worlds of adults and infants. Although some changes with age have been documented, not much is known about the causes of change. Advancing our understanding of mechanisms of perceptual change remains a high priority for future research.

## References

- Ames, A. (1951). Visual perception and the rotating trapezoidal window. *Psychological Monographs*, Series No. 324.
- Andersen, G. J., & Cortese, J. M. (1989). 2-D contour perception resulting from kinetic occlusion. *Perception & Psychophysics*, *46*, 49–55.
- Arterberry, M. E., & Yonas, A. (1988). Infants' sensitivity to kinetic information for three-dimensional object shape. *Perception & Psychophysics*, *44*, 1–6.
- Arterberry, M., Yonas, A., & Bensen, A. S. (1989). Self-produced locomotion and the development of responsiveness to linear perspective and texture gradients. *Developmental Psychology*, *25*(6), 976–982.
- Aslin, R. N. (1977). Development of binocular fixation in human infants. *Journal of Experimental Child Psychology*, *23*, 133–150.
- Aslin, R. N. (1988). Perceptual development in infancy: The Minnesota symposia on child psychology, Vol. 20. Hillsdale, NJ: Erlbaum.
- Aslin, R. N. (1981). Development of smooth pursuit in human infants. In D. F. Fisher, R. A. Monty, & J. W. Senders (Eds.), *Eye movements: Cognition and visual perception* (pp. 31–51). Hillsdale, NJ: Erlbaum.
- Aslin, R. N., & Shea, S. L. (1990). Velocity thresholds in human infants: Implications for the perception of motion. *Developmental Psychology*, *26*, 589–598.
- Atkinson, J., & Braddick, O. (1976). Stereoscopic discrimination in infants. *Perception*, *5*, 29–38.
- Atkinson, J., & Braddick, O. J. (1981). Development of optokinetic nystagmus in young infants: An indicator of cortical binocularity? In D. F. Fisher, R. A. Monty, & J. W. Senders (Eds.) *Eye movements: Cognition and visual perception*. Hillsdale, NJ: Erlbaum.
- Atkinson, J., Braddick, O., & Moar, K. (1977). Contrast sensitivity of the human infant for moving and static patterns. *Vision Research*, *17*(9), 1045–1047.
- Ball, W., & Tronick, E. (1971). Infant response to impending collision: Optical and real. *Science*, *171*, 818–820.
- Banks, M. S. (1980). The development of visual accommodation during early infancy. *Child Development*, *51*, 646–666.
- Banks, M. S., & Dannemiller, J. L. (1987). Infant visual psychophysics. In P. Salapetek & L. B. Cohen (Eds.), *Handbook of infant perception: From sensation to perception* (pp. 115–184). New York: Academic Press.
- Banks, M. S., & Salapetek, P. (1983). Infant visual perception. In M. M. Haith & J. Campos (Eds.), *Infancy and biological development* (pp. 435–572). New York: Wiley.
- Barten, S., Birns, B., & Ronch, J. (1971). Individual differences in the visual pursuit behavior of neonates. *Child Development*, *42*, 313–319.



- Berkeley, G. (1910). *Essay toward a new theory of vision*. London: Dutton. (Original work published 1709.)
- Bertenthal, B. I., & Campos, J. J. (1990). A systems approach to the organizing effects of self-produced locomotion during infancy. In C. Rovee-Collier (Ed.), *Advances in infancy research* (Vol. 6, pp. 1–60). Norwood, NJ: Ablex.
- Birch, E. E., Gwiazda, J., & Held, R. (1982). Stereoaquity development for crossed and uncrossed disparities in human infants. *Vision Research*, 22, 507–513.
- Bower, T. G. R., Broughton, J., & Moore, M. (1970). Infant responses to approaching objects: An indicator of response to distal variables. *Perception & Psychophysics*, 9, 193–196.
- Braddick, O., Atkinson, J., French, J., & Howland, H. C. (1979). A photo refractive study of infant accommodation. *Vision Research*, 19, 1319–1330.
- Bridger, W. H. (1961). Sensory habituation and discrimination in the human neonate. *American Journal of Psychiatry*, 117, 991–996.
- Brookman, K. E. (1980). Ocular accommodation in human infants. Doctoral dissertation, Indiana University.
- Caron, A. J., Caron, R. F., & Carlson, V. R. (1979). Infant perception of the invariant shape of objects varying in slant. *Child Development*, 50, 716–721.
- Craton, L., & Yonas, A. (1988). Infants' sensitivity to boundary flow information for depth at an edge. *Child Development*, 59, 1522–1529.
- Craton, L., & Yonas, A. (1990). Kinetic occlusion: Further studies of the boundary flow cue. *Perception & Psychophysics*, 47, 169–179.
- Dannemiller, J. L., & Freedland, R. L. (1989). The detection of slow stimulus movement in 2- to 5-month-olds. *Journal of Experimental Child Psychology*, 47, 335–337.
- Dannemiller, J. L., & Freedland, R. L. (1991). Speed discrimination in 20-week-old infants. *Infant Behavior and Development*, 14, 163–174.
- Dayton, G. O., Jones, M. H., Steele, B., & Rose, M. (1964). Developmental study of coordinated eye movements in the human infant: II. An electrooculographic study of the fixation reflex in the newborn. *Archives of Ophthalmology*, 71, 871–875.
- Epstein, W. (1982). Percept-percept couplings. *Perception*, 11, 75–83.
- Fantz, R. L. (1958). Pattern vision in young infants. *Psychological Record*, 8, 43–47.
- Fantz, R. L. (1964). Visual experience in infants: Decreased attention to familiar patterns relative to novel ones. *Science*, 146, 668–670.
- Fantz, R. L., & Nevis, S. (1967). Pattern preferences and perceptual-cognitive development in early infancy. *Merrill-Palmer Quarterly*, 13, 77–108.
- Field, T. (1990). *Infancy*. Cambridge, MA: Harvard University Press.
- Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology*. Cambridge, MA: MIT Press.
- Fox, R., Aslin, R. N., Shea, S. L., & Dumais, S. T. (1980). Stereopsis in human infants. *Science*, 207, 323–324.
- Freedland, R. L., & Dannemiller, J. L. (1987). Detection of stimulus motion in 5-month-old infants. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 566–576.
- 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: Erlbaum.
- Gibson, E. J., & Walk, R. D. (1960). The "visual cliff." *Scientific American*, 202, 64–71.
- 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. A., Reynolds, H. N., & Wheeler, K. (1969). The change from visible to invisible: A study of optical transitions. *Perception & Psychophysics*, *5*, 113–116.
- Gogel, W. C. (1977). The metric of visual space. In Epstein, W. (Ed.), *Stability and Constancy in visual perception* (pp. 129–181). New York: Wiley.
- Gogel, W. C. (1980). The sensing of retinal motion. *Perception & Psychophysics*, *28*(2), 155–163.
- Gogel, W. C. (1982). Analysis of the perception of motion concomitant with a lateral motion of the head. *Perception & Psychophysics*, *32*(3), 241–250.
- Gogel, W. C., & Tietz, J. D. (1974). The effect of perceived distance on perceived movement. *Perception & Psychophysics*, *16*, 70–78.
- Gottschaldt, K. (1926). Über den Einfluss der Erfahrung auf die Wahrnehmung von Figuren I. *Psych. Forsch.* *8*, 261–317.
- Granrud, C. E. (1987). Size constancy in newborn human infants. *Investigative Ophthalmology and Visual Science*, *28* (Suppl.), 5.
- Granrud, C. E., Haake, R. J., & Yonas, A. (1985). Infants' sensitivity to familiar size: The effect of memory on spatial perception. *Perception & Psychophysics*, *37*(5), 459–466.
- Granrud, C. E., & Yonas, A. (1984). Infants' perception of pictorially specified interposition. *Journal of Experimental Child Psychology*, *37*(3), 500–511.
- Granrud, C. E., Yonas, A., & Opland, E. A. (1985). Infants' sensitivity to the depth cue of shading. *Perception & Psychophysics*, *37*(5), 415–419.
- Granrud, C. E., Yonas, A., Smith, I. M., Arterberry, M. E., Glicksman, M. L., & Sorknes, A. (1984). Infants' sensitivity to accretion and deletion of texture as information for depth at an edge. *Child Development*, *55*, 1630–1636.
- Hainline, L., Riddell, P., Grose-Fifer, J., & Abramov, I. (1992). Development of accommodation and convergence in infancy. *Behavioral Brain Research*, *49*, 33–50.
- Haith, M. (1983). Spatially determined visual activity in early infancy. In A. Hein & M. Jeannerod (Eds.), *Spatially oriented behavior*. New York: Springer.
- Harris, P. (1983). Infant cognition. In M. M. Haith & J. J. Campos (Eds.), *Cognitive development* (pp. 689–782). New York: Wiley.
- Haynes, H., White, B. L., & Held, R. (1965). Visual accommodation in human infants. *Science*, *148*, 528–530.
- Held, R. (1985). Binocular vision—behavioral and neural development. In J. Mehler & R. Fox (Eds.), *Neonate cognition: Beyond the blooming, buzzing confusion*. Hillsdale, NJ: Erlbaum.
- Held, R. (1988). Normal visual development and its deviations. In G. Lennerstrand, G. K. von Noorden and E. C. Campos (Eds.), *Strabismus and amblyopia* (pp. 247–257). NY: Plenum.
- Held, R. (1993). What can rates of development tell us about underlying mechanisms? In G. Carl (Ed.), *Visual perception and cognition in infancy. Carnegie Mellon symposia on cognition*, (pp. 75–89). Hillsdale, NJ: Erlbaum.
- Held, R., Birch, E. E., & Gwiazda, J. (1980). Stereoacuity in human infants. *Proceedings of the National Academy of Sciences of the 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. (1925). *Handbook of physiological optics*, Vol. 3. J. P. S. Southall, Ed. and Trans.) New York: Dover. (Original work published 1867).
- Hershberger, W. (1970). Attached-shadow orientation perceived as depth by chickens reared in an environment illuminated from below. *Journal of Comparative & Physiological Psychology*, *73*(3), 407–411.

- Hess, E. H. (1956). Space perception in the chick. *Scientific American*, 195, 71–80.
- Hickey, T., & Peduzzi, J. (1987). Structure and development of the visual system. In P. Salapatek and L. Cohen (Eds.), *Handbook of infant perception*, Vol. I, pp. 1–42. New York: Academic Press.
- Hochberg, J. (1971). Perception: Space and movement. In J. W. Kling & L. A. Riggs (Eds.), *Woodworth & Schlosberg's experimental psychology* (pp. 475–550). New York: Holt, Rinehart & Winston.
- Hochberg, J. (1974). Higher-order stimuli and inter-response coupling in the perception of the visual world. In R. B. McLeod & H. Pick (Eds.), *Essays in honor of J. J. Gibson*, (pp. 17–39). Ithaca, NY: Cornell University Press.
- Hofsten, C. von (1977). Binocular convergence as a determinant of reaching behavior in infancy. *Perception*, 6, 139–144.
- Hofsten, C. von (1980). Predictive reaching for moving objects by human infants. *Journal of Experimental Child Psychology*, 30(3), 369–382.
- Hofsten, C. von (1983). Catching skills in infancy. *Journal of Experimental Psychology: Human Perception and Performance*, 9(1), 75–85.
- Hofsten, C. von, Kellman, P. J., & Putaansuu, J. (1992). Young infants' sensitivity to motion parallax. *Infant Behavior and Development*, 15, 245–264.
- Hubel, D. H., & Wiesel, T. N. (1970). Cells sensitive to binocular depth in area 18 of the Macaque monkey striate cortex. *Nature*, 225, 41–42.
- 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.
- Kaplan, G. (1969). Kinetic disruption of optical texture: The perception of depth at an edge. *Perception & Psychophysics* 6, 193–198.
- Kaufman, L. (1974). *Sight and mind*. New York: Oxford University Press.
- Kaufmann, F., Stucki, M., & Kaufmann-Hayoz, R. (1985). Development of infants' sensitivity for slow and rapid motions. *Infant Behavior and Development*, 10, 1–10.
- Kaufmann-Hayoz, R., Kaufmann, F., & Stucki, M. (1986). Kinetic contours in infants' visual perception. *Child Development*, 57(2), 292–299.
- Kellman, P. J. (1984). Perception of three-dimensional form by human infants. *Perception & Psychophysics*, 36(4).
- Kellman, P. J. (1988). Theories of perception and research in perceptual development. In Y. Albert (Ed.), *Perceptual development in infancy. The Minnesota symposia on child psychology*, Vol. 20., (pp. 267–281). Hillsdale, NJ: Erlbaum.
- Kellman, P. J. (1993). Kinematic foundations of perceptual development. In C. Granrud, (Ed.), *Visual perception and cognition in infancy* (pp. 121–193). Hillsdale, NJ: Erlbaum.
- Kellman, P. J., Gleitman, H., & Spelke, E. (1987). Object and observer motion in the perception of objects by infants. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 586–593.
- Kellman, P. J., & Hofsten, C. von (1992). The world of the moving infant: Perception of objects, motion and space. In C. Rovee-Collier & L. Lipsitt (Eds.), *Advances in infancy research* (pp. 147–184). 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, Vandewalle, G., & Condry, K. (1990, April). *Perception of motion and stability during observer motion by pre-stereoscopic infants*. Paper presented at the Seventh International Conference on Infant Studies, Montreal, Quebec, Canada.
- Kellman, P. J., & Short, K. R. (1987a). Development of three-dimensional form perception. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 545–557.

- Kellman, P. J., & Short, K. R. (1987b, 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*(1), 72–86.
- Kremenitzer, J. P., Vaughan, H. G., Kurtzberg, D., & Dowling, K. (1979). Smooth-pursuit eye movement in the newborn infant. *Child Development*, *50*(2), 442–448.
- Lee, D. (1974). Visual information during locomotion. In R. B. MacLeod & H. L. Pick (Eds.), *Perception: Essays in honor of J. J. Gibson* (pp. 250–267). Ithaca, NY: Cornell University Press.
- Lee, D. N., Lishman, J. R., Roly, & Thomson, J. A. (1982). Regulation of gait in long jumping. *Journal of Experimental Psychology: Human Perception and Performance*.
- Leibowitz, H., Shiina, K., & Hennessy, R. T. (1972). Oculomotor adjustments and size constancy. *Perception & Psychophysics*, *12*, 497–500.
- Mandler, J. (1988). How to build a baby: On the development of an accessible representational system. *Cognitive Development*, *3*, 113–136.
- Manny, R., & Klein, S. (1984). The development of vernier acuity in infants. *Current Eye Research*, *3*, 453–462.
- Marr, D. (1982). *Vision*. San Francisco: Freeman.
- Nakayama, K., & Shimojo, S. (1992). Experiencing and perceiving visual surfaces. *Science*, *257*(5075), 1357–1363.
- Oross, S., Francis, E., Mauk, D., & Fox, R. (1987). The Ames window illusion: Perception of illusory motion by human infants. Special Issue: The Ontogenesis of perception. *Journal of Experimental Psychology: Human Perception & Performance*, *13*(4), 609–613.
- Petrig, B., Julesz, B., Kropfl, W., Baumgartner, G., & Anliker, M. (1981). Development of stereopsis and cortical binocularity in human infants: Electrophysiological evidence. *Science*, *213*, 1402–1405.
- Pettigrew, J. D. (1974). The effect of visual experience on the development of stimulus specificity by kitten cortical neurones. *Journal of Physiology*, *237*, 49–74.
- Piaget, J. (1954). *The construction of reality in the child*. New York: Basic Books.
- Ramachandran, V. S., Clarke, P. G. H., & Whitteridge, D. (1977). Cells selective to binocular disparity in the cortex of newborn lambs. *Nature*, *268*, 333–335.
- Schiff, W. (1965). The perception of impending collision: A study of visually directed avoidant behavior. *Psychological Monographs*, *79*, Whole No. 604.
- Senden, M. von (1960). *Space and sight: The perception of space and shape in the congenitally blind before and after operations* (P. Heath, Trans.). London: Methuen.
- Shepard, R. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving, imaging, thinking, and dreaming. *Psychological Review*, *91*, 441–447.
- Shimojo, S., Birch, E. E., Gwiazda, J., & Held, R. (1984). Development of vernier acuity in infants. *Vision Research*, *24*(7), 721–728.
- Shiple, T. F., & Kellman, P. J. (1994). Spatiotemporal boundary formation: Boundary, form and motion perception from transformations of surface elements. *Journal of Experimental Psychology: General*, *123*(1), 3–20.
- Slater, A. M., & Findlay, J. M. (1975). Binocular fixation in the newborn baby. *Journal of Experimental Child Psychology*, *20*, 248–273.
- Slater, A., Kellman, P. J., Spelke, E., & Johnson, S. (1994). The role of three-dimensional depth cues in infants' perception of partly occluded objects. *Journal of Early Development and Parenting*.

- 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. (1985). Shape constancy and slant perception and birth. *Perception*, *12*, 707–718.
- 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., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, *99*(4), 605–632.
- Timney, B. (1981). Development of binocular depth perception in kittens. *Investigative Ophthalmology and Visual Science*, *21*, 493–496.
- Volkman, 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., & Floor, L. (1971). The use of size matching to demonstrate the effectiveness of accommodation and convergence as cues for distance. *Perception & Psychophysics*, *10*, 423–428.
- Wallach, H., & O'Leary, A. (1982). Slope of regard as a distance cue. *Perception & Psychophysics*, *31*(2), 145–148.
- Wallach, H., & Zuckerman, C. (1963). The constancy of stereoscopic depth. *American Journal of Psychology*, *76*, 404–412.
- Wattam-Bell, J. (1991). Development of motion-specific cortical responses in infancy. *Vision Research*, *31*(2), 287–297.
- Wattam-Bell, J. (1992). The development of maximum displacement limits for discrimination of motion direction in infancy. *Vision Research*, *32*(4), 621–630.
- Westheimer, G., & McKee, S. P. (1980). Stereoscopic acuity with defocused and spatially filtered retinal images. *Journal of the Optical Society of America*, *70*, 772–778.
- White, B., Castle, R., & Held, R. Observations on the development of visually directed reaching. *Child Development*, *35*, 349–364.
- Yonas, A. (1981). Infants' responses to optical information for collision. In R. N. Aslin, J. R. Alberts, & M. R. Peterson (Eds.), *Development of perception: Psychobiological perspectives: Vol. 2. The visual system* (pp. 313–334). New York: Academic Press.
- Yonas, A., Arterberry, M. E., & Granrud, C. E. (1987). Space perception in infancy. In R. Vasta (Ed.), *Annals of child development* (pp. 1–34). Greenwich, CT: JAI Press.
- Yonas, A., Bechtold, A. G., Frankel, D., Gordon, F. R., McRoberts, G., Norcia, A., & Sternfels, S. (1977). Development of sensitivity to information for impending collision. *Perception & Psychophysics*, *21*, 97–104.
- Yonas, A., Cleaves, W., & Pettersen, L. (1978). Development of sensitivity to pictorial depth. *Science*, *200*, 77–79.
- Yonas, A., & Granrud, C. E. (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: Nijhoff.
- Yonas, A., & Granrud, C. E. (1985). Development of visual space perception in young infants. In J. Mehler & R. Fox (Eds.), *Neonate cognition: Beyond the blooming buzzing confusion*. Hillsdale, NJ: Erlbaum.
- Yonas, A., Granrud, C. E., & Arterberry, M. E. (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. E., & Pettersen, L. (1982). Infants' sensitivity to relative size information for distance. *Developmental Psychology, 21*(1), 161-167.
- Yonas, A., & Owsley, C. (1987). Development of visual space perception. In P. Salapetek & L. B. Cohen (Eds.), *Handbook of visual space perception*. New York: Academic Press.
- Yonas, A., Pettersen, L., & Granrud, C. E. (1982). Infants' sensitivity to familiar size as information for distance. *Child Development, 53*(5), 1285-1290.
- Yonas, A., Pettersen, L., & Lockman, J. (1979). Young infants' sensitivity to optical information for collision. *Canadian Journal of Psychology, 33*, 268-276.