CHAPTER 3

Infant Visual Perception

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How visual perception develops has long been a central question in understanding psychological development generally. During its emergence as a separate discipline in the late 1800s, psychology was focused primarily on how human knowledge originates (e.g., Titchener, 1910; Wundt, 1862), an emphasis inherited from concerns in philosophy. Much of the focus was on the relation between sensation and perception, especially in vision. The prevailing view, inherited from generations of empiricist philosophers (e.g., Berkeley, 1709/1963; Hobbes, 1651/1974; Hume, 1758/1999; Locke, 1690/1971), was that at birth, a human being experiences only meaningless sensations. Coherent, meaningful, visual reality emerges only through a protracted learning process in which visual sensations become associated with each other and with touch and action (Berkeley, 1709/1963).

Through most of the twentieth century, even as psychology increasingly emphasized findings of empirical research, this primarily philosophical view cast a long shadow. Its influence was so great as to be essentially a consensus view of development. William James (1890) echoed its assumptions in his memorable pronouncement that the world of the newborn is a "blooming, buzzing, confusion." Modern developmental psychology, shaped greatly by Piaget, incorporated the same ideas. Although Piaget combined contributions of both maturation and learning in his theories, his view of the starting points of perception was standard empiricist (e.g., Piaget, 1952, 1954). He did place greater emphasis on *action,* rather

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than mere sensory associations, as the means by which meaningful reality emerges from initially meaningless sensations.

This basic story about early perception and knowledge persisted, in part, because researchers lacked methods for investigating these topics scientifically. The arguments of Berkeley and others were primarily logical ones. Claims about the origins of knowledge in the association of sensations initially came from theory and thought experiments. Later, a few experiments with adults were used to make inferences about aspects of perception that might be based on learning (e.g., Wallach, 1976) or not so based (e.g., Gottschaldt, 1926). Finding a more direct window into perception and knowledge of a young infant seemed unlikely. As Riesen (1947, p. 107) put it: "The study of innate visual organization in man is not open to direct observation in early infancy, since a young baby is too helpless to respond differentially to visual excitation."

In the time since Riesen's (1947) observation, the scientific landscape in this area has changed entirely. Although the development of visual perception is among the most long-standing and fundamental concerns in the field, it is also an area that is conspicuous in terms of recent and rapid progress. Beginning in the late 1950s, the door to progress has been the development of methods for studying sensation, perception, and knowledge in human infants. The results of scientific efforts, continuing to the present, have changed our conceptions of how perception begins and develops. These changes, in turn, have generated important implications about the early foundations of cognitive, linguistic, and social development.

In this chapter, we consider current knowledge of early visual perception and its development. Besides describing the origins and development of these perceptual capabilities, we use them to illustrate general themes: the several levels of explanation required to understand perception; the roles of hardwired abilities, maturation, and learning in perception; and some of the methods that allow assessment of early perception. These themes all have broader relevance for cognitive and social development.

THEORIES OF PERCEPTUAL DEVELOPMENT

As a backdrop for considering research in early vision, we describe two general theories of perceptual development. These serve as valuable reference points in understanding how recent research has changed our conceptions of how perception begins.

The Constructivist View

The term *constructivism* here refers to the view that perceptual reality must be constructed through extended learning. Choosing one term to label this idea is efficient, but also unfortunate, as this set of ideas has many names. In philosophy, this kind of account is most often called *empiricism,* emphasizing the role of input from experience in forming perception. If, as is usually the case, associations among sensations are held to dominate perceptual development, the position may also be aptly labeled *associationism.* In the earliest days of psychology as an independent discipline, the merging of current and remembered sensations to achieve objects in the world was called *structuralism* (Titchener, 1910). Helmholtz (1885/1925) is often credited with applying the label *constructivism* to the idea that sensations are combined with previously learned information using unconscious inference to achieve perceptual reality. This pedigree, along with Piaget's later emphasis on inputs from the learner's actions in constructing reality, make constructivism perhaps the best term to characterize modern versions of this view. Unfortunately, the term has been used elsewhere with different shades of meaning. In considering issues in learning, developmental and educational psychologists often contrast constructivism with associationism, where constructivism emphasizes the active contributions of the learner. Although a common thread extends through the uses of constructivism, its use here will be confined to the notion that perception is constructed from sensations and actions through learning. Our primary concern in addressing perception is to consider, not particular modes of learning, but whether basic perceptual abilities are learned at all. For this reason, and others, the verdict on constructivism in this domain may differ from the fates of constructivisms in other studies of development.

The constructivist account of how perception develops is familiar to many. The key assumption is that at birth, sensory systems function to produce only their characteristic sensations. Stimulation of the visual system yields sensations of brightness and color, along with some quality (a "local sign") correlating with a position on the retina. Stimulation of the auditory system produces loudnesses and pitches, and so on. Of course, perceptual reality consists not of disembodied colors and loudnesses, but of objects arranged in space, relations among them, and events, characterized by motion and change within that space. On the constructivist view of perceptual development, all these commonplace occupants of adult perceptual reality—*any* tangible, material object existing in the external world and, indeed, the external spatial framework itself—are hard-won constructions achieved by *learning.* What allows construction of external reality is associative processes. Experiences of visual sensations coupled with touch, according to Berkeley (1709/1963), allow creation of the idea that seen objects have substance. Connecting the muscular sensations of reaching with visual sensations allows the creation of depth and space. Sensations obtained from one view of an object at a given time are associated by contiguity in space and time, and by similarity. Sensations obtained a moment later from another view may become associated with the previous ones. An object becomes a structure of associated sensations stored in memory. In John Stuart Mill's memorable formulation, for the mind, an object consists of all the sensations it might give us under various circumstances: An object is "the permanent possibilities of sensation" (Mill, 1865). For Piaget (1952, 1954), the account is similar, except that voluntary *actions,* not just tactile and muscular sensations, become associated, making objects consist initially of "sensorimotor" regularities.

How did this basic story of perceptual development attain such preeminent status in philosophy and psychology? The question is puzzling because the account was not based on scientific study in any meaningful way. Just to anticipate a different possibility, we might consider the life of a mountain goat. Unlike a human baby, a mountain goat is able to locomote soon after birth. Remarkably, the newborn mountain goat appears to perceive solid surfaces on which to walk and precipices to avoid. When tested on a classic test apparatus for the study of depth perception—the "visual cliff"—newborn mountain goats unfailingly avoid the side with the apparent drop-off (Walk & Gibson, 1961).

This example puts a fine point on the issue. Although mountain goats appear innately able to perceive solidity and depth, generations of philosophers and psychologists have argued that, as a matter of logic, humans must be born helpless and must construct space, substance, and objects through a long associative process. The humble mountain goat, as well as many other species, provides a stark contradiction to any logical argument that perception must be learned. From an evolutionary perspective, it might also be considered curious that humans have been so disadvantaged, beset with a frail and complicated scheme for attaining what mountain goats possess from birth.

The preceding questions are not meant to be critical of generations of serious thinkers who have held the constructivist position. Asking these questions helps to highlight what the issues were and how things have now changed. The key fact is that the constructivist position was embraced nearly universally because the arguments for it were logical. If valid, these arguments admitted few alternatives. We can better understand current views if we briefly review these logical arguments, sometimes described as the *ambiguity* argument and the *capability* argument (Kellman & Arterberry, 1998).

The ambiguity argument traces to Berkeley and his 1709/1963 book *Essay toward a New Theory of Vision.* Analyzing the projection of light onto the retina of a single eye, Berkeley pointed out that while the projection onto different retinal locations might carry information into the image about the left-right and up-down relations of objects in the world, there was no direct information to indicate the distance to an object. A given retinal image could be the product of an infinitely large set of possible objects (or, more generally, scenes) in the world. Because of this ambiguity, vision cannot provide knowledge of the solid objects in the world or their three-dimensional (3D) positions and relations. Since vision is ambiguous, the seeming ability of adult perceivers to see objects and space must derive from associating visual sensations with extravisual sensations (such as those involved in eye-muscle adjustments, and with touch and locomotion).

The capability argument drew more on physiology than philosophy. The history of progress in understanding the nervous system reflects a progression from the outside in. Long before much was known about the visual cortex of the brain, parts of the eye were somewhat understood. Even in the nineteenth century, it was clear that the retina contained numerous tiny receptors and that information left the eye for the brain in a bundle of fibers (the optic nerve). It is not surprising that reasoning about the capabilities of the visual system centered on these known elements. Consider the world of a single visual receptor, at some location on the retina. If it absorbs light, this receptor can signal its activation at that point. Receiving only tiny points of light, the receptor can know nothing of objects and spatial layout and, as

Berkeley contended, certainly nothing about the third dimension (depth). To understand the system in aggregate, one need only think of many receptors in many locations, each capable of signaling locally activations that the visual system encodes as brightness and color. Clusters of brightnesses and colors are not objects or scenes; thus, perceiving objects and scenes requires something beyond sensations generated by activity in these receptors.

To make matters worse, it was understood as a logical matter that such sensations existed not in the world but in the mind. As Johannes Muller (1838/1965) had emphasized in his famous doctrine of *specific nerve energies,* whether one presses on the eyeball or whether retinal receptors absorb light, the mind experiences brightness and color. Similarly, pressure or shock to the auditory system produces experiences of sound. It seems that sensory qualities are specific to the separate senses, regardless of the energy used to evoke them. If the visual system can produce only its own characteristic sensations, how can it be said to obtain knowledge of the world? This is the capability argument: The visual system, as a system that generates its own characteristic sensations, usually on stimulation by light, is not capable of directly revealing the objects, layout, and events of the external world.

These powerful logical arguments have two consequences. One is that the apparent direct contact that we have through vision with a structured, meaningful, external world must be a developmental achievement, accomplished through learning to infer the meanings of our sensations. The other consequence is that perceptual knowledge in general must be an inference. Different versions of this theoretical foundation have characterized perception as inference, hypothesis, results of past experience, and imagination. In Helmholtz's classic statement: "Those objects are imagined to be in the field of view that have frequently given rise to similar sensations in the past" (Helmholtz, 1885/1925). Lest one think that this section has only historical significance, it is not uncommon to encounter precisely these same arguments today (e.g., Purves & Lotto, 2003).

The Ecological View

Until recently, students of development have been less familiar with an alternative to constructivist views of perceptual development. The view is important, not only as a viable possibility, but as we will see, a perspective compatible with much of the scientific evidence about how perception develops.

We call this view *ecological* because it connects perceptual capabilities to information available in the world of the perceiver. Crucial among this information are regularities and constraints deeply connected to the basic structure and operation of the physical world. These regularities have existed across evolutionary time, and have shaped the operation of perceptual mechanisms.

The emergence of ecological views of perception and perceptual development owes most to the work of James J. and Eleanor J. Gibson (E. Gibson, 1969; J. Gibson, 1966, 1979). Earlier influences included the work of the physiologist Hering (1861–1864), who described the operation of the two eyes in binocular depth perception as an integrated, and likely innate, system, and the Gestalt psychologists (e.g., Koffka, 1935; Wertheimer, 1923/1958) who emphasized the importance of abstract form and pattern, rather than concrete sensory elements, in perception. Important strands of J. Gibson's theories of perception have since been advanced in computational approaches to perception, especially that of Marr (1982).

Numerous facts lead naturally to a consideration of ecological ideas in perceptual development. Perhaps the simplest is the observation that some species exhibit effectively functioning perceptual systems from birth, as in the case of the mountain goat. Historically, however, the issue that raised the curtain for contemporary views is the nature of *information* in perception (J. Gibson, 1966, 1979).

In a certain sense, this is the logical starting point. If the constructivist view was deemed correct because of logical limits on information received by the senses, then any alternative view would need to address the ambiguity and capability arguments head-on. This is one way of summarizing a several-decades-long effort led by J. Gibson, foreshadowed in his 1950 book, *The Perception of the Visual World,* and emerging fully in *The Senses Considered as Perceptual Systems* (1966) and *The Ecological Approach to Visual Perception* (1979). According to Gibson, both the ambiguity and capability arguments rest on misunderstandings of the information available for perception.

Ecology and Ambiguity

Ambiguity claims about vision centered on analysis of static retinal images given to a single eye. If these constraints are admitted, the analyses by Berkeley and others are correct: For any given retinal image, there are infinitely many possible configurations in the world that could give rise to it. The problem with the analysis, however, is that the inputs to human vision are not restricted to single, static retinal images. As Hering (1861–1864) had already noted, the two eyes sample the world from two distinct vantage points. This arrangement makes possible direct information about the third dimension (which lay at the heart of Berkeley's ambiguity concerns). J. Gibson argued that another primary fact had been missed: Sophisticated visual systems are the property of *mobile* organisms. Motion and change provide important information for perception. Although a single retinal image is ambiguous, the transformations over time of the optic array as the perceiver *moves* are highly specific to the arrangement of objects, space, and events. If one can assume that the world is not deforming contingent on the perceiver's motion, this kind of information *specifies* the layout. Evolution may well have picked up on such sources of information, allowing perceptual systems to deliver meaningful information not derived from learning. Whereas the mountain goat provides an existence proof of functional perception without learning, the analysis given by J. Gibson explained how this might be possible.

Ecology and Capability

Ambiguity issues focus on the information in the world. Corresponding to the arguments about information are revised ideas about the capabilities of a perceptual system (J. Gibson, 1966). The description of inputs to vision in terms of brightness and color responses at individual locations is inadequate. Further along in the system are mechanisms sensitive to higher order relationships in stimulation. There were precedents to this view. Corresponding to Hering's point about triangulation (sampling from two positions) was his assessment that the brain handled inputs to the two eyes as a system, detecting disparities between the two eyes' views to perceive depth. Likewise, the Gestalt psychologists emphasized the contribution of brain mechanisms in processing relations in the input. J. Gibson pointed out the importance of higher order information and suggested that perceptual systems are naturally attuned to pick up such information. He did not deal much with neurophysiological or computational details, and he confused some by saying that perceptual systems "resonate" to information. Gibson's views still evoke controversy, yet researchers in perception and perceptual development have been busy ever since exploring the computations and mechanisms that extract higher order information.

The Contemporary Situation in Perceptual Theory

Philosophers, most cognitive scientists, and psychologists embrace the notion that, in a formal sense, perception has the character of an inference (specifically, an *ampliative* inference, in which the conclusion is not guaranteed by the premises or data, Swoyer, 2003). As virtual reality systems show us (and as dreams and hallucinations impressed Descartes and others), the perceptual experience of 3D space and certain objects and events does not guarantee their objective existence.

Such arguments have been elaborated in detail (Fodor & Pylyshyn, 1981; Ullman, 1980; but see Turvey, Shaw, & Reed, 1981) to attack J. Gibson's assertion that perception is "direct" (it does not require inference). If perception is formally inferential, perhaps Berkeley and his intellectual descendants were correct after all about how perception must develop. Is there a paradox in holding an ecological view while admitting that perception has a formally inferential character?

Resolving this apparent paradox by separating the two issues is important to understanding perceptual development. Perception has the formal character of an inference, but that does not imply that perception in humans must be learned, or that vision must be supplemented by touch or action. Perceptual inferences may be exactly the kinds of things that have been built into perceptual systems by evolution. Rock (e.g., 1984), a perceptual theorist who stressed the inferential nature of perception, and Marr (1982), who put computational approaches to perception on a clear footing, were among the earliest to articulate that perception could be both inferential *and* innate.

The analyses by the Gibsons and later investigators influenced the debate about perceptual development by altering conceptions of the information available for perception. For a moving, two-eyed observer with mechanisms sensitive to stimulus relations, the ambiguities envisioned by Berkeley—many different ordinary scenes leading to the same retinal image—do not exist. For Berkeley, visual ambiguity is so expansive that vision requires lots of outside help. For J. Gibson (1979), visual information specific to arrangements of scenes and events is available, and humans possess perceptual mechanisms attuned to such information. In Marr

(1982) may be found a synthesis of the two extremes: Visual ambiguity is intrinsic but can be handled by relatively few, general constraints. The interpretation of optic flow patterns in terms of 3D spatial layout requires the assumption that the scene (or whatever provides images to the two eyes) is not changing contingent on the observer's movements. This assumption is rarely, if ever, violated in ordinary perception, although it is exactly the assumption that is violated when an observer dons the viewing goggles or helmet in a virtual reality system. Many researchers have suggested that certain assumptions (e.g., the lack of observer-contingent scene changes or the movement of objects on continuous space-time paths) have come to be reflected in perceptual machinery through evolution (J. Gibson, 1966; Johansson, 1970; Kellman, 1993; Kellman & Arterberry, 1998; Shepard, 1984).

This possibility has far-reaching consequences with the potential to overturn a persistent and dominant view of perception based on learning. Yet it is important to recognize that the mere *possibility* of innate perceptual mechanisms (incorporating assumptions about the world) does not decide their reality. Unlike mountain goats, human infants are not mobile at birth, and until recently, their perceptual abilities were mostly unknown. Our discussion of constructivist and ecological views of perceptual development culminates in the observation that the answer is a matter for empirical science. Moreover, different perceptual abilities may have different contributions from native endowments, maturation, and learning. Researchers must write the story of each perceptual capacity based on experimental evidence.

This conclusion sets our agenda for the remainder of this chapter. We consider the emerging scientific picture of development for the crucial components of visual perception. This picture indicates decisively that, although learning may be involved in calibration and fine-tuning, visual perception depends heavily on inborn and early maturing mechanisms. This picture has begun to strongly influence views in other areas of development, as well as conceptions of the nature of perception. More unsettling is the failure to attend to the evidence on infant perception in some recent trends in cognitive science and neuroscience. After considering the evidence, we return to these issues at chapter's end.

Our review of the field is necessarily selective. A goal of the present chapter is to place what has been learned about infant vision in a more general historical and philosophical context, so that it may be easily appreciated and used by those in related fields. The particular topics reflect our areas of expertise and our views of areas that are rapidly advancing and in which important knowledge has been gained. Some parts of this chapter are modestly updated from the previous edition of the *Handbook of Child Psychology* (Kellman & Banks, 1998), whereas others are new. In what follows, we first consider basic visual sensitivities in the infant, including acuity and contrast sensitivity, sensitivity to color, pattern, and motion. We then consider spatial perception, object perception, and face perception.

BASIC VISUAL SENSITIVITIES IN INFANCY

The function of visual perception is to provide the perceiver with information about the objects, events, and spatial layout in which he or she must think and act. Starting from this concern, the study of basic visual sensitivity and the psychophysical methods used to study infants' visual perception may seem arcane to the non-specialist. Yet, all higher-level abilities to see the forms, sizes, textures, and positions of objects, as well as to apprehend spatial relations of objects at rest and in motion, depend on basic visual capabilities to resolve information about spatial position. For this reason, the development of spatial vision has been a topic of great concern to those interested in infant perception.

We begin an examination of spatial vision by considering sensitivities to variation across changing locations in the optic array. Two of the most basic dimensions of sensitivity in describing spatial vision are visual acuity and contrast sensitivity. Our discussion of these basic capacities leads naturally into an assessment of basic pattern discrimination abilities. We then consider color vision and motion perception.

Visual Acuity

Acuity is a vague term, meaning something like "precision." A particular variety of acuity is so often used to describe visual performance that the phrase "visual acuity" has become its common label. This type of acuity is more technically known as *minimum separable acuity* or *grating acuity.* Object recognition and identification depend on the ability to encode differences across positions in the retinal image in luminance or spectral composition. *Visual acuity* thus refers to the resolving capacity of the visual system—its ability to distinguish fine details or differences in adjacent positions.

Measuring this type of visual acuity by various means is by far the most common way of assessing ocular health and suitability for specific visual tasks, such as operating cars or aircraft.

To assess acuity, high-contrast, black-and-white patterns of various sizes are presented at a fixed distance. The smallest pattern or smallest critical pattern element that can be reliably detected or identified is taken as the threshold value and is usually expressed in angular units. Many different acuity measures have been used with adults, but only two have been widely used in developmental studies, grating acuity and vernier acuity.

Grating acuity tasks require resolving the stripes in a repetitive pattern of stripes. The finest resolvable grating is taken as the measure of acuity and it is generally expressed in terms of spatial frequency, which is the number of stripes per degree of visual angle. Adult grating acuity under optimal conditions is 45 to 60 cycles/degree, which corresponds to a stripe width of ½ to ⅔ minutes of arc (Olzak & Thomas, 1986). By optimal conditions, we mean that the stimulus is brightly illuminated, high in contrast, presented for at least ½ second, and viewed foveally with a well-focused eye. Change in any of these viewing parameters causes a reduction in grating acuity.

Vernier acuity is tested in tasks requiring discrimination of positional displacement of one small target relative to another. The most common variety involves distinguishing whether a vertical line segment is displaced to the left or right relative to a line segment just below it. In adults, the just-noticeable offset under optimal conditions is 2 to 5 seconds of arc (Westheimer, 1979). Because this distance is smaller than the diameter of a single photoreceptor in the human eye, this kind of performance has been called *hyperacuity* (Westheimer, 1979). As with grating acuity, the lowest vernier acuity thresholds are obtained when the stimulus is brightly illuminated, high in contrast, presented for at least ½ second, and viewed foveally with a well-focused eye.

There have been numerous measurements of grating acuity (the highest detectable spatial frequency at high contrast) in human infants. Figure 3.1 plots grating acuity as a function of age for some representative studies. The displayed results were obtained using three response measurement techniques: Forced-choice preferential looking (FPL), optokinetic nystagmus (OKN), and the visual evoked potential (VEP). This figure illustrates two points. First, acuity is low at birth and develops steadily during the 1st year. Grating acuity during the neonatal period is so low that these infants could be classified as legally blind. Second, the acuity estimates obtained with behavioral techniques such as FPL and OKN are generally lower than those obtained using electrophysiological techniques such as VEP. Grating acuity develops beyond the 1st year and reaches adult levels around 6 years of age (e.g., Skoczenski & Norcia, 2002). We discuss the optical, receptoral, and neural factors that determine grating acuity as a function of age in the section on contrast sensitivity.

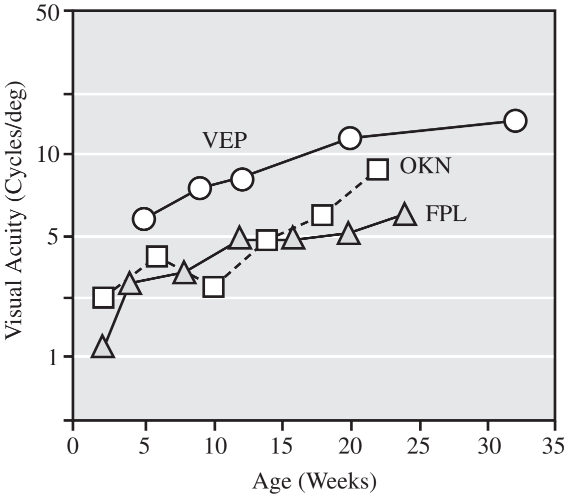

Figure 3.1 Visual acuity estimates at different ages. The highest detectable spatial frequency of a high-contrast grating stimulus is plotted as a function of age. Circles: Visual evoked potential estimates. Squares: Optokinetic nystagmus (OKN) estimates. Triangles: Forced-choice preferential looking estimates. *Sources:* "Measurement of Visual Acuity from Pattern Reversal Evoked Potentials," by S. Sokol, 1978, *Vision Research, 18,* pp. 33–40. Reprinted with permission; "Maturation of Pattern Vision in Infants during the First 6 Months," by R. L. Fantz, J. M. Ordy, and M. S. Udelf, 1962, *Journal of Comparative and Physiological Psychology, 55,* pp. 907–917. Reprinted with permission; "Visual Acuity Development in Human Infants up to 6 Months of Age," by J. Allen, 1978, unpublished master's thesis, University of Washington, Seattle, WA. Reprinted with permission.

There have been fewer measurements of vernier acuity; nonetheless, some intriguing observations have been reported. Shimojo and colleagues (Shimojo, Birch, Gwiazda, & Held, 1984; Shimojo & Held, 1987) and Manny and Klein (1984, 1985) used FPL to measure the smallest offset infants could respond to at different ages. They found that vernier acuity was much poorer in 8- to 20-week-old infants than in adults. The ratio of adult vernier acuity divided by 8-week olds' vernier acuity is significantly greater than the corresponding ratio for grating acuity. A similar finding has emerged from VEP measurements of vernier and grating acuity; adult levels of hyperacuity were not reached until 10 to 14 years of age (Skoczenski & Norcia, 2002). This suggests that the visual mechanisms that limit vernier acuity undergo greater change with age than do the mechanisms limiting grating acuity. Different hypotheses have been offered concerning the differing growth rates (Banks & Bennett, 1988; Shimojo & Held, 1987; Skoczenski & Norcia, 2002); however, direct empirical tests are needed.

Contrast Sensitivity

Contrast sensitivity refers to the ability to detect variations in luminance. Most acuity testing is done at high contrast (e.g., black characters on a white background or gratings varying from white to black). Testing for contrast sensitivity involves finding the least difference between luminances that allows detection of structure. The contrast sensitivity function (CSF) represents the visual system's sensitivity to sinusoidal gratings of various spatial frequencies. The CSF has generality as an index of visual sensitivity because any two-dimensional pattern can be represented by its spatial frequency content and, consequently, one can use the CSF along with linear systems analysis to predict visual sensitivity to a wide range of spatial patterns (Banks & Salapatek, 1983; Cornsweet, 1970). Thus, measurements of contrast sensitivity as a function of age should allow the prediction of sensitivity to and even preference for many visual stimuli (Banks & Ginsburg, 1985; Gayl, Roberts, & Werner, 1983).

The adult CSF has a peak sensitivity at 3 to 5 cycles/degree, so the lowest detectable contrasts occur for gratings of medium spatial frequency. At those spatial frequencies, the just-detectable grating has light stripes that are only 0.5% brighter than the dark stripes. At progressively higher spatial frequencies, sensitivity falls monotonically to the so-called high-frequency cutoff at about 50 cycles/degree. This is the finest grating an adult can detect when the contrast is 100% and it corresponds to the person's grating acuity. At low spatial frequencies, sensitivity falls as well, although the steepness of this falloff is highly dependent on the conditions of measurements.

Adult contrast sensitivity and grating acuity are limited by optical, receptoral, and neural factors. Sensitivity is best with good lighting, foveal fixation, sufficiently long stimulus duration, and a well-focused eye. Decreased illumination reduces both contrast sensitivity and the high-frequency cutoff (van Nes & Bouman, 1967). Similar changes in contrast sensitivity occur when the stimulus is imaged on the peripheral retina (Banks, Sekuler, & Anderson, 1991) or the eye is not well focused (Green & Campbell, 1965). Understanding limitations on adult vision has been aided by modeling the early stages of vision as a series of filtering stages. Visual stimuli pass sequentially through the eye's optics, which are responsible for forming the retinal image; the photoreceptors, which sample and transduce the image into neural signals; and two to four retinal neurons, which transform and transmit those signals into the optic nerve and eventually to the central visual pathways. In these early stages of visual processing, considerable information is lost. The high-frequency falloff observed in the adult CSF is determined, by and large, by the filtering properties of the eye's optics and the photoreceptors (Banks, Geisler, & Bennett, 1987; Pelli, 1990; Sekiguchi, Williams, & Brainard, 1993). The loss of high-frequency sensitivity with peripheral viewing has been modeled successfully by examination of the optics, receptors, and retinal circuits of the peripheral retina (Banks et al., 1991). The sensitivity loss that accompanies a reduction in illumination has also been modeled reasonably successfully, at least at high spatial frequencies (Banks et al., 1987; Pelli, 1990) as has the loss that accompanies errors in the eye's focus (Green & Campbell, 1965). From the emerging understanding of the optical, receptoral, and neural mechanisms that determine contrast sensitivity in adults, attempts have been made to use similar techniques to understand the development of contrast sensitivity in human infants.

Figure 3.2 displays an adult CSF measured using a psychophysical procedure, along with infant CSFs measured using forced-choice preferential looking (Atkinson, Braddick, & Moar, 1977; Banks & Salapatek, 1978) and the visual evoked potential (Norcia, Tyler, & Allen, 1986; Pirchio, Spinelli, Fiorentini, & Maffei, 1978). These data illustrate two common observations. First, contrast sensitivity (and grating acuity) in young infants is substantially lower than that of adults, with the difference diminishing rapidly during the 1st year. Second, as we saw earlier in Figure 3.1, measurements with the visual evoked potential typically yield higher sensitivity

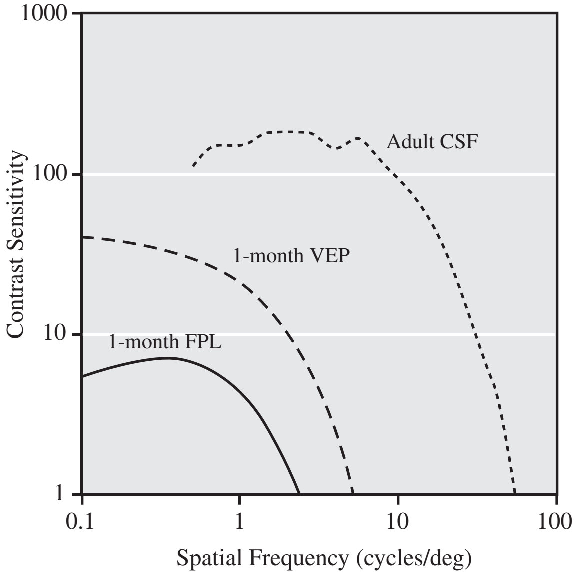

Figure 3.2 Adult and 1-month-old infant contrast sensitivity functions (CSFs). Contrast sensitivity is plotted as a function of spatial frequency (the numbers of grating cycles per degree of visual angle). The upper dotted curve is an adult CSF that was measured psychophysically. The lower solid curve is the average of 1-month CSFs, measured using forced-choice preferential looking. The middle dash curve is the average of 1-month CSFs, measured using visual-evoked potential. *Sources:* "Acuity and Contrast Sensitivity in 1-, 2-, and 3-Month-Old Human Infants," by M. S. Banks and P. Salapatek, 1978, *Investigative Ophthalmology and Visual Science, 17,* pp. 361–365. Reprinted with permission and "Development of Contrast Sensitivity in the Human Infant," by A. M. Norcia, C. W. Tyler, and R. D. Hammer, 1990, *Vision Research, 30,* pp. 1475–1486.

(and acuity) estimates than do behavioral techniques (see Mayer & Adrendt, 2001 for a review). The time course differs depending on whether a behavioral or electrophysiological technique is used. With evoked potential measurements, peak sensitivity approaches adult values by 6 months of age, whereas behavioral measurements exhibit a slower developmental time course. Not illustrated is the systematic variability in the CSF across infants (Peterzell, Werner, & Kaplan, 1995). Although group functions are smooth in shape, individual functions are not.

What accounts for the development of acuity and contrast sensitivity? Infants who experience visual deprivation early in life due to monocular or binocular cataracts show newborn levels of acuity once the cataract(s) are removed (Maurer & Lewis, 1999), despite being 1 to 9 months of age. Longitudinal follow-up, however, shows rapid increases in acuity suggesting that visual input is necessary for visual functioning. Beyond knowing that visual input is necessary, the specific causes, anatomical and physiological, of the striking functional deficits observed during the first few months of life are still being debated. Some investigators have proposed that one can explain the low contrast sensitivity and grating acuity of neonates as due to information losses caused by optical and retinal immaturities (Jacobs & Blakemore, 1988; Wilson, 1988, 1993); others have argued that those immaturities are not the whole story (Banks & Bennett, 1988; Banks & Crowell, 1993; Brown, Dobson, & Maier, 1987).

Development of the eye and retina are important factors. Large ocular and retinal changes occur in development and they have profound effects on the ability to see spatial patterns. The eye grows significantly from birth to adolescence, with most growth occurring in the 1st year. The distance from the cornea at the front of the eye to the retina at the back is 16 to 17 mm at birth, 20 to 21 mm at 1 year, and 23 to 25 mm in adolescence and adulthood (Hirano, Yamamoto, Takayama, Sugata, & Matsuo, 1979; Larsen, 1971). Shorter eyes have smaller retinal images. So, for example, a 1-degree target subtends about 200 microns on the newborn's retina and 300 microns on the adult's (Banks & Bennett, 1988; Brown et al., 1987; Wilson, 1988). Thus, if newborns had the retinae and visual brains of adults, one would expect their visual acuity to be about two-thirds that of adults simply because they have smaller retinal images to work with.

Another ocular factor relevant to visual sensitivity is the relative transparency of the ocular media. Two aspects of ocular media transmittance are known to change with age: the optical density of the crystalline lens pigment and that of the macular pigment. In both cases, transmittance is slightly higher in the young eye, particularly at short wavelengths (Bone, Landrum, Fernandez, & Martinez, 1988; Werner, 1982). Thus, for a given amount of incident light, the newborn's eye actually transmits slightly more to the photoreceptors than does the mature eye. This developmental difference ought to favor the newborn compared with the adult, but only slightly.

The ability of the eye to form a sharp retinal image is yet another relevant ocular factor. This ability is typically quantified by the optical transfer function. There have been no measurements of the human neonate's optical transfer function, but the quality of the retinal image almost certainly surpasses the resolution performance of the young visual system (Banks & Bennett, 1988). Thus, it is commonly assumed that the optical transfer function of the young eye is adultlike (Banks & Crowell, 1993; Wilson, 1988, 1993). Refractive errors or accommodation errors diminish the sharpness of the retinal image and thereby decrease sensitivity to high spatial frequencies (Green & Campbell, 1965). Hyperopic and astigmatic refractive errors are common in infants (Banks, 1980a; Howland, 1982); they tend not to accommodate accurately until 12 weeks (Banks, 1980b; Braddick, Atkinson, French, & Howland, 1979; Haynes, White, & Held, 1965). Nonetheless, it is widely believed that infants' refractive and accommodative errors do not constrain sensitivity or visual acuity significantly (Banks, 1980a, 1980b; Braddick et al., 1979; Howland, 1982).

If optical imperfections do not contribute significantly to the visual deficits observed in young infants, receptoral and postreceptoral processes must do so. The retina and central visual system all exhibit immaturities at birth (Banks & Salapatek, 1983; Hendrickson, 1993; Hickey & Peduzzi, 1987; Yuodelis & Hendrickson, 1986), but morphological immaturities are evident in the fovea, particularly among the photoreceptors.

The development of the fovea is dramatic in the 1st year of life, but subtle morphological changes continue until at least 4 years of age (Yuodelis & Hendrickson, 1986). The fovea, defined as the part of the retina that contains no rods, is much larger at birth than in adulthood: Its diameter decreases from roughly 5.4 degrees at birth to 2.3 degrees at maturity. Moreover, the individual cells and their arrangements are very different at birth than they will be later on. The newborn's fovea possesses three discernible layers of neurons—the photoreceptors, the neurons of the outer nuclear layer, and the retinal ganglion cells—whereas the mature fovea contains only one layer, which is composed of photoreceptors. The most dramatic histological differences, however, are the sizes and shapes of foveal cones. Neonatal cones have inner segments that are much broader and shorter. The outer segments are distinctly immature, too, being much shorter than their adult counterparts. These shape and size differences render the newborn's foveal cones less sensitive than those of the adult (Banks & Bennett, 1988; Brown et al., 1987).

To estimate the efficiency of the neonate's lattice of foveal cones, Banks and colleagues calculated the ability of the newborn's cones to capture light in the inner segment, funnel it to the outer segment, and produce a visual signal (Banks & Bennett, 1988; Banks & Crowell, 1993). They concluded that the adult foveal cone lattice is dramatically better at absorbing photons of light and converting them into visual signals. By their calculations, if identical patches of light were presented to newborn and adult eyes, roughly 350 photons would be effectively absorbed in adult foveal cones for every photon absorbed in newborn cones. Similar estimates were obtained by Wilson (1988, 1993). The newborn's fovea is less able to use light entering the eye than is the mature fovea.

The cones of the immature fovea are also more widely spaced than those of the adult (Banks & Bennett, 1988; Banks & Crowell, 1993; Wilson, 1988, 1993). Cone-to-cone separation in the center of the fovea is about 2.3, 1.7, and 0.58 minutes of arc in neonates, 15-month-olds, and adults, respectively. These dimensions impose a physical limit (the so-called Nyquist limit) on the highest spatial frequency that can be resolved without distortion or aliasing (Williams, 1985). From the current estimates of cone spacing, the foveas of newborns, 15-month-olds, and adults should theoretically be unable to resolve gratings with spatial frequencies above 15, 27, and 60 cycles/degree, respectively.

Investigators have calculated the contrast sensitivity and visual acuity losses that ought to be observed if the only difference between the spatial vision of newborns and adults were the eye's optics and the properties of the foveal cones (Banks & Bennett, 1988; Banks & Crowell, 1993; Wilson, 1988, 1993). The expected losses are substantial: Contrast sensitivity to medium and high spatial frequencies is predicted to be as much as 20-fold lower in neonates than in adults. Nonetheless, the observed contrast sensitivity and grating acuity deficits in human newborns are even larger than predicted (e.g., Skoczenski & Aslin, 1995), so this analysis of information losses in the optics and receptors implies that there are other immaturities, presumably among retinal neurons and central visual circuits, that contribute to the observed loss of contrast sensitivity and grating acuity.

Another hypothesis concerning the contrast sensitivity and visual acuity of young infants has been offered. Because of the obvious immaturity of the fovea, perhaps infants use another part of the retina to process points of interest in the visual scene. Cones in the parafoveal and peripheral retina are relatively more mature at birth than their foveal counterparts, but they, too, undergo postnatal development (Hendrickson, 1993). The data, however, do not support this hypothesis: Young infants' best acuity and contrast sensitivity is obtained with foveal stimulation. Lewis, Maurer, and Kay (1978) found that newborns could best detect a narrow light bar against a dark background when it was presented in central vision, and D. Allen, Tyler, and Norcia (1996) showed that visual evoked potential (VEP) acuity and contrast sensitivity is higher in central than in peripheral vision in 8- to 39-week-olds, by an average factor of 2.3.

An important question that will be pursued vigorously in future research is what factors not considered in the preceding analyses account for the unexplained portion of the contrast sensitivity and grating acuity losses. There are numerous candidates including internal neural noise (such as random addition of action potentials at central sites; Skoczenski & Norcia, 1998), inefficient neural sampling, and poor motivation to respond.

Orientation Sensitivity

Sensitivity to orientation is an important foundation of much of higher level vision, such as perception of edges, patterns, and objects. In monkeys, it is well established that orientation sensitivity is innately present (Wiesel & Hubel, 1974), and in cats orientation sensitivity also appears soon after birth, with or without visual experience (Hubel & Wiesel, 1963). Paradoxically, development of orientation sensitivity has been the topic of numerous learning simulations in recent years (Linsker, 1989; Olshausen & Field, 1996; von der Malsburg, 1973). These results suggest interesting relations between orientation-sensitive cortical units and the statistics of images of natural scenes. Such studies are often interpreted as showing how the visual brain gets "wired up by experience" after birth (e.g., Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1996).

Yet the evidence suggests that basic orientation sensitivity in humans, as in monkeys and cats, is present at birth. Some maturation of orientation processing was suggested by visual evoked potential (VEP) studies by Braddick, Atkinson, and Wattam-Bell (1986). Their results showed responses emerging at 2 to 3 weeks for slowly modulated orientation changes (3 reversals/second) and responses at 5 to 6 weeks for more rapid orientation changes. In an elegant analysis, these investigators showed that the pace of these developments was maturational, in that preterm infants of the same gestational age showed patterns of development similar to full-term infants. In other words, gestational age, not weeks of visual experience was crucial.

Direct behavioral tests of orientation sensitivity have revealed evidence that it is innate. Slater, Morison, and Somers (1988) used habituation measures with high-contrast striped patterns. They found dishabituation to changed orientation in situations where other stimulus variables (such as whether a particular screen position was black or white) could be ruled out. Their results were confirmed by Atkinson, Hood, and Wattam-Bell (1988). Orientation sensitivity appears to be innate in humans, although it improves in the early weeks of life.

Pattern Discrimination

Assessing acuity and contrast sensitivity largely involve comparing responses to something versus nothing. The exquisite spatial resolution of vision, however, serves functions beyond mere detection. Encoding and discriminating patterns, surfaces, and objects are key tasks of visual processing. Thus, describing pattern-processing capabilities in infant vision is important. But how can pattern-perception capabilities be assessed in a comprehensive way? As in studies of adult vision, linear systems theory from mathematics and signal processing is useful. Any distribution of luminance (light and dark) in an image can be described, using a 2D Fourier transform, as a set of sinusoidally varying luminance components having particular frequencies and amplitudes, in particular orientations. Because any image can be analyzed in this way, the frequency components form an important characterization of the pattern. If the spatial phase of each component is also encoded, the pattern is completely described. Researchers have made progress characterizing infant pattern discrimination using linear systems concepts. This work has used tests of infants' abilities to distinguish simple, suprathreshold patterns that vary in contrast or in phase.

Sensitivity to contrast differences is typically measured by presenting two sine-wave gratings of the same spatial frequency and orientation but differing contrasts. In experiments with adults, a participant is asked to indicate the grating of higher contrast. The increment in contrast required to make the discrimination varies depending on the common contrasts of the two stimuli; as the common contrast is increased, a successively larger increment is required (Legge & Foley, 1980). Six- to 12-week-old infants require much larger contrast increments than adults when the common contrast is near detection threshold. At high common contrasts, however, infants' discrimination thresholds resemble those of adults (Brown, 1993; Stephens & Banks, 1987). These findings suggest that infants' ability to distinguish spatial patterns on the basis of contrast differences is poor at low contrast and reasonably good at high contrast. Different explanations for infants' performance in this task have been offered, but none has been confirmed by empirical observation (Brown, 1993; Stephens & Banks, 1987).

Studies have also addressed discrimination based on spatial phase differences. Spatial phase refers to the relative position of the spatial frequency components (the sine-wave gratings) of which the pattern is composed (Piotrowski & Campbell, 1982). Phase information is crucial for the features and relations that are involved in object perception, such as edges, junctions, and shape. Altering phase information in a spatial pattern greatly affects its appearance and perceived identity to adults (Oppenheim & Lim, 1981). In phase discrimination tasks, the subject is asked to distinguish between two patterns—usually gratings—that differ only in the phase relationships among their spatial frequency components. Adults are able to distinguish patterns that differ only slightly in the phases of their components when the stimulus is presented to the fovea (Badcock, 1984). The ability to discriminate phase can fall dramatically, however, when the stimulus is presented in the peripheral visual field (Bennett & Banks, 1987; Rentschler & Treutwein, 1985).

Relatively little work has directly addressed infants' ability to use phase differences to discriminate spatial patterns. Braddick et al. (1986) presented periodic patterns composed of different spatial frequency components. When the components were added in one phase relationship, the resultant was a square-wave grating (a repeating pattern of sharp-edged light and dark stripes); when the components were added in another phase, the resultant appeared to adults to be a very different, more complex pattern. Eight-week-olds were able to discriminate these patterns. Remarkably, however, 4-week-olds seemed unable to make the discrimination.

In a similar vein, Kleiner (1987) and Kleiner and Banks (1987) examined visual preferences for patterns in which the phases of the constituent components were altered. Kleiner and colleagues found that newborns and 8-week-olds exhibit reliable fixation preferences for a schematic face over a rectangle lattice (Fantz & Nevis, 1967). To examine the influence of spatial phase on fixation preference, Kleiner used an image-processing technique in which the contrasts of the constituent spatial frequencies from one pattern were combined with the phases of the constituent frequencies from the other pattern. The perceptual appearance of these hybrid patterns is most closely associated with the pattern from which the phases rather than the contrasts came (Oppenheim & Lim, 1981; Piotrowski & Campbell, 1982); stated another way, the hybrid pattern that appears most facelike is the one that contains the phases from the original schematic face. Not surprisingly, 8-week-olds preferred to fixate the hybrid that contained the phases of the face and the contrasts of the lattice. Newborns' preferences, however, were for the hybrid that contained the phases of the lattice and the contrasts of the face. One interpretation of this finding is that newborns are relatively insensitive to spatial phase, but other interpretations have been suggested (e.g., Badcock, 1990).

The observation that young infants seem relatively insensitive to variations in spatial phase is extremely important. If valid, it suggests that young infants' ability to discriminate spatial patterns has a significant deficiency that is at least qualitatively similar to the deficiency observed in the peripheral visual field of normal adults (Bennett & Banks, 1987; Rentschler & Treutwein, 1985) and in the central visual field of amblyopic adults (Levi, Klein, & Aitsebaomo, 1985). In functional terms, infants' processing of basic perceptual properties of objects, such as unity, size, shape, texture, and so on depend implicitly on processing of phase information. To the extent that it is poor in the earliest weeks of life, these abilities will be limited. Conversely, tests of certain of these perceptual abilities, to be discussed, indicate striking newborn perceptual competencies (e.g., for seeing object size and faces). One of the challenges of infant vision research is reconciling certain poor sensitivity to basic sensory properties, such as phase, with evidence of higher order abilities, such as face perception. The most likely resolution of the apparent paradox is that infant sensory capacities for properties such as phase and orientation are worse than adults' but not completely lacking, even at birth (for further discussion, see Kellman & Arterberry, 1998).

Color Vision

The term *color* refers to the component of visual experience characterized by the psychological attributes of *brightness, hue,* and *saturation.* Two of these—hue and saturation—are chromatic attributes, and the other—brightness—is actually an achromatic attribute. Hue is primarily correlated with the dominant wavelength of the stimulus whereas brightness is primarily correlated, but not isomorphic, with stimulus intensity. Saturation is correlated with the distribution of wavelengths in a stimulus; stimuli with more broad band light mixed in are seen as less saturated. We refer to visual discriminations on the basis of differences in hue or saturation as *chromatic discriminations* and discriminations on the basis of differences in brightness as *achromatic discriminations.*

The functional importance of perceiving color has been a matter of debate. Humans readily perceive objects and events from nonchromatic displays, such as those in black-and-white movies or television. Why, then, have we evolved elaborate color vision mechanisms? In ordinary seeing, chromatic information probably aids object segmentation and recognition. In cases in which an object and its background are equal or nearly equal in luminance, the object's shape can be perceived from chromatic differences. Chromatic information can also help distinguish one version of an object (a red apple) from another (a green apple). Less well understood, but important, are the obvious contributions of color to our aesthetic experiences.

The human visual system has four types of photoreceptors, one type of rod and three types of cones. The cones are active under daylight viewing conditions and subserve color vision; rods are active under quite dim illumination. We consider only cones in our discussion of color vision.

The three cone types are sensitive to different, but overlapping, bands of wavelength. The cone types are generally called *short-wavelength-sensitive (S), medium-wavelength-sensitive (M),* and *long-wavelength-sensitive (L)* cones. (We prefer this terminology to the terms *blue, green,* and *red* cones because those terms imply that each cone type is responsible for the perception of a particular hue, and this is not the case.) Each type of photoreceptor responds in an untagged fashion; that is, only response quantity, and nothing else, varies with changes in the incident light. The consequences of untagged responding are profound. The output of any single photoreceptor type can be driven to a given level by virtually any wavelength of light simply by adjusting the light's intensity. Thus, information about the wavelength of a stimulus cannot be extracted from the output of a single photoreceptor type. Instead the visual system must use the relative activities of the three photoreceptor types to distinguish different colors.

The subsequent stages of the visual process must utilize the outputs of the different receptor types in a complex way to produce the conscious experience of color. Psychophysical evidence from adult humans and physiological evidence from adult monkeys indicate that the signals of the three cone types undergo a major transformation in the retina. Signals from two or three kinds of cones are combined additively to form achromatic channels (coding brightness primarily) and are combined subtractively to form two kinds of chromatic channels (coding hue primarily). The subtractive, chromatic channels (red/green and blue/yellow) have been called *opponent processes* because different wavelength bands evoke different directions of neural response.

Many of the characteristics of photoreceptors and subsequent neural stages were originally inferred from adult behavioral studies. Our discussion of color vision centers on two questions:

1. What hues are infants sensitive to and when?
2. What mechanisms account for the development of color vision?

Origins of Hue Discrimination

When can infants discriminate stimuli on the basis of hue alone? Before 1975, a large number of behavioral studies attempted to answer this question, but they all failed to eliminate the possibility that infants were basing their discriminations on brightness cues rather than hue (or saturation) cues (Kessen, Haith, & Salapatek, 1970). To demonstrate convincingly that infants can discriminate on the basis of hue alone, researchers have used two strategies to rule out brightness artifacts. (Elsewhere, we describe in detail the importance and difficulty of separating hue from brightness responses; Kellman & Arterberry, 1998; Kellman & Banks, 1997.)

The methods involve presenting two stimuli differing in hue (e.g., red and green) and looking for a systematic response (e.g., directional eye movement, VEP, or FPL) to one as evidence for hue discrimination. One strategy for eliminating brightness artifacts involves using the spectral sensitivity function to match the brightnesses of two stimuli to a first approximation and then by varying the luminances (a measure of stimulus intensity) of the stimuli unsystematically from trial to trial over a wide-enough range to ensure that one is not always brighter than the other. Systematic responding by the infant to one of the two chromatic stimuli, across luminances, can therefore not be attributed to discrimination on the basis of brightness. Using this strategy, Oster (1975), and Schaller (1975) demonstrated hue discrimination in 8- and 12-week-old infants, respectively.

The second strategy for eliminating brightness cues was developed by Peeples and Teller (1975); subsequently, many others have used this strategy, so we explain it in some detail. They also used spectral sensitivity data to match approximately the brightnesses of their stimuli. They then varied luminance systematically around the estimate of the brightness match. Several luminances were presented, bridging a 0.8 log unit range in small steps. Consequently, at least one of the luminance pairings must have been equivalent in brightness for each of the infants. Peeples and Teller showed that 8-week-olds could discriminate red from white for all luminance pairings. They concluded that 8-week-olds make true hue discriminations.

Thus, three reports in 1975, using different techniques, provided the first convincing evidence that 8- to 16-week-olds can make chromatic discriminations. Today, the story has been further refined: M and L cones appear to function by 8 weeks of age and possibly as early as 4 weeks (e.g., Bieber, Knoblauch, & Werner, 1998; Kelly, Borchert, & Teller, 1997); however, S cone functionality does not appear to emerge until at least 3 to 4 months of age (e.g., Crognale, Kelly, Weiss, & Teller, 1998; Suttle, Banks, & Graf, 2002). At birth, infants may have very limited color experience, and during the first 4 months of life their world becomes increasingly filled with color. And by 4 months, infants have color preferences that mirror adults: Saturated colors (such as royal blue) are preferred over less saturated colors (such as pale blue; Bornstein, 1975).

Assessing Color Vision

Three sorts of hue discriminations—Rayleigh, tritan, and neutral-point—are particularly interesting theoretically, and research on infants' ability to make these discriminations fills out the picture of early competencies and deficits.

The *neutral-point test* is based on the observation that color-normal adults are able to distinguish all spectral (single wavelength) lights from white; that is, they do not exhibit a neutral point in such a comparison. Peeples and Teller (1975) and Teller, Peeples, and Sekel (1978) used a neutral-point test to examine 8-week-olds' color vision. They examined both white-on-white luminance discrimination and discrimination of chromatic targets from white. The colors of the test targets and background are represented in Figure 3.3, which is a chromaticity diagram. Eight-week-olds discriminated many colors from white: red, orange, some greens, blue, and some purples; these colors are represented by the filled

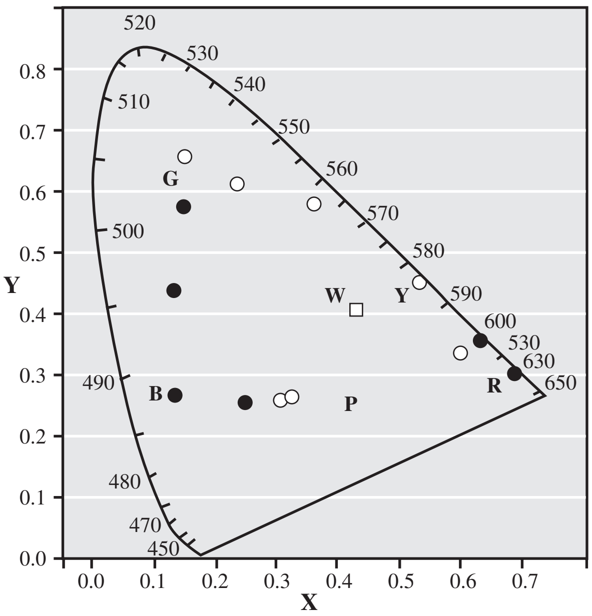

Figure 3.3 The stimuli used in neutral-point experiments. Participants in both experiments were 8-week-old infants. The format of the figure is the CIE Chromaticity diagram, which allows one to plot chromatic stimuli differing in hue and saturation. Saturated colors are represented at the exterior of the diagram, and unsaturated colors toward the middle. The right corner of the diagram (around 650) represents a hue of red, the top of the diagram represents a hue of bluish-green (labeled 520) and the lower left corner represents a hue of violet (near 400). Each circular symbol represents a color that was presented to infants in these two experiments. Open symbols represent hues that all infants failed to discriminate from white (W). Half-filled symbols represent hues that some, but not all, infants discriminated from white. Filled symbols represent hues that all infants reliably discriminated from white. *Sources:* "Color Vision and Brightness Discrimination in Human Infants," by D. R. Peeples and D. Y. Teller, 1975, *Science, 189,* pp. 1102–1103. Reprinted with permission and "Discrimination of Chromatic from White Light by 2-Month-Old Human Infants," by D. Y. Teller, D. R. Peeples, and M. Sekel, 1978, *Vision Research, 18,* pp. 41–48. Reprinted with permission.

symbols in the figure. Eight-week-olds did not discriminate yellow, yellow-green, one green, and some purples from white; these are represented by the open symbols in the figure. Thus, 8-week-old infants seemed to exhibit a neutral zone running from short wavelengths to yellow and green, resulting from deficient S cones (in color parlance, they have tritanopia or tritanomalous trichromacy; Teller et al., 1978). Later, Adams, Courage, and Mercer (1994) reported that the majority of newborns were able to discriminate broadband red from white and the majority were unable to discriminate blue, green, and yellow from white. These results are quite similar to the 8-week results reported by Teller et al. (1978).

A *tritan test* is designed to assess the function of S cones. By presenting two lights that activate M and L cones equally, the test isolates the S cones. Varner, Cook, Schneck, McDonald, and Teller (1985) asked whether 4- to 8-week infants could distinguish two such lights. Specifically, they presented violet targets in a green background. Eight-week-olds distinguished the two lights at all luminances, so they do not appear to have an S-cone deficiency. Four-week olds, on the other hand, did not discriminate the two lights reliably, suggesting that they have an S-cone defect. D. Allen, Banks, and Schefrin (1988) and Clavadetscher, Brown, Ankrum, and Teller (1988) confirmed this finding: In their experiment, 3- to 4-week-olds could not distinguish a violet target on a green background, but 7- to 8-week-olds could. More recently, Teller, Brooks, and Palmer (1997) found that tritan stimuli did not drive directionally appropriate eye movements even at 16 weeks of age.

Rayleigh discrimination tests involve distinguishing brightness-matched, long-wavelength lights such as red and green. They are diagnostically important because adults with the most common color defects—deuteranopia (lacking M cones) and protanopia (lacking L cones)—are unable to make such discriminations. Hamer, Alexander, Teller (1982) and Packer, Hartmann, and Teller (1984) examined the ability of 4-, 8-, and 12-week-olds to make Rayleigh discriminations. Either a green or red target was presented at one of a variety of luminances on a yellow background. Most 8-week-olds and essentially all 12-week-olds made these discriminations reliably, providing clear evidence that most infants do not exhibit deutan or protan defects by 8 weeks of age. In contrast, the majority of 4-week-olds did not exhibit the ability to make either discrimination. Packer et al. (1984) also found a significant effect of target size. Twelve-week-olds were able to make Rayleigh discriminations with 4- and 8-degree targets, but not 1- and 2-degree targets. D. Allen et al. (1988) and Clavadetscher et al. (1988) confirmed the Rayleigh discrimination finding. They reported that 3- to 4-week-olds could not distinguish a red target on a green background; 7- to 8-week-olds could make this discrimination reliably.

In sum, there is little evidence that the majority of infants 4 weeks of age or younger make hue discriminations with the exception of discriminating red from white. The paucity of positive evidence is consistent with the hypothesis that human neonates are generally color deficient. By 4 months of age, infant color vision abilities approximate adult abilities, although there continue to be differences between infants' and adults' chromatic profiles throughout the 1st year of life (Crognale et al., 1998). We now turn to the question of what mechanism(s) underlie this development.

How Does Early Color Vision Develop?

Two explanations have been proposed to account for young infants' hue discrimination failures. One possibility is the absence or immaturity of different cone types or immaturities among postreceptoral chromatic channels. Banks and Bennett (1988) have called this the *chromatic deficiency hypothesis.* There is, however, another possibility, raised initially by Banks and Bennett (1988) and elaborated by Brown (1990), Banks and Shannon (1993), Teller and Lindsey (1993), and D, Allen, Banks, and Norcia (1993). Perhaps neonates have a full complement of functional cone types and the requisite neural machinery to preserve and compare their signals, but overall visual sensitivity is so poor that it does not allow them to demonstrate their chromatic capabilities. On this account, older infants may exhibit reliable chromatic discrimination because of increased visual sensitivity. In this context, visual sensitivity might include discrimination performance of a visual system limited by optical and photoreceptor properties plus a general postreceptoral loss. This hypothesis has been called the *visual efficiency hypothesis* (D. Allen et al., 1993) and the *uniform loss hypothesis* (Teller & Lindsey, 1993).

There is an interesting way to compare the chromatic efficiency and visual efficiency explanations experimentally. Consider measurements of hue discrimination threshold (e.g., the chromatic contrast required to mediate the discrimination of two lights of equal brightness but different wavelength compositions—the "chromatic threshold") and a brightness discrimination threshold (e.g., the luminance contrast required to mediate the discrimination of two lights of the same wavelength composition but different luminances—the "luminance threshold"). The chromatic deficiency hypothesis predicts that the ratio of luminance threshold divided by chromatic threshold will decrease with increasing age. That is, luminance and chromatic thresholds may both improve with age, but chromatic thresholds change more. The visual efficiency or uniform loss hypothesis predicts that the ratio of luminance threshold divided by chromatic threshold is constant with age. That is, luminance and chromatic thresholds decrease at the same rates with increasing age because they are both limited by a common factor such as overall visual sensitivity. Banks and Bennett (1988) and Banks and Shannon (1993) showed that this hypothesis can in fact account for the poor Rayleigh and neutral-point discriminations of neonates.

Other investigators have tested the chromatic deficiency and visual efficiency hypotheses empirically, but no clear consensus has yet emerged. The challenge has been to develop paradigms in which infants' sensitivity can be made high enough to distinguish the predictions of the two hypotheses. In particular, recent work has focused on determining which hypothesis provides a better account of young infants' ability to use M and L cones to make Rayleigh discriminations (e.g., Adams & Courage, 2002; D. Allen et al., 1993, 1988; Clavadetscher et al., 1988; Morrone, Burr, & Fiorentini, 1993; Teller & Lindsey, 1993; Teller & Palmer, 1996; Varner et al., 1985). On balance, the discrimination failures observed with the youngest children and, for small targets, with older children do not necessarily imply deficiencies among chromatic mechanisms per se. Rather the ratio of chromatic divided by luminance sensitivity may well remain constant across age, suggesting that neonates' apparent inability to make Rayleigh and neutral-point discriminations is caused by an overall loss in visual efficiency. The predictions of the visual efficiency hypothesis, however, are inconsistent with the tritan discriminations. Therefore, young infants may in fact possess some form of color anomaly involving a deficiency among S cones.

Future work will be needed to illuminate infants' loss of visual efficiency and/or deficiency in S cones. Researchers are also taking an interest in the difference between processing moving versus static chromatic stimuli, which has implications for the relative involvement and development of the magnocelluar and parvocelluar pathways, which are responsible for spatial and temporal locations of chromatic changes and color identity, respectively (e.g., Dobkins & Anderson, 2002; Dobkins, Anderson, & Kelly, 2001; Dobkins, Lia, & Teller, 1997; Teller, 1998; Thomasson & Teller, 2000).

Motion Perception

Moving and perceiving are deeply linked. Many of the most significant features of an environment to be perceived are moving objects and the events in which they participate. Motion of the observer is also crucial, in two ways. To locomote safely through space requires that our visual system be structured to deal with continuously changing views of the environment. Moreover, information given by transforming views of the world turn out to be a rich indicator not only of events but of persisting properties of the world, such as spatial layout (J. Gibson, 1966, 1979; Johansson, 1970). Later, in discussing space perception, we consider ways in which motions of objects and observers offer high-fidelity information about spatial layout and object form.

Early research on infant visual motion perception showed that motion strongly attracts infant attention (Fantz & Nevis, 1967; Haith, 1983; Kremenitzer, Vaughan, Kurtzberg, & Dowling, 1979; White, Castle, & Held, 1964). Progress has been made in analyzing the limits and probable mechanisms of motion sensitivity, including directional sensitivity, velocity sensitivity, and perception of motion and stability.

Directional Selectivity

The ability to detect motion direction is one of the most basic and important perceptual capacities, but its development has been poorly understood until the last decade or so. Using both behavioral and visual evoked potential (VEP) measures, Wattam-Bell (1991, 1992) tested directional sensitivity in longitudinal studies. In the VEP studies, it was expected that if infants detected direction reversals in an oscillating checkerboard pattern, a measurable electrical response should be found at the frequency of the stimulus reversals. Reliable VEPs were first found at a median age of 74 days for 5 degrees/second patterns and 90 days for 20 degree/second patterns. Behavioral studies (Wattam-Bell, 1992) employed a different type of display. In one condition, an array of randomly changing dots was shown in which appeared a vertical strip of coherently (vertically) moving dots. In another condition, the vertical motion was shown against a background having opposite direction motion. A visual preference paradigm was used in which the target display appeared adjacent to a control display having random or uniform motion. If an infant detected the vertical target strip having unique, coherent motion, the infant was expected to look longer at this display. The element displacement per frame was manipulated to find the greatest displacement that supported motion detection (d_{max}). This measure was found to increase markedly from 8 to15 weeks of age. The younger infants (8 to 11 weeks) could tolerate only about a .25 degree of visual angle displacement (frame duration was 20 millisecond), whereas 14 to 15-week-olds showed a d_{max} of about .65. (The value for adults is about 2 degrees in this task.)

Poor performance in the earliest weeks may be due to a lack of motion detectors sensitive to high velocities, that is, large displacements in short time intervals. This interpretation is supported by additional data that showed an increase in d_{max} when the temporal interval between frames was lengthened (Wattam-Bell, 1992).

Velocity Sensitivity

Human adults perceive motion over a great range of velocities. Under optimal conditions, a motion as slow as 1 to 2 minutes of visual angle per second may be detected as motion, as may faster motions up to 15 to 30 degrees/second, at which blurring or streaking occurs (Kaufman, 1974). Estimates of the slowest velocity to which infants respond have varied. Volkmann and Dobson (1976) used checkerboard patterns (check size = 5.5 degrees) and found a moving display was clearly preferred to a stationary one by 2- and 3-month-olds for a velocity as slow as 2 degrees/second. One-month-olds showed a weaker preference. Using rotary motion displays, Kaufmann, Stucki, and Kaufmann-Hayoz (1985) estimated thresholds at about 1.4 degrees/second at 1 month and 0.93 degrees/second at 3 months, also using a visual preference technique.

Later studies designed to distinguish various possible mechanisms by which moving patterns might be detected have yielded higher threshold estimates. Dannemiller and Freedland (1989), using unidirectional linear motion of a single bar, found no reliable motion preferences at 8 weeks. They estimated thresholds at about 5 degrees/second for 16-week-olds and about 2.3 degrees/second for 20-week-olds. For vertically moving gratings, Aslin and Shea (1990) found velocity thresholds of about 9 degrees/second at 6 weeks dropping to 4 degrees/second at 12 weeks. Thresholds for detecting a difference between two velocities were studied by Dannemiller and Freedland (1991) using paired displays with horizontal bars oscillating at different rates; their 20-month-old subjects distinguished bars moving at 3.3 degrees/second from 2.0 degrees/second, but not from 2.5 degrees/second.

Much lower thresholds for motion detection were obtained by von Hofsten, Kellman, and Putaansuu (1992). In habituation studies of observer-contingent motion with 14-week-olds, von Hofsten et al. found sensitivity to a differential velocity of .32 degrees/second but not .16 degrees/second. Infants were also found to be sensitive to the relation of the motion direction to their own motion. Higher sensitivity in this paradigm might have two explanations. It is possible that visual preference paradigms understate infant capacities. As is true in general with preference measures, infants might detect a difference (e.g., between moving and stationary patterns) but have no differential interest or attention to the two displays. A second possibility is that the key difference relates to observer motion contingency in the von Hofsten et al. study. It is plausible that small, observer-contingent motions are processed by the motion perspective system as specifiers of object depth, rather than as moving objects. Thus, a depth-from-motion system may have greater sensitivity than a motion detection system, and the former might be engaged only by observer movement (von Hofsten et al., 1992).

Mechanisms for Processing Moving Patterns: Velocity, Flicker, and Position

A moving stimulus may be characterized in different ways. Similarly, a response to a moving stimulus may be based on more than one kind of mechanism. Consider a vertical sine-wave grating drifting horizontally. Each edge moves at a certain velocity. At a given point, alternating dark and light areas will pass at a certain rate, presenting a temporal frequency of modulation or flicker rate. This flicker rate depends both on the velocity of the pattern and on its spatial frequency (cycles per degree). Now consider preferential attention to such a stimulus over a nonmoving grating or a blank field. The preference could be based on a direction-sensitive mechanism, a velocity-sensitive mechanism, or a flicker-sensitive mechanism. Sustained flicker could be avoided by use of a single object in motion as opposed to a repetitive pattern, but then the possibility arises that the motion could be detected by noting the change in position of some unique object feature, that is, a position-sensitive mechanism may operate. Some research on motion sensitivity has aimed to separate these possibilities experimentally.

Perhaps the first effort to disentangle velocity-sensitive, position-sensitive, and flicker-sensitive mechanisms was carried out by Freedland and Dannemiller (1987). Several combinations of temporal frequency and spatial displacement were presented with random black and white checkerboard displays. Infants' preferences were affected by both of these factors and were not a simple function of velocity. The role of flicker could not be directly assessed in these experiments. Sensitivity to flicker versus velocity was examined by Aslin and Shea (1990) with vertically moving, square-wave gratings. Various combinations of spatial frequency and velocity were used to vary flicker independent of velocity. For example, the flicker rate (temporal frequency) at any point in the display remains constant if spatial frequency is doubled and velocity is cut in half. Aslin and Shea (1990) found that velocity, not flicker, determines preferences in infants 6 and 12 weeks of age. Converging evidence for velocity-sensitive mechanisms was reported by Dannemiller and Freedland (1991). By using a display with motion of a single bar flanked by stationary reference bars, they excluded ongoing flicker in any spatial position. Moreover, manipulating extent of displacement allowed them to test the possibility that infants' responses were determined by the extent of positional displacement. Results were consistent with velocity-sensitive mechanisms.

Perceiving Motion and Stability

Perceiving moving objects is inextricably tied to its converse: perceiving nonmoving objects and surfaces as stationary. The latter ability is less straightforward than it might at first appear. Neural models of motion detectors suggest that these should respond to image features, such as edges, that change position on the retina over time. Yet such retinal displacement occurs in perfectly stationary environments whenever perceivers make eye, head, or body movements. Perception of objects remaining at rest during observer motion, called *position constancy,* requires use of information beyond that available to individual motion-sensing units. Such information might involve comparison of retinal changes with those expected from self-produced movements (von Holst, 1954; Wallach, 1987) or more global relationships among optical changes occurring at a given time (Duncker, 1929; J. Gibson, 1966).

In the case of passive (non-self-produced) observer motion, relations in optic flow or some contribution from the vestibular system must be used in perceiving a stable world. There is some indication that young infants show position constancy under such conditions. Later, we mention work in object perception (Kellman, Gleitman, & Spelke, 1987) suggesting that moving infants discriminate moving from stationary objects and perceive object unity only from real object motion. More direct studies of position constancy and motion perception by moving observers have also been carried out (Kellman & von Hofsten, 1992). In these studies, infants were moved laterally while viewing an array of objects. On each trial, one object in the array, either on the left or right, moved while others remained stationary. The object motion was parallel to the observer's motion. Whether the optical change given to the observer in this situation comes from a moving or stationary object depends on the object's distance. Thus, a stationary object placed on the opposite side of the array at a different distance matched the optical displacement of the moving object. Infants were expected to look more at the moving object if its motion was detected. Both 8- and 16-week-olds showed this pattern when the object and observer motions were opposite in phase, but only 16-week-olds appeared to detect the motion when object and observer moved in phase (Kellman & von Hofsten, 1992). It is not clear why the younger infants showed detection of the moving object only in the opposite phase condition. Further study indicated that motion detection was eliminated in monocular viewing. It appears that some ability to distinguish moving and stationary objects during observer motion is in place as early as 8 weeks of age and that binocular convergence may provide the distance information needed in this task (Kellman & von Hofsten, 1992).

SPACE PERCEPTION

In considering how we obtain knowledge through perception, the philosopher Kant (1781/1902) concluded that the mind must contain built-in (*a priori*) categories of space and time into which experience is organized. Psychologically, understanding the origins and development of spatial perception has more nuances. Whether we approach perception from the perspective of the philosopher, cognitive scientist, psychologist, or engineer, however, we will rediscover Kant's insight that space is fundamental. Our earlier treatment of basic spatial vision set out the sensory limitations—in acuity, contrast sensitivity, and sensitivity to pattern variation—that constrain the pickup of information. As we explore space perception here, our main concern is the acquisition of knowledge of positions and arrangements of objects and surfaces in the three-dimensional environment.

Theoretical controversy about the development of visual space perception has centered on depth perception. When we examine the human visual apparatus, it is relatively easy to see how we acquire information about two of three spatial dimensions. The optics of the eye ensure, to a high degree, that light originating from points in different directions from the observer will be mapped onto distinct points on the retina. The result is a map that preserves information about adjacency in two spatial dimensions (up-down and left-right). The apparent problem lies in the third (depth) dimension. Nothing in this map immediately indicates how far a ray of light has traveled to get from an object to the eye.

Traditionally, it has most often been claimed that perception of three-dimensional (3D) space is a product of learning (Berkeley, 1709/1963; Helmholtz, 1885/1925). Before the invention of methods to study infants' perception, the basis for this view was the logical problem of recovering three dimensions from a projection of the world onto a surface of two dimensions (the retina). Learning might overcome the limitation through the associating and storing of sensations of vision and touch, allowing relevant information about tactile correlates of visual sensations; these in turn could be retrieved when familiar visual input recurred (Berkeley, 1709/1963; Helmholtz, 1885/1925; Titchener, 1910). Piaget went a step further in arguing that self-initiated action and its consequences provide the necessary learning.

Modern analyses of the information available for vision have raised a radically different possibility for the origins of spatial perception. Transforming optical input given to a moving organism carries information specific to the particular 3D layout (J. Gibson, 1966, 1979; Johansson, 1970), and humans and animals may well have evolved mechanisms to extract such information. On this *ecological* view of development (E. Gibson, 1979; Shepard, 1984), the rudiments of 3D perception might be present even in the newborn, and their refinement might depend on sensory maturation and attentional skill, rather than on associative learning.

Research on spatial perception has gone a considerable distance toward answering this question of the constructivist versus ecological origins of the third dimension. Moreover, the emerging picture of early abilities provides important insights about functionally distinct classes of information and their neurophysiological underpinnings. Anticipating some of these distinctions, we divide spatial perception abilities into four categories: kinematic, oculomotor, stereoscopic, and pictorial. The classification reflects both differences in the nature of information and in the perceptual mechanisms at work in extracting information (Kellman, 1995; Kellman & Arterberry, 1998; Yonas & Owsley, 1987).

Kinematic Information

For guiding action and furnishing information about the 3D environment, kinematic or motion-carried information may be the most important class of visual information for adult humans. One reason for its centrality is that it overcomes the ambiguity problems present with some other kinds of information, such as pictorial cues to depth. A stationary image given to one eye may be a cuddly kitten or a gigantic tiger further off, as Berkeley noted, or even a flat, 2D cutout of a cat or tiger. To the moving observer, the transforming optic array reveals whether the object is planar or 3D and furnishes information about relative distance and size. The mapping between the optical transformations and the 3D scene is governed by projective geometry, and under reasonable constraints, it allows recovery of many properties of the layout (Koenderink, 1986; Lee, 1974; Ullman, 1979). Among the residual ambiguities is a problem analogous to the one Berkeley raised about a single image. If objects and surfaces in the scene *deform* (alter their shapes) contingent on the observer's motion, a unique 3D scene is not recoverable. Now the problem is recovering four dimensions (spatial layout plus change over time) from three (two spatial dimensions of the input plus time). In ordinary perception, simulation of the exact projective changes consistent with a particular, but not present, layout, would almost never occur by chance.

It does, however, make possible the realistic depiction of 3D space in television, motion pictures, and in virtual reality setups. Because kinematic information about space depends on geometry, not on knowledge of what particular spatial layouts exist in the world, it is imaginable that perceptual mechanisms have evolved to make use of it. An additional reason to suspect that sensitivity to this kind of information might appear early is that early learning about the environment may be optimized by relying on sources of information that are most accurate (Kellman, 1993; Kellman & Arterberry, 1998). On the other hand, adults acquire much kinematic information from their own movements through the environment. The human infant does not self-locomote until the second half-year of life although kinematic information could still be made available from moving objects, from the infant being carried through the environment, or from self-produced head movements.

Motion-carried or kinematic information is often divided into subcategories, of which we consider three. Relative depths of surfaces can be specified by *accretion/deletion of texture.* Relative motion between an object and observer may be given by *optical expansion/contraction.* Relative depth, and under some conditions perhaps metric information about distance, can be provided by *motion parallax* or *motion perspective.* Another important kinematically based spatial ability, recovery of object shape from transforming optical projections (*structure-from-motion*), is discussed in connection with object perception.

Accretion/Deletion of Texture

In the late 1960s, Kaplan, Gibson, and their colleagues discovered a new kind of depth information, a striking achievement given that depth perception had at that point been systematically studied for over 200 years (J. Gibson, Kaplan, Reynolds, & Wheeler, 1969; Kaplan, 1969). Most surfaces have visible texture—variations of luminance and color across their surfaces. The new type of depth information involves what happens to visible points of texture (texture elements) when an observer or object moves. When the observer moves while viewing a nearer and more distant object, the elements on the nearer surface remain visible whereas those on the more distant surface gradually pass out of sight along one side (deletion) of the nearer object and come into view along the other side (accretion). The same kind of transformation occurs when the motion is given by a moving object instead of a moving observer. This kind of information has been shown to be used in adult visual perception, to establish both depth order and shape, even when no other sources of information are available (Andersen & Cortese, 1989; Kaplan, 1969; Shipley & Kellman, 1994).

Infants' shape perception from accretion/deletion of texture was studied by Kaufmann-Hayoz, Kaufman, and Stucki (1986). They habituated 3-month-olds to one shape specified by accretion/deletion and tested recovery from habituation to the same and a novel shape. Infants dishabituated more to the novel shape. Although this result suggests that accretion/deletion specifies edges and shape at 3 months, we cannot tell much about perceived depth order from this study. That accretion/deletion specifies depth order at 5 to 7 months is suggested by a different study (Granrud, Yonas, et al., 1985). These investigators assumed that infants would reach preferentially to a surface perceived as nearer than another. Computer generated, random dot, kinematic displays were shown in which a vertical boundary was specified by only accretion/deletion information. Infants of 5 and 7 months of age were tested, and both groups showed modestly greater reaching to areas specified as nearer by accretion/deletion than to areas specified as farther. More recently Johnson and Mason (2002) provided evidence that 2-month-olds are able to use accretion/deletion of texture for perceiving depth relations.

Craton and Yonas (1990) suggested that ordinary accretion/deletion displays actually contain two kinds of information. In addition to the disappearance and appearance of texture elements, there are relationships of individual elements to the location of the boundary between surfaces. A visible element on one side of a boundary remains in a fixed relation to it, whereas an element on the other side (the more distant surface) changes its separation from the boundary over time. This separate information, termed *boundary flow,* appears to be usable by adults in the absence of element accretion/deletion (Craton & Yonas, 1990) and possibly by 5-month-old infants (Craton & Yonas, 1988).

Optical Expansion/Contraction

When an object approaches an observer on a collision course, its optical projection expands symmetrically. It can be shown mathematically that a ratio of an object point's retinal eccentricity and its retinal velocity gives its *time to contact,* that is, the time until it will hit the observer. Newborns of other species show defensive responses to this kind of information (Schiff, 1965).

When presented with optical expansion patterns, human infants of 1 to 2 months of age were reported to retract their heads, raise their arms, and blink (Ball & Tronick, 1971; Bower, Broughton, & Moore, 1970). Not all of these responses, however, may indicate perception of an approaching object (Yonas et al., 1977). Head movement may result from infants tracking visually the top contour of the pattern, and relatively undifferentiated motor behavior may cause the arms to rise in concert. Yonas et al. tested this hypothesis using a display in which only the top contour moved. This optical change is not consistent with approach of an object. Infants from 1 to 4 months displayed similar head and arm movements to this new display as to an optical expansion display. The result supports the hypothesis that tracking the top contour, rather than defensive responding, accounts for the behavior infants show to expansion displays.

It turns out, however, that both the tracking hypothesis and the hypothesis of defensive responding appear to be correct. When eye blink was used as the dependent measure, reliably more responding was observed to the approach display than to the moving top contour display. It appears that blinking may best access infant perception of object approach and does so reliably from about 1 month of age (Nanez, 1988; Nanez & Yonas, 1994; Yonas, 1981; Yonas, Pettersen, & Lockman, 1979).

Motion Perspective

Motion perspective is an important source of spatial layout information. When an observer moves and looks perpendicular to the movement direction, the visual direction of a nearer object changes at a faster velocity than that of a more distant object. Comparing two such objects or points defines the classical depth cue of motion parallax. J. Gibson (1950, 1966) argued that perceptual systems might use relative velocities of many points, that is, gradients of relative motion provide more information than a pair of points. To express this concept, he coined the term *motion perspective.* Some experimental evidence indicates that gradients are in fact used by human perceivers (e.g., E. Gibson, Gibson, Smith, & Flock, 1959).

Motion perspective is virtually always available to a moving observer in a lighted environment, and it ordinarily provides unambiguous indication of depth order. Given these considerations, one might expect that neural mechanisms have evolved to exploit this kind of information, and that accordingly, it might appear early in development. Several investigators have suggested that it functions quite early, but these suggestions have been based on indirect evidence (Walk & Gibson, 1961; Yonas & Owsley, 1987). Walk and Gibson (1961) studied newborns of various species on the visual cliff and noted that some species made lateral head movements before choosing the "shallow" side of the cliff over the "deep" side. It is difficult to make a similar inference about human infants, because they do not self-locomote until around 6 months of age.

Some results relevant to the development of motion perspective in 4-month-old infants were reported by von Hofsten et al. (1992). Infants moved back and forth while viewing an array of three vertical bars. The middle bar was moved in concert with the infant's chair, giving it an optical displacement that would have been consistent with a stationary rod placed somewhat further away. If motion perspective operates, the observer contingent motion should indicate that the middle rod is furthest from the subject (see Figure 3.4). After habituation to such an array, moving infants looked more at a stationary array consisting of three aligned, stationary rods than to another stationary array with the middle rod 15 cm further away than the others. (The latter display produced identical motion perspective as the habituation display.) Two other experiments showed that the effect disappeared if the contingent motion was reduced from the original .32 degrees/second to .16 degrees/second and that infants were sensitive to the contingency between the optical changes and their own movement. These results are consistent with infants' early use of motion perspective. They might also be explained, however, by infants responding to particular optical changes and the contingency of these optical changes on the observer's movement. The results do not include any test to verify that the optical changes were taken to indicate depth. An interesting possibility is that the perceptual process that uses motion perspective to assign depth is far more sensitive to optical displacement than processes used to see moving objects.

Stereoscopic Depth Perception

Stereoscopic depth perception refers to the use of differences in the optical projections at the two retinas to determine depth. This ability is among the most precise in adult visual perception. Under optimal conditions, an adult observer may detect depth when the angular difference in a viewed point's location at the two eyes

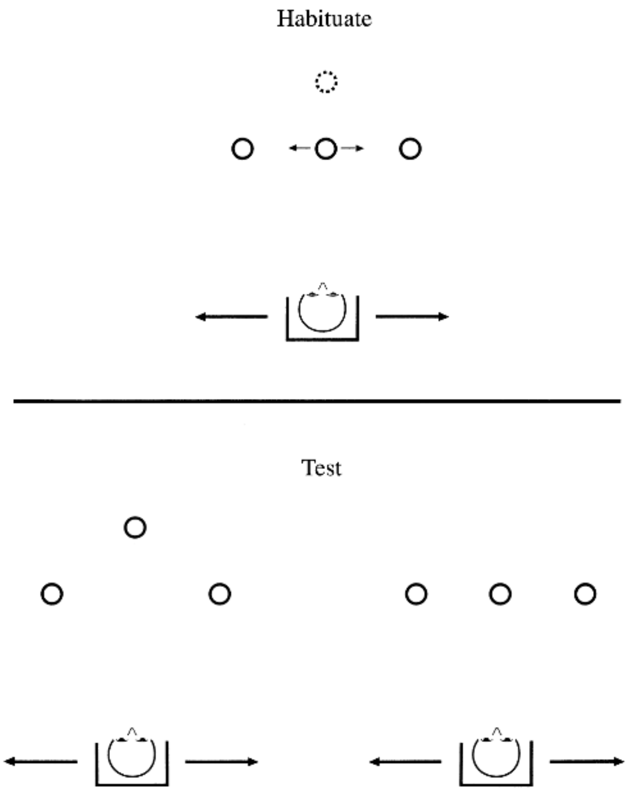

Figure 3.4 Top views of displays used in motion parallax experiment. *Top:* Moving observers were habituated to a linear array of rods in which the center rod moved in phase with the observer. The dotted line indicates the virtual object specified by motion parallax. *Bottom:* The two test arrays pictured were shown after habituation. *Source:* "Young Infants' Sensitivity to Motion Parallax," by C. von Hofsten, P. Kellman, and J. Putaansuu, 1992, *Infant Behavior and Development, 15*(2), pp. 245–264. Reprinted with permission.

(binocular disparity) is only 5 to 15 seconds of arc (Westheimer & McKee, 1980). A 5-second disparity would translate into detection of a 1.4 mm depth difference between two objects at a distance of one meter. We can distinguish two types of binocular disparity, *crossed* and *uncrossed.* A prerequisite for precise computation of disparity between the two eyes is fixation by the two eyes on a common environmental point. We can measure the disparities of other imaged points by comparison to this zero disparity fixation point. Other points at roughly the same distance from the observer as the fixated point will project to corresponding retinal locations, that is, having the same angular separation and direction from the fovea on each of the two eyes. Points more distant than the fixation point will have *uncrossed disparity.* The visual direction of such a point will be more to the left in the visual field of the left eye than in the right eye. *Crossed disparity* characterizes points nearer than the fixated point. The visual direction of these points will be more leftward in the right eye than in the left.

Observations from other species suggest the existence of innate brain mechanisms subserving stereoscopic depth perception, specifically, cortical cells tuned to particular disparities at birth or soon after (Hubel & Wiesel, 1970; Pettigrew, 1974; Ramachandran, Clarke, & Whitteridge, 1977). Such single-cell recording studies are not possible in human infants; moreover, they do not directly address functional operation of stereoscopic depth perception. Evidence about human infants comes mostly from behavioral studies and suggests that stereoscopic depth perception arises around 4 months of age as a result of maturational processes.

A number of studies have used stationary displays and preferential looking as the dependent variable. One of two adjacently presented displays contains binocular disparities that might specify depth differences within the pattern. Infants are expected to look longer at a display containing detectable depth differences than at a similar one having no depth variation (Atkinson & Braddick, 1976; Held, Birch, & Gwiazda, 1980). A different method eliminates any possible monocular cues. Using random dot kinematograms, Fox, Aslin, Shea, and Dumais (1980) presented disparity information that would, if detected, specify a moving square. Using the forced-choice preferential looking method, adult observers judged the direction of motion on each trial solely by watching the infant's responses.

Estimates of the age of onset of disparity sensitivity from these methods show reasonable agreement. In longitudinal studies by Held and his colleagues (Birch, Gwiazda, & Held, 1982; Held et al., 1980), reliable preferences for a vertical grating pattern with disparity variation appeared at 12 weeks for crossed disparities and 17 weeks for uncrossed. Fox et al. (1980) found that 3- to 5-month-olds reliably oriented to a moving square specified by disparity, but infants younger than 3 months did not. Petrig, Julesz, Kropfl, and Baumgartner (1981) found a similar onset of sensitivity using recordings of visual evoked potentials.

A thorny issue in the interpretation of these studies is whether the observed behavioral responses index depth perception from binocular disparity or merely sensitivity to disparity itself. It is hard to settle this issue with certainty; however, some observations suggest that depth is perceived. Held et al. (1980), for example, found that infants who showed clear preferences for vertical line displays containing horizontal disparity showed no such preferences when the displays were rotated 90 degrees to give 34 minutes of vertical disparity (a condition that produces rivalry for adults). Fox et al. (1980) observed that infants did not track a moving object specified by very large disparities that do not signal depth to adults. They found instead that infants reliably looked away from such displays. This result is double-edged: Although it shows different reactions by infants to different magnitudes of disparity as might be expected if only some disparities produce perceived depth, it also shows that disparities per se can affect infants' fixation. From these studies, it is plausible but not certain that infants' responses in these studies indicate functional stereoscopic depth perception. Other studies have shown that disparity-sensitive infants outperform disparity-insensitive infants on tasks involving depth and three-dimensional shape perception (Granrud, 1986; Yonas, Arterberry, & Granrud, 1987a).

What mechanisms are responsible for the onset of stereoscopic sensitivity after several months of life? An argument for maturational causes is that sensitivity very quickly attains adultlike precision. Held et al. (1980) reported that thresholds change over 3 to 4 weeks from greater than 60 minutes to less than 1 minute of disparity, with the latter measured value limited by the apparatus; even so, this value is comparable to adult sensitivity under some conditions.

What mechanisms might be maturing at this time? One possibility is that disparity-sensitive cortical cells are coming online. Another is that improvements in the mechanisms of convergence or visual acuity that are prerequisites to fine stereopsis might explain the observed onset of disparity sensitivity. Some evidence suggests that the onset of stereopsis is not dependent on improvements in visual acuity (grating acuity). When both acuity and disparity sensitivity are measured longitudinally in the same infants, little or no change in grating acuity is found during the period in which stereopsis appears (Held, 1993). A different method pointing toward the same conclusion comes from a study by Westheimer and McKee (1980). Adults were given artificially reduced acuity and contrast sensitivity designed to approximate those present at 2 months of age. Under these conditions, stereoacuity was reduced substantially, but not sufficiently to explain infants' inability to respond to large disparities before 3 to 4 months of age. Developmental changes in convergence also appear unlikely to explain the onset of stereoacuity. Evidence on the development of convergence (Hainline, Riddell, Grose-Fifer & Abramov, 1992) indicates that it may be nearly adultlike at 1 to 2 months of age. Also, convergence changes would not explain differences in the onset of crossed and uncrossed disparity (Held et al., 1980).

Given these considerations, most investigators believe the explanation for the onset of stereoscopic vision is some maturational change in cortical disparity-sensitive units. Such a mechanism underlies improvement of stereoscopic discrimination performance in kittens (Pettigrew, 1974; Timney, 1981). In humans, it has been suggested that the particular change in disparity-sensitive cells may be segregation of *ocular dominance columns* in layer 4 of the visual cortex (Held, 1985, 1988). At birth, cells in layer 4 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). Eye-of-origin information is needed to extract disparity information, so this neurological development is a plausible candidate for the onset of stereoscopic function.

Pictorial Depth Perception

The *pictorial cues* are so named because they allow depth to be portrayed in a flat, two-dimensional picture. Sometimes these are called the classical depth cues, because they have been discussed and used by artists and students of perception for centuries. Theoretically, they have been central to classical arguments about the need for learning in spatial perception. The fact that the same information can be displayed in a flat picture or a real 3D scene immediately points to their ambiguity as signifiers of reality. It is a short step to the classical perspective on the acquisition of such cues: If these cues are not unequivocally tied to particular spatial arrangements, our perception of depth from these cues must derive from learning about what tends to be the case in our particular environment. (The environment, until recently, had many more 3D scenes offering information than 2D representations.)

Ecologically, the pictorial cues to depth are diverse, but many of them rest on similar foundations. The laws of projection ensure that a given physical magnitude projects an image of decreasing extent at the retina with increasing distance from the observer. Applying this geometry in reverse, if two physical extents are known or assumed to have the same physical (real) size, then differences in their projected size can be used to establish their depth order. This information comprises the depth cue of *relative size*. Very similar is *linear perspective*. If two lines in the world are known or assumed to be parallel, then their convergence in the optical projection may be taken to indicate their extending away from the observer in depth. Generalizing this notion to whole fields of visible elements comprises the rich source of information in natural scenes known as *texture gradients* (J. Gibson, 1950). If a surface is assumed to be made up of physically uniform or stochastically regular tokens (pebbles, plants, floor tiles, etc.), then the decreasing projective size of texture elements indicates increasing depth. A different kind of assumed equality is illustrated by the depth cue of *shading*. If the light source comes from above, a dent in a wall will have a lower luminance at the top because the surface is oriented away from the light, whereas the bottom part, oriented toward the light, will have higher luminance. Perception of depth from these luminance variations implicitly assumes that the surface has a homogeneous reflectance; variations in luminance are then taken to indicate variations in surface orientation.

Pictorial cues are not as ecologically valid as kinematic or stereoscopic information because the assumptions behind them, such as the assumption of physical equality, may be false. In a picture, it is easy to make two similar objects of different sizes or two parts of a connected surface with different reflectances. Misleading cases of pictorial depth information are not difficult to find in ordinary environments. Sometimes apparently converging lines really are converging lines, and sometimes the average size of texture elements changes with distance, as do the sizes of particles at the seashore (smaller particles get washed further up the beach).

Studies of the development of pictorial depth perception reveal a consistent pattern. Sensitivity to these cues appears to be absent until about 7 months of age. Around 7 months of age, infants seem to be sensitive to virtually all pictorial depth cues that have been tested. Much of this emerging picture of the origins of pictorial depth has come from systematic studies by Yonas and his colleagues (see Yonas, Arterberry, & Granrud, 1987b; Yonas & Owsley, 1987 for reviews). For brevity, we consider only two examples: interposition and familiar size. The development of other pictorial cues that have been studied, such as linear perspective and shading, appears to be similar.

Interposition

The depth cue of *interposition,* sometimes called overlap, specifies relative depth of surfaces based on contour junction information. When surface edges form a "T" junction in the optical projection, the edge that comes to an end at the intersection point (the vertical edge in the letter T; see Figure 3.5A) belongs to a surface passing behind the surface bounded by the other edge (the horizontal edge in the letter T). Interposition is a powerful depth cue in human vision (Kellman & Shipley, 1991). Infant use of interposition information was tested by Granrud and Yonas (1984). They used three similar displays made of three parts each but differing in the presence of interposition information. In the interposition display, the left panel overlapped the middle, which overlapped the right. In a second display, all contours changed direction at intersection points, giving indeterminate depth order. In a third display, the three surface sections were displayed slightly separated, so that no contour junctions were relating them. Infants at 5 and 7 months of age viewed these displays monocularly (to eliminate conflicting binocular depth information), and reaching was measured. All parts of the displays were coplanar and located the same distance from the subjects. Infants' reaches to different parts of the displays were recorded. In one ex-

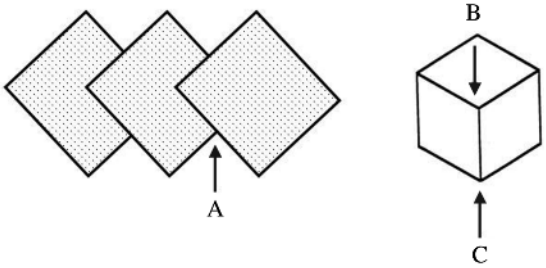

Figure 3.5 Examples of line junctions giving information for three-dimensional structure. A shows a T junction specifying ordering in depth. B and C show Y and arrow junctions, respectively, that contribute to the perception of three-dimensional structure.

periment, the interposition display was compared with the indeterminate control display and in a second experiment, the interposition display was compared with the control display having separated areas. In both experiments, 7-month-old infants reached reliably more often to the "nearest" part of the interposition display than to the same region in the control displays. Five-month-olds showed some tendency to reach more to the nearest part of the interposition display than one of the control displays, but not the other. These results provide evidence that interposition is usable by 7 months, but the results are equivocal or negative about its availability at 5 months of age.

Familiar Size

Perhaps the clearest case of learning in space perception involves the cue of familiar size. If an object has a known physical size (and this size is represented in memory) and the object produces a particular projective size in a given viewing situation, the distance to the object can in principle be calculated (Ittleson, 1951). Using a preferential reaching method, Yonas, Pettersen, and Granrud (1982) tested infants' perception of depth from familiar size. As with interposition, 7-month-olds showed evidence of using familiar size, whereas 5-month-olds did not. In a later experiment, Granrud, Haake, and Yonas (1985) tested familiar size using two pairs of objects unfamiliar to the subjects before the experiment. Each pair consisted of a large and small version of an object having identical shape and color. Infants were encouraged to play with the small object from one pair and the large object from the other pair for 6 to 10 minutes. After this familiarization period, infants viewed a simultaneous presentation of both large objects. It was expected that infants would reach more often to the object whose small version had been handled during familiarization if the cue of familiar size influenced perceived distance. (Memory for the physical sizes in the earlier exposure, combined with equal projective sizes in the test, would lead to interpretation of the previously smaller object as being much closer.) Infants at 7 months of age who viewed the test displays binocularly reached equally to the two objects, but infants of the same age who viewed the test displays monocularly reached more to the previously smaller object. Five-month-olds showed no variations in reaching related to the size of objects in the familiarization period. These results suggest that by 7 but not 5 months infants may obtain depth information from familiar size, but this information is overridden when conflicting stereoscopic information is available.

Conclusions Regarding Pictorial Depth

Two decades ago little was known about the development of pictorial depth. Today, largely due to programmatic research by Yonas, Granrud, and their colleagues, we have a fairly clear picture about the timing of the appearance of pictorial cues. The picture is strikingly consistent across members of the category. Pictorial cues to depth arise sometime between the 5th and 7th month of age, and tests of individual infants across time reveal variability in the age of onset across this 2-month period (Yonas, Elieff, & Arterberry, 2002). It is possible that younger infants are sensitive to some of the informational properties of pictorial depth cues, such as different line junctions or textural arrangements, which may provide a foundation for perceiving the third dimension (Bhatt & Bertin, 2001; Bhatt & Waters, 1998; Kavsek, 1999).

The appearance of various pictorial cues around the same time has been interpreted as suggesting that maturation of some higher visual processing area in the nervous system is the mechanism (Granrud & Yonas, 1984). Research with macaque monkeys lends additional support to a maturational explanation. Pictorial cues appear as a group around 7 to 8 weeks of life (Gunderson, Yonas, Sargent, & Grant-Webster, 1993). As Gunderson et al. put it, this result is compatible with the idea that "pictorial depth perception may have ancient phylogenetic origins" (p. 96). A key to this interpretation is that the timing fits the rough ratio of 1:4 in terms of time after birth in nonhuman primates and humans, a relation that fits the maturation of numerous other abilities (a function that matures at 4 weeks in nonhuman primates appears at about 16 weeks in human infants).

Alternatively, the similarity of onset of these sources of information might be explained by learning. It is suggestive that the depth cue of familiar size, which necessarily involves learning, becomes operative in the same period as other pictorial depth cues. Their appearance at this time could reflect enhanced possibilities for learning brought about by some other developmental advances, such as the appearance of crawling abilities around 6 months of age. One study that correlated individual sensitivity to linear perspective and texture gradients with crawling ability (Arterberry, Yonas, & Bensen, 1989) found no predictive relationship, however. Seven-month-olds seemed to utilize pictorial depth in their reaching regardless of whether they had learned to crawl.

Further research is needed to discover the mechanisms underlying the onset of pictorial depth perception. Longitudinal studies of multiple pictorial depth cues would be helpful, as would be formulation and tests of more specific neurophysiological candidates for maturation and, alternatively, potential processes of learning.

OBJECT PERCEPTION

One of the most important functions of visual perception is to deliver representations of the environment in terms of discrete physical entities or *objects.* There are many ways to describe and encode the streams of light that hit the retinas of the eyes. In ordinary perceiving, we receive, not descriptions of light, but descriptions of the physical objects that last reflected the light. These descriptions of the locations, boundaries, shapes, sizes, and substances of objects are indispensable for action and thought. Normally, the separate objects in our perceptual world correspond to units in the physical world. This knowledge allows us to predict the results of action: how the world divides, which things will detach from adjacent things, and which will remain coherent if moved, thrown, or sat on. All this we can know visually from a distance, without actually contacting the objects.

Beyond these most basic kinds of knowledge, perception of shapes and sizes, object rigidity, and so on, gives us a wealth of information about objects' possible affordances for action. For the experienced observer, storing in memory the shapes and surface qualities of many perceived objects makes possible rapid and automatic recognition of familiar objects, even from partial information. The adaptive value of object perception and recognition systems can hardly be overestimated. Matching this importance is the complexity of understanding the processes and mechanisms of object perception. The challenges become apparent when we see how little of human object perception can currently be emulated by artificial vision systems. For the ordinary observer in a familiar environment, however, the task seems not complex, but easy.

The lack of a complete scientific understanding of adult object perception abilities might seem to handicap efforts to trace their development. Examining object perception in infancy has at least one advantage. The minimal experience of infants makes it easier to examine object perception *per se* as opposed to recognition from partial information, reasonable inferences based on prior knowledge, and other valuable cognitive talents that adults use to ruin otherwise sound perceptual experiments. Studies of early object perception reveal the developmental course of these abilities and shed light on the complexities of object perception in general.

Multiple Tasks in Object Perception

As the study of object perception has advanced, it has become clear that it is computationally complex, involving multiple tasks. (For recent discussions of the information processing tasks in object perception, see Kellman, 2003). One component is *edge detection*—locating significant contours that may indicate where one object ends and another object or surface begins. Edge detection alone is ambiguous, because visible contours can result from object boundaries but also from other sources, such as shadows or markings on a surface. A second requirement, then, is *edge classification*—sorting visible contours into object boundaries as opposed to other sources. Next is *boundary assignment.* When an edge corresponding to an object boundary is located, it most commonly bounds one object, while the surface or object seen on the other side of the boundary passes behind the first object. Determining which way each boundary bounds is crucial for knowing, for example, whether we are viewing objects or holes. Along with edge processes, detection and classification of junctions of edges is important in the segmentation and grouping processes that lead to perceived objects.

Early processes involving edges and junctions do not by themselves yield perceived objects. Several other problems need to be solved to accomplish object formation. For one thing, because of occlusion a single object in the world may project to multiple, spatially separated locations on the retinas of the eyes. Also, at each occlusion boundary, some surface continues behind; recovering the structure of objects in the world requires solutions to how visible parts connect. These are the questions of *segmentation* and *unit formation.* A single static image raises these issues; more complex versions occur when observers move, causing the visible fragments of objects to change continuously. To form units, the visual system assigns shape descriptions. Thus perceiving *form*—the three-dimensional arrangement of the object—is another important component. Finally, there are perceptible properties relating to *object sub-*

stance: its rigidity or flexibility, surface texture, and so on. We consider what is known about each of these aspects of object perception early in development.

Edge Detection and Edge Classification

What information makes edge detection possible? In general, the answer is discontinuities across space in some perceptible properties. These differences can be in the luminance or spectral composition of light coming from adjacent areas. These differences may mark object boundaries because objects tend to be relatively homogeneous in their material composition. Parts of a homogeneous object will absorb and reflect light in similar fashion, whereas an adjacent object, made of some different material, may differ. Thus, discontinuities of luminance and spectral composition in the optic array may mark object boundaries. When average luminance and spectral characteristics are similar for adjacent objects, higher order patterns of optical variation—texture—may distinguish them. Another source of information comes from depth gradients. Depth values of visible points of a continuous object will change smoothly, but at an object boundary discontinuities will often occur. In similar fashion, optic flow provides information about edges. When the observer moves, the optical displacements for visible points will tend to vary more smoothly within objects than between objects.

None of these sources of information for detecting objects' edges is unequivocal. Discontinuities in luminance and/or spectral values may arise from reflectance differences of cast shadows along the surface of a continuous object. They may also come from surface orientation differences in a complex object, due to different geometric relations between a light source, surface patches, and the observer. The same may be true for depth or motion discontinuities: They will often but not always mark object boundaries. A second requirement for object perception, then, is edge classification. Which luminance variations are probably object edges and which arise from illumination changes, such as shadows or patterns on a continuous surface?

We have primarily indirect evidence about infant edge detection and edge classification abilities. The literatures on visual acuity and pattern discrimination both offer useful clues. One implication of newborns' poor acuity relative to adults is that their ability to process object edges must be much reduced, especially for distant objects.

If the shape of a 2D pattern is detected, one might argue, the contour comprising that edge must certainly be detected and perhaps classified as an object boundary. Since the pioneering studies of Fantz and colleagues (e.g., Fantz, Fagan, & Miranda, 1975), many studies have shown that infants discriminate patterns from the earliest weeks of life. Discrimination, however, can be based on any registered difference between patterns; contour perception may not necessarily be implied. A visual pattern may be analyzed into sinusoidal luminance components. An object's edge may trigger responses in a population of cortical neurons but not be represented as a single pattern feature. In short, different patterns may evoke different neural activity but not perception of edges or forms per se. This possibility is consistent with the evidence noted earlier that infants are somewhat insensitive to spatial phase information before about 8 weeks of age.

Other lines of research, however, imply that edges and forms may be perceived by newborns under at least some circumstances. Slater and colleagues (Slater, Matock, & Brown, 1990) reported evidence for some degree of size and shape constancy in the first few days of life. Size constancy is the ability to perceive the physical size of an object despite changes in the object's projected size for an observer at different distances. Shape constancy in this context refers to the perceiver's ability to detect a constant planar (2D) shape despite variations in its 3D slant (e.g., perceiving a rectangle although its slant in depth produces a trapezoidal retinal projection). Size and planar shape constancy are discussed later in this chapter. Here we merely note that both seem to require some boundary perception abilities. It is hard to imagine any way to achieve constancy if the newborn's visual representation consists of an unintegrated collection of activations in independent frequency channels. More likely, higher stages of processing function to some degree to localize edges of objects.

Several observations suggest that early edge classification and boundary assignment capacities may depend selectively on a subset of information sources available to adults. For adults, surface quality differences such as luminance and spectral differences can specify object boundaries. As noted by Rubin (1915) in his classic studies of figure-ground organization, an area whose surround differs in luminance or spectral characteristics ordinarily appears as a bounded figure in front of a background surface. There is reason to believe that infants do *not* segregate objects using this information before about 9 months of age. Piaget (1954) noted that his son Laurent at 7 months reached for a box of matches when it was placed on the floor but not when it was placed on a book; instead he reached for the edges of the book. If the box slid on the book, Laurent reached for the box. This sort of observation led to three tentative conclusions:

1. A stationary object on a large extended surface (a floor or table) may be segregated from the background.
2. A stationary object adjacent to another stationary object will not be segregated by surface quality differences.
3. Two objects can be segregated by relative motion.

Subsequent experimental work has supported Piaget's interpretations. Spelke, Breinlinger, Jacobson, and Phillips (1993) tested infants' responses to adjacent object displays. *Homogeneous* displays had parts with identical luminance, color, and texture, and the parts' boundaries were continuous at their intersection points. *Heterogenous* displays had two adjacent parts differing in luminance and color, and also had discontinuities (T junctions) at the intersection points. After familiarization with a display, infants viewed two test events. In one, both parts moved together, whereas in the other only the top part moved, detaching from the other part. If the original display had been perceived as two separate objects, infants were expected to look longer at the event in which the whole display moved as a unit. If the two parts had been perceived as connected, infants were expected to look longer at the detachment event. Three-month-old infants showed this latter result, suggesting they had perceived both the homogeneous and heterogeneous displays as connected. Ambiguous results were found with 5- and 9-month-olds; infants looked longer at the detachment event for the homogeneous display, but when the heterogeneous display moved as one piece, they did not show a novelty effect. Similarly, Needham (1999) showed that 4-month-olds did not respond to differences in surface features for segregating static objects.

These conclusions are consistent with earlier research. Von Hofsten and Spelke (1985) used infants' reaching behavior to address perceived unity. Displays were designed to approximate closely the situations considered by Piaget. Spatial and motion relationships were varied among a small, near object, a larger, further object, and an extended background surface. It was assumed that reaches would be directed to perceived boundaries of graspable objects. When the whole array was stationary and the objects were adjacent, greater reaching was observed to the edges of the larger, further object. Separation of the two objects in depth led infants to reach more for the nearer, smaller object. When the larger object moved while the smaller object did not, reaching was directed more toward the smaller object. This result suggested that motion segregated the objects rather than merely attracted reaching, because infants reached more to the stationary object. From these results, it appears that discontinuities in motion or depth segregate objects, whereas luminance discontinuities and overall shape variables do not. These results make sense in that motion and depth indicate object boundaries with greater ecological validity than luminance or spectral variations alone (Kellman, 1995; von Hofsten & Spelke, 1985). That is, ambiguous or misleading cases are less likely to arise with motion or depth discontinuities.

Detection and Classification of Contour Junctions

Detecting and classifying contour junctions is important for many aspects of object perception. Many models of object perception and recognition, as well as other aspects of perceptual organization, include contour junctions as important sources of information (e.g., Heitger, Rosenthaler, von der Heydt, Peterhans, & Kubler, 1992; Hummel & Biederman, 1992; Kellman & Shipley, 1991). Junctions are important in unit formation, both in segmenting objects from their backgrounds and in triggering contour interpolation processes (e.g., Heitger et al., 1992; Kellman & Shipley, 1991) and in encoding object representations for recognition (Barrow & Tenenbaum, 1986; Hummel & Biederman, 1992; Waltz, 1975). Beyond mere detection, classification of junction type is important (see Figure 3.5). As mentioned, a T junction in an interposition display indicates where one contour intersects another contour, thus allowing for the separation of the two surfaces in depth (Waltz, 1975; Winston, 1992). Line junctions can also play a role in specifying the three-dimensional shape of an object. For example, "Y" and "arrow" junctions specify the three-dimensional structure and orientation of objects.

Until recently, not much was known about the development of sensitivity to contour junctions. Studies on interposition suggest that by 7 months of age, infants are responsive to T junctions. In addition, Yonas and Arterberry (1994) showed that 7.5-month-olds distinguish between lines in two-dimensional drawings that represent edge contours (arrow and Y junctions) and lines that represent surface markings, an important first step in using line junction information for perceiving spatial structure. More recently, Bhatt and Bertin (2001) found evidence that 3-month-olds are sensitive to line junction cues that signal three-dimensional structure and orientation information to adults. Whether infants perceive the three-dimensional structure has not been directly tested but would be a good question for future investigation.

Boundary Assignment

The question of boundary assignment applies to perhaps the most important subcategory of edges—occluding edges. These are contours that mark the end of an object or surface. As has been known for a long time (Koffka, 1935), most such edges are "one-sided," in that the contour marks the edge of an object on one side but on the other, some surface continues behind. Boundary assignment involves the question of which way such edges bound. Some of the same considerations we raised regarding edge classification apply to boundary assignment. Evidence that infants distinguish shapes, or figures from grounds, might indicate that boundary assignment is occurring. It is problematic, however, to prove that infants perceive shape rather than a hole. These two possibilities differ in terms of the direction of boundary assignment.

We noted that early shape constancy seems to presuppose boundary assignment. If this inference is correct, the relevant information probably comes from discontinuities in depth at object edges. Boundary assignment from depth discontinuities follows the straightforward rule that the nearer surface owns the boundary. Another source of boundary assignment information is accretion/deletion of texture. When one surface moves relative to a more distant surface, texture elements on the latter surface go out of sight at the leading edge of the nearer object and come into sight at the trailing edge. This information constitutes a powerful source of boundary information, depth order, and shape in adult perception (Andersen & Cortese, 1988; J. Gibson et al., 1969; Shipley & Kellman, 1994). Infants as young as 3 and 5 months of age respond to accretion and deletion of texture to perceive object shape and depth, respectively, suggesting perception of both depth order and boundary ownership (Granrud, Yonas, et al., 1985; Kaufmann-Hayoz, Kaufmann, & Stucki, 1986).

Other behavior suggests appropriate detection of object boundaries in younger infants. When an object approaches an infant, certain defensive responses often occur, including withdrawal of the head and blinking, as discussed earlier. The importance of boundary assignment for this ability was tested by Carroll and Gibson (1981). They presented 3-month-old-infants with arrays in which all surfaces were covered with random dot texture. Using accretion/deletion of texture, an approaching object was specified in one condition and an approaching aperture (opening in the surface) was specified by the information in the other condition. Infants appeared to use the information: They responded defensively more often to approaching objects than to approaching apertures.

Perception of Object Unity

Processes of edge detection, classification, and boundary assignment parse the optic array into significant pieces and reveal some of the boundaries of objects, but they do not yield representations corresponding to physical objects. Together, they may feed into a representation of distinct visible areas along with the labeling of which way contours dividing these areas bound (Kellman, 2003; Palmer & Rock, 1994). As mentioned earlier, the difference between such representations and perceived objects is that objects may unify multiple visible areas. How can the visual system move from visible pieces to complete objects when some parts of objects are partly hidden? This is the question of perceiving object unity, or unit formation. It involves problems of spatial occlusion as a 3D world is projected onto 2D receptive surfaces and also changes in the optic projections over time as the observer or objects move.

Multiple Processes in Unity Perception

Research suggests several kinds of information lead to perceived unity. One is the common motion process ("common fate") first described by Wertheimer (1923/1958): Things that move together are seen as connected. Some more rigorous definition of "move together" is needed, of course. The class of rigid motions as defined in projective geometry, as well as some nonrigid motion correspondences, can evoke perception of unity in human adults (Johansson, 1970, 1975). The common motion process does not depend on relationships between oriented edges and for that reason has been called the *edge-insensitive process* (Kellman & Shipley, 1991).

The other process depends on continuity in edge relationships. Related to the Gestalt principle of good continuation (Wertheimer, 1923/1958), it has been termed the *edge-sensitive process.* Whereas good continuation applies to the breakup of fully visible arrays into parts, perception of unity across gaps in the input depends on particular relationships of oriented edges. Specifically, they appear to be governed by a mathematical criterion of *relatability* (Kellman, Garrigan, & Shipley, 2005; Kellman & Shipley, 1991). Informally, relatability characterizes boundary completions as smooth (differentiable at least once) and monotonic (singly inflected). Figure 3.6 gives some examples of relatable and nonrelatable edges. These are illustrated both in occlusion cases and in illusory figure cases (in which completed surfaces appear in front of other surfaces, rather than behind). Research suggests that interpolation of contours in occluded and illusory contexts depend on common mechanisms (Kellman et al., 2005; Kellman, Yin, & Shipley, 1998; Ringach & Shapley, 1996). Complementing the contour interpolation process is a surface interpolation process. Correspondences in surface quality (e.g., lightness and color) can also unify visible areas (Grossberg & Mingolla, 1985; Kellman & Shipley, 1991; Yin, Kellman, & Shipley, 1997, 2000).

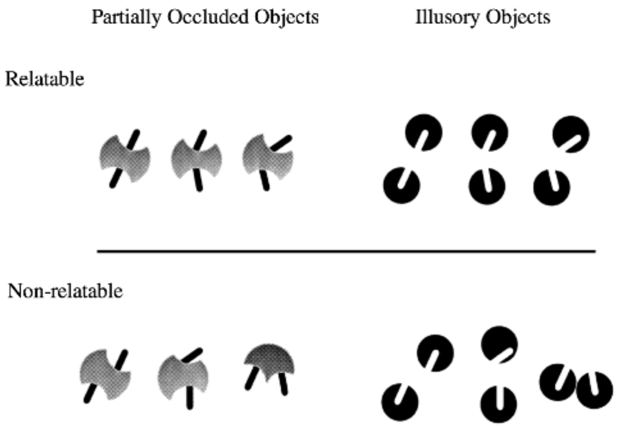

Figure 3.6 Relatable and nonrelatable edges. Connections (occluded surfaces or illusory surfaces between the two visible bars) are seen in the relatable displays, but not in the nonrelatable ones.

How does unit formation develop? We consider these several information sources in attempting to answer that question.

The Edge-Insensitive Process: Common Motion

Evidence suggests that the edge-insensitive (common motion) process appears earliest in development. Infants' perception of partly occluded objects can be assessed using generalization of habituation (Kellman & Spelke, 1983). If two visible parts whose possible connection is occluded are perceived as connected, then after habituation of visual attention to such a display, infants should look less to an unoccluded complete object (because it is familiar) and more to an unoccluded display containing unoccluded, separate pieces (because it is novel).

In a series of studies of 16-week-old infants, Kellman and Spelke (1983) found evidence that common motion of two object parts, visible above and below an occluding object, led to infants' perception of unity. After habituation to such a display, infants attend more to a moving "broken" display—two parts separated by a visible gap—than to a moving complete display. This outcome occurs no matter whether the two visible parts are similar in orientation, color, and texture. Initial studies used a common lateral translation (horizontal motion, perpendicular to the line of sight), but later research indicated that vertical translation and translation in depth also specify object unity at 16 weeks (Kellman, Spelke, & Short, 1986). Translation in depth is especially informative about the underlying perceptual process, because its stimulus correlates are much different from the other translations. Whereas translation in the plane (a plane perpendicular to the line of sight) is given in terms of image displacements at the retina or pursuit eye movements to cancel such displacements, translation in depth is specified by optical expansion or contraction in the object's projection or by changes in convergent eye movements as the object moves. The use of stimuli that specify object translation in space suggests that infants' unity perception depends on registered object motion, not on a particular stimulus variable.

The class of motion relationships effective early in life does not appear to encompass the full range of rigid motions as defined mathematically. Rigid motions include all object displacements in 3D space that preserve 3D distances among object points. After habituation to a rotation display in which two visible parts rotate around the line of sight, 16-week-olds generalized habituation equally to rotating complete and broken displays (Eizenman & Bertenthal, 1998; Kellman & Short, 1987b). Eizenman and Bertenthal (1998) found that 6-month-olds perceived a rotating rod as complete only if it underwent a complete rotation (360 degrees) as opposed to merely oscillated (90-degree rotation with reversal of direction). It appears that infants' unity perception is governed by a subset of rigid motions.

Further research revealed that perception of object unity is dependent on perceived object motion, not merely retinal motion (Kellman, Gleitman, & Spelke, 1987). Most experiments on motion relationships in unity perception have used stationary observers and moving objects. Many theorists have observed that certain optical consequences of motion may be duplicated when a moving observer looks at a stationary object (Helmholtz, 1885/1925; James, 1890). The retinal displacement of a laterally moving object, for example, may be duplicated by an observer's head or body movement while a stationary object is in the observer's visual field. This similarity raises a crucial question about the role of motion in object unity: Does perceived unity depend on actual object motion or on certain optical events, such as image displacement, that may be caused by either observer motion or object motion?

Embedded in this question is another one, at least as fundamental. Can infants tell the difference between optical changes caused by their own motion and those caused by the motions of objects? Recall this ability is called position constancy: perceiving the unchanging positions of objects in the world despite one's own motion. Kellman et al. (1987) took up these questions in a study of 16-week-olds. In each of two conditions, the infant's chair moved in a wide arc around a point between the observer and occlusion displays in front. In one condition (conjoint motion), the moving chair and a partly occluded object were rigidly connected underneath the display table, so that they both rotated around a point in between. In this condition, the object's motion was real; however, there was no subject-relative displacement. Thus, no eye or head movements were required to maintain fixation on the object. If perceiving the unity of this partly occluded display depends on real object motion, infants were expected to perceive unity in this condition. In the other condition (observer movement) the observer's chair moved in the same way, but the partly occluded object remained stationary. If optical displacement caused by observer motion can specify unity, infants were expected to perceive a complete object in this condition. As in earlier research, dishabituation patterns to unoccluded complete and broken displays after habituation were used to assess perception of unity, and the test displays in each condition had the same motion characteristics as in habituation.

Results indicated that only the infants in the conjoint-motion condition perceived the unity of the partly occluded object. Analyses based on looking-time differences suggested that infants in the conjoint-motion condition perceived object motion during their own motion, whereas observer-movement infants responded as if they perceived the occlusion display as stationary. These results suggest that the common motion or edge-insensitive process depends on perceived object motion. The outcome makes sense ecologically, in that rigid relationships in truly moving visible parts are highly unlikely to occur unless the parts are actually connected. For optical displacements caused by movement of the observer, areas at similar distances from the observer will share similar displacements, yet it is hardly the case that all objects near each other are connected.

What are the origins of the edge-insensitive process? From findings that the motion relationships specify object unity to infants before they actively manipulate objects or crawl through the environment, Kellman and Spelke (1983) hypothesized that perceiving unity from motion is accomplished by innate mechanisms. The hypothesis also reflects the ecological importance of common motion information. Coherent motion is closely tied to the very notion of an object (Spelke, 1985), and common motion of visible areas has very high ecological validity as a signifier of object unity (Kellman, 1993).

The basis of unity perception in innate or early maturing mechanisms is consistent with more recent studies showing perception of unity by 2-month-old infants under conditions in which the block occluded less of the rod than in traditional displays (Johnson & Aslin, 1995, 1996; Johnson & Nanez, 1995). Also, it has been found that the ability to perceive unity of partly occluded objects from common motion is innate in chicks (Lea, Slater, & Ryan, 1996).

Studies of human newborns, however, have not found evidence for perceived unity from common motion. Slater and his colleagues have shown a consistent preference for the complete rod following habituation to moving rod-block displays (Slater, Johnson, Brown, & Badenoch, 1996; Slater, Johnson, Kellman, & Spelke, 1994; Slater, Morison, Somers, Mattock, Brown, & Taylor, 1990). This finding suggests that newborn infants perceived the rod as broken during the habituation phase, even though the size of the rod and depth separation of the rod and block was increased compared with that used with 4-month-olds (Slater, Johnson, Kellman, & Spelke, 1994) and when the block height was reduced and texture was added to the background to increase the available information specifying the depth relations (Slater, Johnson, Brown, & Badenoch, 1996). The implication of these findings is that newborns make their perceptual judgments based on the visible parts of the displays, and they cannot make judgments about the parts of the visual array that are occluded.

Using a somewhat different stimulus, Kawabata, Gyoba, Inoue, and Ohtsubo (1999) have found at least one condition in which 3-week-old infants perceive a partly occluded region as complete. Instead of using the traditional rod-block display, they presented infants with drifting sine-wave gratings that were occluded by either a narrow or broad (wide) central occluder. When the spatial frequency of the grating was low (.04 cycles per degree [cpd] of visual angle; that is, the black and white bars were thick) and the occluder was narrow (1.33 degrees, LN in Figure 3.7) infants looked significantly longer at the broken test display (SG). This finding suggests that they perceived the low frequency grating as continuing behind the narrow occluder. In contrast, when the spatial frequency was high (1.2 cpd; the black and white bars were narrow) and the occluder was broad (4.17 degrees; HB in Figure 3.7), 3-week-olds looked significantly longer at a complete grating (CG) as opposed to a broken grating (SG). This finding suggests that they perceived the high spatial frequency grating as two separate regions. Further manipulations revealed that there is an interaction between spatial frequency and occluder width. Infants looked equally to the two test gratings when they viewed a high spatial frequency grating behind a narrow occluder (HN in Figure 3.7) and when they viewed a low spatial frequency grating with a broad occluder (LB in Figure 3.7). In both of these conditions, infants provided ambiguous results regarding whether they perceived the gratings as complete or broken.

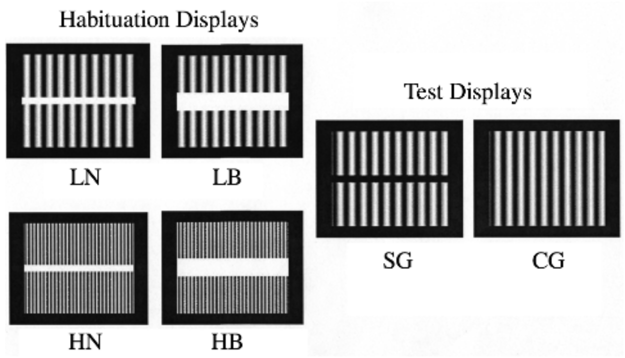

Figure 3.7 Habituation and test displays to test 3-week-old infants' perception of unity. LN refers to the low-spatial frequency display behind a narrow occluder. LB refers to low-spatial frequency display behind a broad occluder. HN refers to a high-spatial frequency display behind a narrow occluder. HB refers to high-spatial frequency display behind a broad occluder. SG refers to "separate grating" (analogous to a broken rod). CG refers to "complete grating" (analogous to a complete rod). *Source:* "Visual Completion of Partly Occluded Grating in Young Infants under 1 Month of Age," by H. Kawabata, J. Gyoba, H. Inoue, and H. Ohtsubo, 1999, *Vision Research, 39,* pp. 3586–3591. Reprinted with permission.

These several findings permit at least two explanations. One is that the use of common motion to specify object unity arises by learning between 3 and 8 weeks of life. This account would fit with classical empiricist notions about the starting point of perceptual development: Infants may see visible patches but may have to construct whole objects. One problem with this account is the learning mechanism. Both the findings of Kawabata et al. (1999) at 3 weeks and several researchers at 8 weeks are inconsistent with any of the traditionally proposed means by which infants might learn about objects, namely association of visual impressions with touch (e.g., Berkeley, 1709/1963) or with self-initiated action (e.g., Piaget, 1954). Infants at these early ages do not walk, crawl, or even perform directed reaching. One can imagine, however, purely visual forms of learning. Two parts of an object seen at one time may emerge from behind an occluder, allowing learning of the rule about common motion. This account, while imaginable, would have as its primary virtue minimizing what must be attributed to innate or rapidly maturing capacities. Paradoxically, as Kellman and Arterberry (1998) noted, this account places a heavy burden on innate concepts of physics. To unlearn an incorrect perceptual rule (two moving visible pieces are not connected) through later images, the child must be constrained by an assumption that it is impossible (or unlikely) for two pieces to have been separate and subsequently to have merged.

A more plausible account of these findings is that infant unity perception from common motion depends on sensory capacities that are maturing in the first 8 weeks of life. Common motion may well be an unlearned principle of object perception, but using it requires accurate mapping of the direction and velocities of separated, moving regions of the visual field. The preference for a complete rod after habituation in newborns may arise from their ability to see motion (allowing segmentation of visible regions) but with poor direction and/or velocity sensitivity. Recall our earlier consideration of the emergence of directional sensitivity in infant motion perception. Programmatic work by Wattam-Bell (1991, 1992, 1996a, 1996b) addressed the emergence of directional sensitivity and velocity perception in infants. Using both behavioral and electrophysiological techniques, Wattam-Bell found no reliable visual evoked potential (VEP) to reversals of motion direction until about 74 days of age. Behavioral discriminations of coherent from random motion in random dot displays showed no evidence of this discrimination in 1-month-olds with either visual preference or habituation methods (Wattam-Bell, 1996a, 1996b). This discrimination was found to be robust at 15 weeks and weakly present at 8 weeks of age.

Connecting these two lines of research, it appears that perception of unity from common motion in humans is found at the same age that reliable discrimination of motion direction is first observed. This account fits with the variation found with stimulus variables (e.g., Kawabata et al., 1999), as directional selectivity is improving steadily through the period studied. It may not be a coincidence that the earliest use of common motion was found in studies using multiple, moving, oriented edges. Developing abilities to detect motion direction may have been better engaged by such displays.

In the absence of accurate encoding of motion direction, it is not surprising that unity based on common motion is not found in the human newborn. The evidence of how motion sensitivity develops is hard to reconcile with a learning account of common motion as a determinant of perceived unity. Based on available evidence, directional sensitivity and perceived unity appear at about the same time. Whereas unit formation from common motion with the standard kinds of stimuli appears around 8 weeks, the first discernible VEP to motion direction was reported at 74 days of age (Wattam-Bell, 1992). In short, in addition to the question of what kind of learning process could generate unity perception at this age, there is no discernible interval during which learning might occur. Available evidence is consistent with the idea that perception of unity from common motion is unlearned, awaiting only the development of mechanisms of direction sensitivity in the infant's visual system.

The Edge-Sensitive Process: Unity Based on Edge Orientations and Relations

Whereas the edge-insensitive process is dependent only on motion relationships, the edge-sensitive process involves completion based on spatial orientations and relations of edges. These relations can be revealed in a static display or dynamically, over time, as when an observer views a scene through shrubbery (Palmer, Kellman, & Shipley, 2004). Thus the edge-sensitive process includes object completion in stationary arrays as well as in dynamic ones where edge relationships are crucial, such as kinetic occlusion and kinetic illusory contours (Kellman & Cohen, 1984).

Most work with infants on the edge-sensitive process has involved static displays. In contrast to the perception of unity from common motion, unity from edge relationships in static displays does not appear during the first half year of life (Kellman & Spelke, 1983; Slater, Morison, et al., 1990). The typical result is that after habituation to a stationary, partly occluded display, infants show equal looking to the complete and broken test displays. Based on evidence that infants do encode the visible areas and are sensitive to occlusion (Kellman & Spelke, 1983), this pattern has been interpreted as indicating the perceiver's neutrality about what happens behind the occluder.

By 6.5 months, infants perceive partly occluded objects as complete in the absence of kinematic information, thus relying on static information. Craton (1996) found that 6.5-month-olds perceived a static rectangle as unified when a bar occluded its center. However, infants at this age provided no evidence of perceiving the shape of the occluded region. When the removal of the occluder revealed a cross instead of a rectangle (the horizontal piece of the cross had been completely hidden behind the occluder), infants younger than 8 months did not show looking patterns indicative of surprise. At 8 months of age, infants looked longer at the "cross event" than at the "complete object event," suggesting that before 8 months infants expected the partially occluded rectangle to be a single unit but were agnostic regarding its specific form. Even when motion is present, such as the case of a rectangle appearing out from either side of a central occluder, infants' perception of unity appears to precede their perception of form (van de Walle & Spelke, 1996). In this case, 5-month-olds perceived the rectangle as unified but showed no evidence of knowing the shape of the occluded parts. Converging evidence comes from studies of illusory contours, which appear to depend on the same underlying process (Kellman et al., 1998). Infants of 7 months, but not 5 months, appear to be sensitive to static and kinetic illusory contour displays (Bertenthal, Campos, & Haith, 1980; Kaufmann-Hayoz, Kaufmann, & Walther, 1988).

How does perceived unity from edge-sensitive process emerge? Maturation, learning, or some combination are possible explanations. Granrud and Yonas (1984) suggested that pictorial depth cues appearing around 7 months of age might depend on maturation of a perceptual module, a finding bolstered by evidence from macaque monkeys (Gunderson et al., 1993). It is possible that edge-sensitive unity perception might be connected to this emergence. It has been noted that the depth cue of interposition is closely related to boundary completion under occlusion (Kellman & Shipley, 1991). Another argument for maturational origins comes from work on the neurophysiology of the edge-sensitive process (von der Heydt, Peterhans, & Baumgartner, 1984). It appears that some edge-sensitive interpolation processes are carried out at very early stages of visual processing, certainly as early as V2 and possibly V1, the first visual cortical area (von der Heydt et al., 1984). Models of early visual filtering at these levels typically postulate operations carried out by dedicated neural machinery in parallel across much of the visual field. Although learning explanations for such circuitry can be imagined, the existence of early parallel operations that carry out interpolation is congenial to maturational accounts. Other considerations suggest that learning may play a role (e.g., Needham, 2001; see Cohen & Cashon, 2001b; Kellman, 2001; Quinn & Bhatt, 2001; Yonas, 2001 for related discussions). Of interest to potential learning accounts is recent work by Geisler and colleagues (Geisler, Perry, Super, & Gallogly, 2001). Their work in analyzing natural scenes suggests that the edge relationships described by contour relatability are highly diagnostic of visible edges that belong to unitary objects. Such ecological facts, of course, might be relevant to both evolutionary and learning accounts of the edge-sensitive process, but the relatively late onset of this ability at least makes it possible that experience with an object's views under occlusion contributes to this ability.

Perception of Three-Dimensional Form

Form is among the most important properties of an object because it is closely tied to its functional possibilities. Representations of form are also primary in triggering object recognition processes. Even when some other property of an object may be of greatest concern to us, we often locate and recognize the object by its form. There are many levels of form—local surface topography, the two-dimensional projection of an object seen from a stationary vantage point, and three-dimensional (3D) form, to name a few. Arguably, it is the 3D forms of objects that are most important in human cognition and behavior. Whereas the particular 2D projection from an object varies with the observer's position, the object's arrangement in 3D space does not. Perceiving the unchanging object given changing optical information constitutes the important ability of *shape constancy.* In addition to being of greatest significance among form concepts, 3D form also constitutes the greatest battleground in perceptual theory. Adults are versatile in their 3D form perception abilities, and each mode of perceiving naturally suggests a different account of the development of 3D form perception (Kellman, 1984). Adults can usually detect the overall form of an object from a single, stationary view. If the object is a familiar one, this ability is compatible with the idea that an object's 3D form is a collection of 2D views obtained from different vantage points, and any single view recalls the whole collection to mind (e.g., Mill, 1865). On this account, 3D form develops from associating experiences of different views, perhaps guided by activity in manipulating objects (Piaget, 1954).

Another way to get whole form from a single view is to apply general rules that extrapolate 3D form. Use of rules would explain how we might see 3D forms of unfamiliar objects from a single viewpoint. Gestalt psychologists argued for unlearned, organizational processes in the brain that serve this purpose. An alternative account of rules of organization was suggested by Helmholtz (1885/1925) and elaborated by Brunswik (1956). Perceptual rules might be abstracted from experiences with objects. These two accounts of perceptual rules that map 2D views into 3D objects make diametrically opposed developmental predictions. On the Helmholtz/Brunswik account, these rules must be learned laboriously through experiences in seeing objects from different viewpoints and manipulating them. On the Gestalt view, organizational processes should operate as soon as the underlying brain mechanisms are mature.

Several decades ago, a new and different analysis of 3D form perception emerged. Based on initial discoveries such as the *kinetic depth effect* (Wallach & O'Connell, 1953) and later programmatic research on *structure-from-motion* (e.g., Ullman, 1979), the idea is that perceived 3D form results from mechanisms specifically sensitive to optical transformations. Transformations in an object's optical projection over time, given by object or observer movement, are governed by projective geometry. These transformations provide information that can specify the 3D structure of an object. Several theorists have proposed that human perceivers extract this kind of information using neural mechanisms specially evolved for this purpose (J. Gibson, 1966; Johansson, 1970; Shepard, 1984). Such an arrangement makes sense for mobile organisms: The complexity and speed of human adult perception of structure from motion makes it seem unlikely that these abilities derive from general purpose mechanisms that encode motion properties and general purpose inference mechanisms that might have allowed relevant regularities to be discovered.

Optical Transformations in Infant Form Perception

Research with human infants indicates that the most basic ability to perceive 3D form involves optical transformations. This dynamic information indicates 3D form as early as it has been tested, whereas other sources of information about form appear unusable by infants until well past the first half year.

A method to separate responses to 3D form from responses to particular 2D views was developed by Kellman (1984). When an object is rotated, its projection contains optical transformations over time, but it also might be registered as several discrete 2D snapshots. A way to separate 3D form from 2D views is to habituate infants to an object rotating around one axis and test for recognition of the object (by generalization of habituation) in a new axis of rotation. For a suitably asymmetrical object, each new axis of rotation provides a different set of 2D views, but providing there is some rotation in depth, each conveys information about the same 3D structure. A remaining problem is that dishabituation by infants may occur for either a novel form or a novel rotation. To combat this problem, infants were habituated to two alternating axes of rotation on habituation trials and tested afterward with familiar and novel 3D objects in a third, new axis of rotation. This manipulation reduced novelty responding for a changed rotation axis in the test trials. Sixteen-week-old infants tested with videotaped displays showed the effects expected if 3D form was extracted from optical transformations. When habituated to one of two 3D objects, they generalized habituation to the same object in a new rotation and dishabituated to a novel object in the same new rotation axis. Two control groups tested whether dynamic information was the basis of response or whether generalization patterns might have come from 3D form perception based on single or multiple 2D views. In the two control groups, infants were shown sequential static views of the objects taken from the rotation sequences. Two numbers (6 and 24) of views were used along with two different durations (2 seconds and 1 second per view); in neither static view case, however, were continuous transformations available as in the dynamic condition. Results showed no hint of recognition of 3D form based on the static views, indicating that 3D form perception in the dynamic case was based on optical transformations.

Later research showed that this result occurs at 16 weeks with moving wire frame objects having no surface shading information, a finding that implicates the importance of projective transformations of edges. Moreover, 3D form perception occurs when infants are moved around stationary objects (Kellman & Short, 1987a), indicating that projective transformations, not object motions per se, provide the relevant information. By 8 weeks, infants perceive 3D form in kinetic random dot displays in which the relative motions of the dots create surfaces and the edges between them (Arterberry & Yonas, 2000). Yonas et al. (1987a) showed that 3D form obtained from optical transformations could be recognized when form information was subsequently given stereoscopically. Paradoxically, transfer does not seem to occur in the other direction; that is, initial representations of 3D form do not seem to be obtained by infants from stereoscopic depth information in stationary viewing.

Static Form Perception

Form perception from optical transformation appears to be a basic foundation of human perception. It appears early and depends on information of great complexity, suggesting the existence of neural mechanisms evolved to map changing 2D projections onto 3D object representations. Another reason for regarding dynamic information as fundamental is that other sources of form information do not seem to be usable in the early months of life. This picture of early form perception turns on its head the classical empiricist notion that psychologically an object's 3D form is a construction from stored collections of static views.

Earlier, we described two conditions in which sequences of static views evoked no representation of 3D form in 16-week-olds. This finding—inability to perceive 3D form from single or multiple static views—has appeared consistently in research using real objects or photographic slides, up to an age of 9 months (Kellman, 1984; Kellman & Short, 1987a; Ruff, 1978). The inability to extract 3D form from static views is perplexing given that adults ubiquitously develop 3D form representations from single or multiple static views of objects. The one situation in which infants show some 3D form perception from static viewing involves recognition of 3D forms that had previously been given kinematically (Owsley, 1983; Yonas et al., 1987a). Perhaps this task of detecting similarity to a previously obtained representation is simpler than developing a full 3D object representation initially by means of static, binocular views. Alternatively, it could be a more general limitation of developing representations based on static information. In studies of categorization, infants transfer information about object category from kinetic to static conditions but not vice versa (Arterberry & Bornstein, 2002).

Nonrigid Unity and Form

Both the concept and process of 3D form perception are easiest to understand in the case of rigid objects whose forms do not change. Perception of rigid structure from motion is well understood computationally in terms of the projective geometry relating 3D structure, relative motion of object and observer, and transforming 2D optical projections at the eye. Many objects of ordinary experience, however, do not have rigid shape. In a moving person, a point on the wrist and one on the waist do not maintain a constant separation in 3D space. Nonrigidities may be given by joints, as in animals or people, but also by flexible substances, as in a pillow whose shape readily deforms. The possibility of perceiving or representing any useful information about shape for an object whose shape varies depends on the existence of constraints on the variation. A human body can assume many, but not unlimited, variations in shape; the class of possibilities is constrained by factors such as joints and musculature. A jellyfish may be even less constrained, but even it has a shape, defined as a constrained class of possibilities, and characteristic deformations that depend on its structure and composition. Some progress has been made in the analysis of nonrigid motion and processes that might allow us to perceive it (Bertenthal, 1993; Cutting, 1981; Hoffman & Flinchbaugh, 1982; Johansson, 1975; Webb & Aggarwal, 1982), but the problems are difficult.

Whereas scientists have not succeeded in discovering the rules for determining nonrigid unity and form, such rules appear to exist in the young infant's visual processing. In work with adult perceivers, Johansson (1950, 1975) pioneered methods for testing form and event perception from motion relationships alone. His use of moving points of light in a dark surround, in the absence of any visible surfaces, has become the method of choice in structure from motion research. When such lights are attached to the major joints of a walking person, adult observers viewing the motion sequence immediately and effortlessly perceive the lights as forming a connected walking person. Turning such a display upside down eliminates recognition of a human form (Sumi, 1984).

Studies of the development of perception of nonrigid unity and form have been carried out by Bertenthal, Proffitt and their colleagues (Bertenthal, 1993; Bertenthal, Proffitt, & Cutting, 1984; Bertenthal, Proffitt, & Kramer, 1987; Bertenthal, Proffitt, Kramer, & Spetner, 1987). A basic finding is that when infants of 3 to 5 months are habituated to films of an upright walking person, specified by light points, they subsequently dishabituate to an inverted display. This result suggests some level of perceptual organization, rather than apprehension of the displays as containing meaningless, individual points. The younger infants (at 3 months) may not perceive a person walking, however. Some later experiments used phase shifting of the lights to disrupt the impression of a walking person. Three-month-olds discriminated phase-shifted from normal walker displays whether the displays were presented in an upright or inverted orientation (Bertenthal & Davis, 1988), and they appear to process the absolute and relative motions within a single limb (Booth, Pinto, & Bertenthal, 2002). Both 5- and 7-month-olds, in contrast, showed poorer discrimination with inverted than with upright displays, and 5-month-olds perceive relations among limbs in walkers and runners (Booth et al., 2002). One interpretation of these findings is that older infants, like adults, perceive only the upright, normal phase displays as a walking person, so that disruption of the phase relations is salient for these displays. Because inverted displays are not perceived as people, phase disruption is not so noticeable. On this line of reasoning, 3-month-olds show perceptual organization of the displays but not classification of the upright displays as a walking person (*biomechanical motion*). The younger infants are thus sensitive to differences in upright or inverted displays.

Although a more direct measure of perception of a walking person has been difficult to devise, the findings suggest the attunement of the infant's visual system to certain nonrigid motion relationships. The basic sensitivity that allows detection and encoding of motion relations may begin much earlier than the point at which recognition performance is measurable. Preferences for motion patterns generated by a walking person or a hand opening and closing have been demonstrated in 2-month-olds (Fox & McDaniel, 1982).

Conclusions Regarding Form Perception

Earliest competence to perceive 3D form depends on mechanisms that recover object structure from optical transformations. These abilities are present before abilities to extrapolate 3D structure from single views of objects and also before the maturation of self-locomotion and directed reaching. Both rigid and nonrigid motion relationships provide structural information to young perceivers. What we know about early 3D form perception fits the conjecture of ecological views that perception of structure from motion depends on dedicated perceptual machinery developed over evolutionary time (J. Gibson, 1966, 1979; Johansson, 1970; Shepard, 1984).

Perception of Size

An object of constant real size projects a larger image on the retina when it is close to the observer than when it is farther away. Perception of constant physical size can be achieved by running this geometry in reverse: From the projective size at the eye and information about distance, the physical size of the object can be perceived (Holway & Boring, 1941). In some situations, relational variables may allow more direct perception of size, such as the amount of ground surface covered by an object in a situation where the surface has regular or stochastically regular texture (J. Gibson, 1950).

Among the most exciting developments in infant perception research has been the emerging conclusion that some degree of size constancy—the ability to perceive the correct physical size of an object despite changes in viewing distance (and resulting changes in projective size)—is an innate ability of human perceivers. Early research suggested that infants of about 4 months of age perceive an object's constant physical size at different distances and show a novelty response to a different-sized object, even when the novel object has a projective size similar to the previously seen object (Day & McKenzie, 1981). Studies of newborns have provided evidence that size constancy may be present from birth. Slater, Mattock, et al. (1990) tested visual preferences for pairs of identically shaped cubes of two real sizes (5.1 cm or 10.2 cm) at different distances (23 to 69 cm). Infants preferred the object of larger retinal (projective) size whenever it differed between the two displays. In a second experiment, infants were familiarized with either a large or small cube of constant physical size that appeared at different distances (and varying projective sizes) across trials in the familiarization period. After familiarization, infants were given a paired-preference test between the large and small cube on each of two test trials. For the test trials, the large and small cubes were placed at distances giving them equal projective sizes. This projective size was novel, that is, the cube that had been presented in familiarization was placed at a distance at which it had not appeared earlier (61 cm away for the 10.2 cm cube and 30.5 cm away for the 5.1 cm cube). Figure 3.8 illustrates the arrangements in familiarization and test conditions. Every infant ($n = 12$) looked longer at the object of novel physical size in the test trials, and the percentage of test trial looking allocated to the novel object was about 84%. Other evidence tends to support the conclusion that size constancy is observable in neonates (Granrud, 1987; Slater & Morison, 1985).

Research on newborn size perception has not addressed directly the possible mechanism(s) underlying constancy. This topic would seem to be an important one for future research. There are not many possibilities, however. The objects in both the Slater et al. (1985) and Granrud (1987) experiments hung in front of homogeneous backgrounds, precluding use of relational information potentially available when an object rests on a textured ground surface. In the situations used, it would

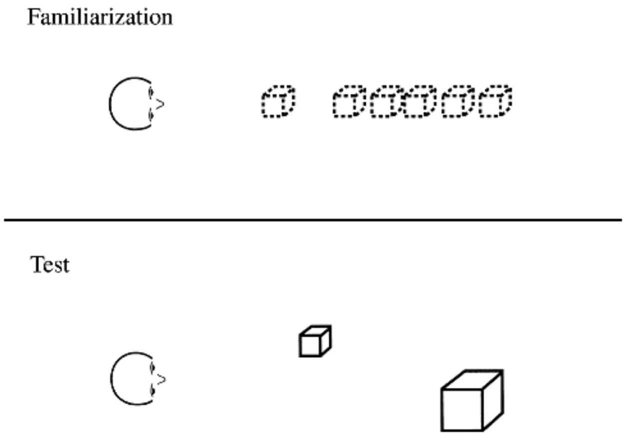

Figure 3.8 Familiarization and test displays used in a size constancy experiment. Each infant was familiarized with one object—either a large (10.2 cm/side) or small (5.1 cm/side) cube—at several viewing distances. The test pair consisted of the large and small cube placed at different distances (61 cm and 30.5 cm) to produce equal projective size. Object distances were different from those used during familiarization. *Source:* "Size Constancy at Birth: Newborn Infants' Responses to Retinal and Real Size," by A. Slater, A. Mattock, and E. Brown, 1990, *Journal of Experimental Child Psychology, 49*(2), pp. 314–322. Reprinted with permission.

appear that some information about egocentric distance, that is, distance from the observer, must be combined with projective size to allow computation of real size. Certain features of the experimental situations and newborns' abilities suggest that binocular convergence is the likely source of egocentric distance information (Kellman, 1995). Estimates of the precision of convergence vary (Aslin, 1977; Hainline et al., 1992; Slater & Findlay, 1975), but some data and an analysis of the required precision of distance estimates needed to support size discriminations in the Slater et al. and Granrud experiments support this possibility (Hainline et al., 1992; Kellman, 1995).

FACE PERCEPTION

Perhaps the most important class of objects in the infant's world is people. Not only are people perceptually very exciting for infants because they move, their motion is nonrigid, and they provide multimodal experiences; people are also important for ensuring the well-being of the infant. It is not surprising, then, that face perception is one of the oldest topics in infant perception, beginning with the writings of Darwin (1872/1965) on facial expressions, and it continues to be one of the most researched topics today. Key questions pertain to how early in life infants perceive faces, information infants obtain from faces (e.g., recognition of familiar people, gender, emotional expression), and what processes underlie face perception.

Preference for Facelike Stimuli

Early work in infants' face perception was concerned with the question of when infants perceive faces and in particular, when they know that faces have a particular set of features arranged in a particular way. Fantz (1961) conducted one of the earliest demonstrations that infants prefer facelike displays over other patterned stimuli. Further work using similar methods showed a consistent preference: Infants before 2 months of age showed no preference for a schematic versus a scrambled face (see Maurer, 1985 for an early review). However, the results were not altogether clear. Complicating the story was the use of different methodologies and different stimulus types by different researchers. In addition, at least one study did not fit this pattern: Goren, Sarty, and Wu (1975) used a tracking paradigm and showed that newborn infants tracked a schematic face farther than a scrambled face or a blank face shape. Replication of these results by Johnson, Dziurawiec, Ellis, and Morton (1991; but see Easterbrook, Kisilevsky, Muir, & Laplante, 1999) demanded a revision of the developmental story to include some face perception abilities by newborn infants.

Perceiving a face, particularly perceiving the internal details to recognize a face or to discriminate a scrambled face from a schematic face, requires a certain level of visual resolution on the part of the perceiver. Some research suggests that newborns lack adequate acuity or some other component of face processing to accomplish the task. As mentioned, Kleiner (1987) suggested that before 2 months of age, infants' face preferences are driven by amplitude spectra (as derived from Fourier analysis). Consequently, infants' early preferences for faces may not be driven by how a stimulus looks but by some rule about the population of frequency detectors. Using a clever manipulation, she presented infants with faces that contained the phase and amplitude spectra of a face or a lattice (see Figure 3.9b), the phase of the lattice and the amplitude of the face, and the phase of the face and the amplitude of the lattice. She found partial support for the sensory hypothesis. Newborn infants

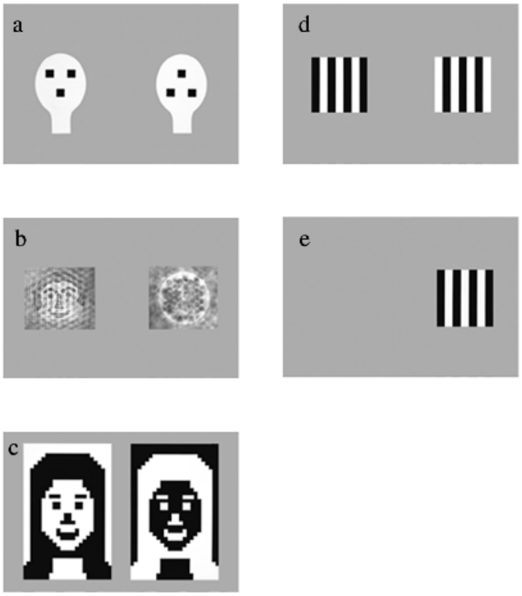

Figure 3.9 Stimuli used by Mondloch et al. (1999) to study newborn, 6-week-old, and 12-week-old infants' face perception. A, B, and C depict displays used previously (see text). D and E are control stimuli. *Source:* "Face Perception during Early Infancy," by C. J. Mondloch et al., 1999, *Psychological Science, 10,* pp. 419–422. Reprinted with permission.

preferred the displays with the amplitude spectrum of the face, although they showed the strongest preference for the stimulus that had *both* the phase and amplitude of the face. Two-month-old infants preferred the displays with the phase spectra of the face.

A different explanation of the early data on face processing was proposed by Morton and Johnson (1991) and revised by M. H. Johnson (1997). Their account suggests that there are two mechanisms for face processing. The first, called CONSPEC, underlies early face perception. This process is innate, and it allows newborn infants to recognize structural information specifying conspecifics without exposure to specific stimuli. Infants respond to facelike stimuli because they look like a face; however, the structural information is very general, such that crude representations of faces (e.g., the upright *config* stimulus shown in Figure 3.9) can trigger this process. Around 2 months of age, a second mechanism emerges. This process, CONLERN, is dependent on visual experiences with faces, and it leads to representations of particular faces.

In an attempt to resolve some of the conflicting findings, Mondloch et al. (1999) conducted a preference study with newborns, 6-week-olds, and 12-week-olds using pairs of stimuli from three different laboratories: the upright and inverted *config* stimulus used by M. H. Johnson, Dziurawiec, Ellis, and Morton (1991, see Figure 3.9a), mixed phase and amplitude spectra stimuli from Kleiner (1987, see Figure 3.9b), and positive- and negative-contrast faces from Dannemiller and Stephens (1988, see Figure 3.9c). In addition, they included a control stimulus to test for no preference (Figure 3.9c) and a clear preference (Figure 3.9e). They found that newborns preferred the *config* stimulus over its inversion and the amplitude spectrum of the face over the phase spectrum of the face (Figure 3.9b), but newborns showed no preference for the positive or negative contrast faces. Six-week-olds showed no preference for the *config* display or its inversion, a preference for the phase of the face over the amplitude of the face, and no preference for the positive or negative contrast faces. Finally, 12-week-olds showed no preference between the *config* stimulus and its inversion, but they showed a preference for the phase of the face over the amplitude of the face and they showed a preference for the positive contrast over the negative contrast face. From these results, Mondloch et al. concluded that newborns' preferences are guided by both the visibility of the stimulus and its resemblance to faces, and it is likely that newborns are predisposed to look toward faces. This explanation is similar to one proposed by Simion, Cassia, Turati, and Valenza (2001). They suggest that newborn preferences are determined by the match between both the sensory properties and the structural properties of the stimulus and the constraints of the visual system. One other finding worth mentioning is that 6- and 12-week-olds preferred the phase spectrum of a face—they looked more at the stimulus that looked like a face. These results suggest that face processing improves rapidly after birth, through maturation or through experience with faces, consistent with (but a bit earlier) than the sequence proposed by Morton and Johnson (1991).

These explanations for the early development of face processing are sensitive to the nuances of some experiments, but they may yet understate the capabilities of newborns. A number of startling findings have appeared, suggesting that newborn abilities go well beyond merely discriminating a schematic face from a scrambled face. Infants just a few hours old are reported to discriminate their mothers from a stranger (Bushnell, 2001; Bushnell, Sai, & Mullin, 1989; Pascalis, de Schonen, Morton, Deruelle, & Fabre-Grenet, 1995), and they show a preference for attractive faces over unattractive faces as older infants do (Rubenstein, Kalakanis, & Langlois, 1999; Slater, Quinn, Hayes, & Brown, 2000; Slater et al., 1998). Newborns' recognition of their mothers may be based on external features such as hairline (Pascalis et al., 1995), but perception of attractiveness appears to rely on internal features and possibly their configuration (Bartrip, Morton, & de Schonen, 2001; Slater et al., 2000). The data on attractiveness suggest that infants must process the internal features of faces to a fine level of detail. At this time, we do not know how they do it, either in terms of specific face perception mechanisms or general capacities of the neonate visual system.

Perceiving Information about People through Faces

Beyond the newborn period, infants are sensitive to facial information that may be useful for recognizing specific people, perceiving characteristics of people, and for engaging in nonverbal communication. The ability to recognize a person across different views, or person constancy, is an important skill because faces (and people in general) are dynamic objects. Faces show differing expressions, and infants have the opportunity to view them from different perspectives. To recognize key people in their environment, infants must be able to perceive the constancy of a person despite proximal stimulus differences. One of the earliest studies of infants' perception of people across different views was conducted by Cohen and Strauss (1979). In this study, infants were habituated to views of the same female and then tested with an *enface* view. Infants did not recognize the *enface* view as the same person until 7 months of age. More recent studies have shown that babies may be able to recognize familiar faces (their mother but not a stranger) in different views, *enface,* but not in profile, as early as 1 month of age (Sai & Bushnell, 1988); and babies recognize faces across differing intensities of an emotional expression, namely smiling, at least by 5 months of age (Bornstein & Arterberry, 2003).

Infants have the opportunity to view faces in many perspectives, and certainly from angles different from those adults typically experience. Supine infants may often see faces oriented at 90 degrees or even completely upside down. For adults and older children, inversion of a face significantly disrupts recognition. This has been attributed to a processing strategy based on the relation between facial features ("configural" processing) as opposed to processing the facial features independent of each other ("featural" processing; e.g., Carey & Diamond, 1977, 1994; Sergent, 1984). If and when infants are susceptible to this inversion effect (reduced recognition of inverted faces) has generated interest because of its implications for how infants may be processing faces. Presenting stimuli upside down to infants has been a procedure used by some researchers as a control for responding to specific features within a face (e.g., Bahrick, Netto, & Hernandez-Reif, 1998; Kestenbaum & Nelson, 1990; Slater et al., 2000); however, few direct tests of the inversion effect have been conducted. Cashon and Cohen (Cashon & Cohen, 2004; Cohen & Cashon, 2001a) habituated infants to two female faces. They were tested with a familiar face (one of the two viewed in the habituation phase), a novel face, and a combination face that consisted of the internal features of one of the habituation faces and the external features of the other habituation face. For half of the infants, the faces were presented upright and for the other half the faces were inverted. Across 3 to 7 months of age, infants showed movement toward configural processing of upright faces, and this type of processing was clearly evident by 7 months of age (see Cohen & Cashon, Chapter 5, this *Handbook,* this volume, for a representation of these data). For inverted faces, at most of the ages tested, infants showed no evidence of configural processing. An unexpected result was the lack of a monotonic change between 3 and 7 months in configural processing, a finding Cashon and Cohen (2004) attribute to general information-processing strategies that are not necessarily specific to face perception (see Cohen & Cashon, Chapter 5, this *Handbook,* this volume).

In addition to recognizing particular faces, infants may use information contained in faces to categorize people into classes, such as male and female. Perception of gender by adults can be based on superficial cues, such as hair length, facial hair, and makeup or on structural cues, such as the distance between the eye and brow (e.g., Bruce et al., 1993; Campbell, Benson, Wallace, Doesbergh, & Coleman, 1999). Infants' perception of gender has been assessed in the context of categorization tasks; infants are shown either male or female faces and are tested with a novel face of the same gender and a novel face of the opposite gender. Using this procedure, Leinbach and Fagot (1993) showed that infants categorize gender by 9 months of age with the aid of superficial features (stereotyped hair length and clothing). However, their findings were asymmetrical. Infants habituated to male faces looked significantly longer to the female face in the test phase but infants habituated to female faces did not. Quinn, Yahr, Kuhn, Slater, and Pascalis (2002) further explored this asymmetry and found evidence that experience may have an influence on infants' preferences for male or female faces. In their study, 3- to 4-month-old infants were familiarized to either male or female faces and then tested for a preference for a novel same gender face or a novel opposite gender face. Infants familiarized to male faces preferred the female face, but infants familiarized to female faces did not show a preference for the male face. When Quinn et al. presented infants with the male and female test pairs without the familiarization phase, infants showed a strong preference for the female faces: This preference dipped only slightly when the hair was covered. When Quinn et al. recruited infants who had a male primary caregiver, a preference for male faces emerged. Finally, Quinn et al. familiarized infants, who had female primary caregivers with male or female faces and then tested them with a novel and familiar face of the same gender that was presented in the familiarization phase. Infants familiarized to female faces showed a preference for the novel female face, suggesting that they remembered the familiar female face. Infants familiarized to male faces showed equal amounts of attention to the novel and familiar male faces in the test phase. Quinn et al. concluded that infants' caregiver experience provides them with the opportunity to learn the details that define individual female faces relative to male faces. This may be the first study to indicate the role of experience in infants' face perception.

Faces also convey information about emotional states through facial expressions. Facial expressions may play an important role in communication for the nonverbal infant (e.g., Rochat, 1999; Russell & Fernandez-Dols, 1997), and infants have the opportunity to experience a variety of facial expressions. Moreover, there is evidence of similar expressions appearing in child-adult interactions across cultures (Chong, Werker, Russell, & Carroll, 2003). Consequently, perception and discrimination of emotional expressions become crucial for infants to be engaged social partners.

Infants between 5 and 7 months of age show evidence of discrimination of the facial expressions of happiness, anger, fear, and surprise (Bornstein & Arterberry, 2003; Kestenbaum & Nelson, 1990; Ludemann & Nelson, 1988; Serrano, Iglesias, & Loeches, 1992). Moreover, they are able to categorize one or more of these expressions across different people. For example, Bornstein and Arterberry (2003) habituated 5-month-olds to different intensities of smiling, from a slight upturning of the mouth to a full toothy grin, modeled by four females. Following habituation, infants viewed a fifth female modeling a never-before-seen mid-range smile and a sixth female modeling a fearful expression. Infants looked significantly longer to the fearful expression suggesting that they categorized the facial expression of smiling and treated the new smiling exemplar as fitting within that category. Other findings show that infants as young as 3 months discriminate different intensities of smiling (Kuchuk, Vibbert, & Bornstein, 1986), and at least by 6 months infants discriminate different intensities of frowning (Striano, Brennan, & Vanman, 2002). To date, little attention has been paid to the role of experience and infants' perception of facial expressions. However, Striano et al. found some relationship between 6-month-old infants' preferences for smile and frown intensities based on symptoms of depression in their mothers, and Montague and Walker-Andrews (2002) found that 3.5-month-olds can match the voice and facial expression (sad, happy, and angry) of their mothers, but not of their fathers or an unknown male or female.

Mechanisms of Face Perception

Researchers have made considerable progress documenting early infant face perception abilities. Given the wide array of recent findings, we may reconsider what possible mechanisms could underlie these abilities. There is strong evidence that infants are predisposed to attend to faces. Some claim this predisposition is the result of an innate representation for faces (e.g., Slater et al., 1998, 2000), whereas others claim it is the result of a quick learning process (e.g., Bednar & Miikkulainen, 2003; Bushnell, 2001). Advances in neuroimaging and electrophysiological techniques have provided researchers with the opportunity to identify areas of the nervous system that are involved with face perception (e.g., Gauthier & Nelson, 2001). Key areas that have been identified are the middle fusiform gyrus in the right hemisphere for perception of upright faces (Kanwisher, McDermott, & Chun, 1997) and the amygdala for perceiving facial expressions (Whalen et al., 1998). Work with nonhuman primates has identified face-responsive cells in the inferior temporal cortex (e.g., Rolls & Baylis, 1986). Explanations for the development of face perception abilities in infants have to greater and lesser degrees been linked to these neurophysiological findings.

Several proposals have been advanced. One is that face processing in infants shows a right hemispheric advantage with implication of the fusiform gyrus (e.g., Deruelle & de Shonen, 1991). These areas develop more quickly in the right hemisphere than in the left, and experience with faces contributes to the specialization of this area for face perception. A second explanation proposed by Johnson and his colleagues (e.g., Morton & Johnson, 1991) is that the two processes, CONSPEC and CONLERN, are subserved by different mechanisms. They claim that CONSPEC is a subcortical process involving the superior colliculus and that CONLERN is a cortical process involving the primary visual cortex. The later emergence of CONLERN reflects the maturational constraints of these areas.

Nelson (2001) provides a third possibility. Relying on speech perception as a model, he proposes that face perception abilities initially are responsive to a wide variety of facelike stimuli, including faces from other species, and these abilities are tuned with age as a result of specific experiences. The development of speech perception begins with some specific skills—infants recognize their mother's voice, and they discriminate a range of speech sounds. More impressive is that young infants are able to discriminate speech sounds ("nonnative speech contrasts"; Werker, 1994) that adults in their environment cannot. The ability to discriminate nonnative speech contrasts diminishes with exposure to language, and infants' speech perception abilities are generally tuned to their linguistic environment by 10 to 12 months of age. In other words, there is a perceptual window that narrows throughout the 1st year of life depending on experience. Nelson suggests a similar fine-tuning of face perception abilities. For example, young infants are better than adults in recognizing faces of monkeys, an advantage that decreases across the 1st year of life (de Haan, Pascalis, & Johnson, 2002; Pascalis, de Haan, & Nelson, 2002). Nelson also cites other areas of face processing, such as the "other race" effect (e.g., O'Toole, Deffenbacher, Valentin, & Abdi, 1994) and the inversion effect, as examples of the fine-tuning of face perception. Further relying on the speech perception model, Nelson (2001) suggests that neural tissue has the potential to become specialized for face perception, and the nature of this specialization depends on specific experiences. Support for this idea comes from studies of children and adults who were born with cataracts: Visual deprivation during the first 7 weeks of life due to congenital cataracts resulted in significant and apparently permanent impairment in face processing later in life (Geldart, Mondloch, Maurer, de Schonen, & Brent, 2002).

More work is needed to fully understand the underlying mechanisms of face perception. A commonality among emerging explanations is a role for experience in the tuning of face perception abilities.

CONCLUSION

In this concluding section, we touch on a few issues relevant to all the research we have described. We draw some conclusions about levels of analysis in research on perceptual development, identify some priorities for future work, and consider the consequences of what has already been learned for understanding the development of perception.

Levels of Analysis

Research in infant vision involves work at different levels of analysis. Ordinarily, this idea would be offered in an introduction, but perhaps it is easier to see looking back at the research we have surveyed (for a more extensive discussion of levels, see Kellman & Arterberry, 1998, chap. 1; Marr, 1982). Consider the issues about kinematic information in early perception. We described relations in optical transformations, such as motion perspective, that underlie perception of 3D form, and accretion and deletion of texture, which provides information about relative depth. The description of perceptual tasks, such as seeing form and depth, and the information that allows perception to occur, has been called the *computational* (Marr, 1982) or *ecological* (Kellman & Arterberry, 1998) level of analysis. More crucial than the specific name used is the realization that understanding vision (and other information-processing tasks) begins with an account of the task to be achieved and the information and constraints that make it possible. In infant vision, we ask whether and how information in reflected light allows infants to see objects, motion, and the layout of space.

Information at a second level—the level of representation and process—involves the ways that information is represented and transformed. Whereas the ecological level describes how information is manifest in the world, the level of representation and process describes information processing inside the perceiver. Investigations of the common motion process in infant perception of object unity is an example of work that addresses information processing in early perception; evidence showing the combining of distance information with retinal size or motion is another. As we note below, infant perception research has been far more successful at revealing the sensory and perceptual capabilities of infants than at probing detailed processes and representations.

Finally, many of the findings we have reviewed involve the biological mechanisms that carry out perceptual information processing. To encompass both human and artificial systems, Marr (1982) called this level the *level of hardware implementation.* For humans, the question is about *biological mechanisms* (as opposed to silicon and germanium chips that might process stereoscopic disparities in a computer vision system). Work on the maturation of retinal receptors, on color vision mechanisms, neurological regions implicated in face perception, and on the maturation of stereoscopic depth perception are all examples of work primarily at the level of biological mechanism.

It is a relatively recent realization that all three levels must be addressed to understand visual perception. This understanding, which applies to information processing phenomena in general, owes much to the work of J. Gibson (1966, 1979), who emphasized the study of the information available for perception. Although seldom explored, Gibson's work has important parallels with the work of Chomsky (e.g., 1965, 1980) who emphasized that the structure of language is an object of study in its own right and that this study is an important starting point of linguistic analysis. For Gibson, the structure to be uncovered exists in the physical world; for Chomsky, it is in language. Most directly, however, the framework of three levels we have presented here derives from Marr (1982).

The need for multiple levels of analysis has been discussed extensively elsewhere, so here we merely note some of the important implications. One is that the levels are relatively independent of each other. Finding data that disconfirm a particular neural model does not invalidate an accompanying algorithm or ecological theory. Another is that one cannot simply catalog the anatomy and neurophysiology of the optical pathways and brain structures and expect to understand vision (Marr, 1982). One might catalog indefinitely many properties of neural structures but understand their functions only when these are tied to a particular task, process, and representation. One of Marr's (1982) favorite examples was the relation between a bird's feathers and the laws of aerodynamics. It would be foolish to believe that the laws of aerodynamics could have ever been derived from an intensive study of feathers. In fact, the flow of understanding runs in the opposite direction. Knowing something about aerodynamics helps us understand what feathers are doing on birds. Without understanding the demands of flight, we could aimlessly record many details of feathers and note their presence on birds as a curiosity.

Finally, an encouraging trend in the cognitive and neural sciences is an improved ability to understand relations among facts at the three levels. Although a complete understanding of the task, information, processes, and mechanisms is not in hand for any domain of infant visual perception, considerable progress is being made on each level, and on their relationships.

Hardwiring versus Construction in Visual Development

As mentioned, one reason for long-standing interest in infant visual perception is to help understand the contributions of nature and nurture in the development of the mind. Although many important questions remain, we can make some global statements about the origins of visual abilities. Vision develops from innate foundations. The basics of many visual abilities can be discerned at birth, and some others appear to unfold according to a maturational program. Input from the environment may play a role in refining or calibrating many visual functions, and it may yet turn out to be the driving force in the development of a few.

These general statements contradict a long history in philosophy, psychology, and cognitive science in which the dominant view of perception's origins has been that it emerges gradually through a constructive process, shaped largely by external input. The development and ingenious application of methods for studying early perception, over the past several decades, have produced this radical change in perspective in understanding vision. When we look at basic visual sensitivities, such as sensitivity to orientation and pattern, we see that infants' capabilities do not match those of adults, but are clearly present to some degree at birth. Other basic components of visual sensitivity, such as sensitivity to motion direction, appear over the first 6 to 8 weeks of life, a period during which rapid brain maturation occurs and most visual sensitivities improve markedly.

Most interesting for general accounts of how perception works is the story of early *perceptual* abilities. Research on infant vision indicates that infants attend from birth to faces, and they show some face recognition abilities in the first few days of life (Bushnell, 2001; Bushnell et al. 1989). Under at least some conditions, they perceive the shapes and sizes of objects despite variations in their depth and slant (Slater et al., 1990). These findings refute theories claiming that perception of the third dimension and perception of objects are hard-won developmental acquisitions dependent on associative learning. Perception of a 3D world of objects, surfaces, and events appears to be the starting point, not the result, of early perceptual contact with the world (Kellman & Arterberry, 1998).

Propelled in part by interest in connectionist networks, there has been a resurgence in recent years of strongly empiricist views of development (e.g., Elman et al., 1996). One often encounters one or another version of the claim that the human visual system "gets wired up by experience," much as the weights in a connectionist network change by interacting with input patterns (e.g., Purves & Lotto, 2003, although these authors acknowledge that initial architecture providing basic sensitivities, such as orientation, is innate). Evidence of early-appearing abilities, such as face perception, tend to be interpreted as "nonrepresentational" or as attentional biases that can lead to rapid learning (Elman et al., 1996).

Although perceptual learning is important throughout the life span (see Kellman, 2002, for a review), the basic issue of whether perceptual systems reveal a meaningful reality from birth appears to have a positive answer. These abilities seem to pass the tests required of true perceptual knowledge and implicate capacities to represent objects, space, and events (Kellman & Arterberry, 1998). The findings about early perception rule out the time-honored idea that perceptual reality is initially constructed from experience and also casts doubt on the idea that early experience consists of "image schemas" or some other product that falls short of representing aspects of the world. Meaningful perception operates from birth.

This global conclusion may revolutionize our view of early development, but it should not obscure the complexities of infant vision. In one domain after another—in pattern perception, space perception, object perception, and face perception, to name a few—we see a similar picture: Certain kinds of information are usable by infants much earlier than others. The infant has perceptual contact with a 3D world from birth, but does not use pictorial depth cues until 6 to 7 months of age. Perception of object unity from motion can be found in experiments as early as the infant has basic motion direction sensitivity, but the value of edge relatability in producing perceived unity cannot be demonstrated until later. Moreover, most aspects of sensitivity in the infant's visual system improve for many months after birth or first appearance. Many of these changes are not yet well understood. There are ample ways in which both maturation and the effects of external signals in tuning neural circuitry could be involved. Some acquisitions may even fit the classic paradigm of cue learning, such as the depth cue of familiar size.

Future Directions

In the fifth edition of this *Handbook,* the final paragraph of the chapter on infant visual perception began "Further progress in understanding the characteristic pace and sequencing of visual abilities will require a deeper understanding of processes and mechanisms." This statement remains true and suggests some of the most difficult challenges in the field. Obtaining a description of early perceptual abilities, once thought to be scientifically impossible, has turned out to be easier than obtaining detailed insight into the processes and mechanisms of development. Understanding the computations and neural bases underlying specific visual abilities, and discovering the contributions of maturation and learning that build on the infant's early endowment, are among the highest priorities for future research.

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