

HANDBOOK OF CHILD PSYCHOLOGY

FIFTH EDITION

Volume 2: Cognition, Perception, and Language

Editor-in-Chief

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John Wiley & Sons, Inc.

New York • Chichester • Weinheim • Brisbane • Singapore • Toronto

CHAPTER 3

Infant Visual Perception

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There has been a longstanding interest in how infants see. The great Egyptian mathematician, Alhazen, reported in the 11th century that a child who is shown two things will preferentially fixate the more attractive one (Alhazen, 1989; translated by Sabra, 1989) and deduced that some visual capability existed early in life. The evolutionary biologist, Charles Darwin, reported in the 19th century that his infant son preferred to look at some colors over others and concluded that color vision developed during early infancy (Darwin, 1877). Most of what we know about infant visual perception, however, has been learned in the past two decades, so naturally our review will focus on research during this period.

The relatively recent interest in infant visual perception arises from our natural curiosity about how sophisticated devices come to be, but there are important additional reasons. First, the experimental procedures used to study cognitive and social capabilities of infants generally involve visual stimulation, so it has become important to know what infants can and cannot see in order to ensure that immature performance in these procedures can be ascribed to cognitive or social immaturities rather than to an inability to discriminate the stimuli. Second, we learned in the 1970s

that the presence of ocular abnormalities early in life (e.g., cataracts, crossed eyes, refractive errors) cause seemingly permanent deficits in a variety of visual capabilities. Early diagnosis of such abnormalities is essential to successful treatment, so there has been an increasing need to assess the vision of individual infants during their first 6 months. Third, as in many areas of science, progress in our understanding of visual development awaited the invention of techniques for measuring visual capabilities. Three important techniques were refined during the past 20 years: preferential looking (in particular, forced-choice preferential looking; Teller, 1979), visual habituation, and the visual evoked potential (Norcia & Tyler, 1985; Sokol, 1978). These techniques allowed researchers to ask more sophisticated scientific questions than were previously possible.

Understanding vision and its development requires multiple levels of analysis. In his classic work *Vision*, David Marr described three: the levels of computational theory, algorithm, and neural implementation. Computational theory involves the task to be achieved and the sources of information that make it possible. How can objects, motion, or spatial arrangements be perceived from information in reflected light? These are in general complex problems. As perception theorists have emphasized for centuries, patterns of light at the eye could imaginably arise from many causes other than the orderly arrays of objects and spatial

Supported in part by NSF Grant-9496112 to PJK and NIH Grant NIH-EY-10991 to MSB.

layouts we perceive. Thus, an important component of computational theorizing is identifying constraints—basic properties of the way the physical world works—that may simplify the mapping from optical stimulation onto physical arrangements. For example, as we walk around an object, its optical projection transforms. Using projective geometry, the visual system can recover the 3-D shape of the object from the transformations. Doing so assumes, however, that the object's 3-D shape is not changing contingent on our own motion. This constraint seems to be a reasonable one in our physical world, and it is one the visual system seems to incorporate. (This constraint is the primary source of the reality in virtual reality systems, where the optical transformations contingent on the observer's movement do not come from real world objects.)

The second level—the level of representation and algorithm—involves the ways in which information is represented and transformed. The descriptions of information processing we seek at this level, in terms of algorithms and data structures, might plausibly be similar in a human perceiver and in a computer vision system.

The third level is hardware implementation. For humans and animals, what biological mechanisms carry out the pick-up and processing of visual information? Here the human and computer visual systems diverge. Neural circuits and silicon chips may perform similar computations, but they are drastically different physical devices.

The explicit realization that all three levels must be addressed for an understanding of vision, or any complex information processing phenomenon, is a relatively recent development and one with many consequences. One is that the levels are relatively independent of each other. Finding data that disconfirm a particular neural model does not necessarily invalidate an accompanying algorithm or computational theory. At the same time, relationships among facts at the three levels are perhaps most crucial to understanding vision. One might catalog indefinitely many properties of neural structures but understand their functions only when these are tied to a particular computation and algorithm. One of Marr's (1982) favorite examples was the relation between a bird's feathers and the laws of aerodynamics. It would be rather optimistic to believe that the laws of aerodynamics could have ever been derived from intense study of feathers. The reverse is in fact true. Without knowing something about aerodynamics, we could never truly understand feathers or what they are doing on birds.

Development adds yet another dimension to our inquiry. Knowing about visual perception in the adult helps us study perceptual development. To the extent the destina-

tion of development is understood, it helps us to select questions and interpret findings. On the other hand, the starting point of development may be quite remote from the destination. At every level—neural machinery, information processing, and even the computational analysis—there may be important differences between the developing perceiver and the adult. Certain classes of information may not be available to an infant before the maturation of specific neural mechanisms, for example. Even the task of perception may be different early in life (Kellman, 1993). Whereas the adult often uses vision to guide action, the young infant has little capacity to act. Early visual perception probably guides the development of action systems (von Hofsten, 1980; Bertenthal, 1996) and promotes learning about the physical and social worlds.

We will consider research relevant to visual development at all three levels of analysis and their connections. Most of this research has occurred in the last few decades, and it has replaced earlier conjecture with a reasonably detailed sketch of when various perceptual abilities emerge. More difficult has been the understanding of detailed algorithms and underlying mechanisms. Although some advances have been made, continuing to make progress from description to explanation represents a major challenge for developmental research.

Our review of infant visual perception is necessarily quite selective. The areas we have chosen to review reflect our areas of expertise and our biases concerning the most intriguing areas of research since 1983 when one of us last reviewed this field for the *Handbook of Child Psychology* (Banks & Salapatek, 1983). We begin with a discussion of object perception that includes reviews of the development of the ability to extract and partition spatial information, of the ability to detect and classify edges, of the conditions required for perceiving object unity, and of the ability to perceived three-dimensional form. We then move on to space perception including the development of the ability to use pictorial depth cues, motion-based depth cues, and binocular cues. Next is color vision and here we review recent work on infants' ability to use wavelength composition to make visual discriminations. We end with motion perception where we review the ability to make speed and direction discriminations and the ability to use motion information to perceive self- as opposed to object-motion.

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 imaginable ways to describe and encode the streams of light that hit the retinas of the eyes. In ordinary perceiving, however, we obtain 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. Thus, perceptual knowledge allows us to predict the results of action: How the world divides, what things will detach from adjacent things, and what will remain coherent if moved, thrown or sat upon. All this we can know from a distance through vision. We perceive bounded objects as having many other attributes relevant to our actions: shapes, sizes, rigidity or flexibility, and so on. 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. Matched to the richness and importance of object perception is its complexity. The challenges become apparent when we see how little of human object perception can yet be emulated by artificial vision systems. For the experienced observer in a familiar environment, however, the task seems not complex, but effortless, instantaneous, almost trivial.

We begin our discussion of object perception with a review of what we know about the initial stages of visual processing; these provide the spatial information from which surface and object properties are extracted.

Extraction and Partitioning of Spatial Information

The ability to detect and encode spatial variations in the stream of light coming into the eye is fundamental to seeing surfaces and objects. For example, to identify and interact with the book in front of you, your visual system must detect and represent the variations in incoming light intensity (or wavelength) that define the boundary of the book, the letters on the page, and so forth. The study of the ability to detect and discriminate simple visual patterns has dominated research in infant visual perception, so we devote a significant proportion of this review to this topic. Most of the research has been devoted to defining the limits of detection and discrimination capacities: that is, to determining, as a function of age, what kinds of spatial variations in light intensity can be detected and discriminated and what kinds cannot. The picture that emerges from this research is that the detection and discrimination capacity of the

human infant is very limited during the first few months of life and these capacity limitations must necessarily constrain the ability to see and recognize surfaces and objects in the everyday environment.

Visual Acuity

Object recognition and identification depend on the ability to encode the spatial distribution of differences in retinal image intensity or wavelength. The study of visual acuity addresses the question of how accurate the encoding of spatial distribution is. The term *visual acuity* thus refers to the maximum resolving capacity of the visual system. The importance of this capacity is illustrated by the fact that visual acuity measurements are far and away the most common means of assessing ocular health and suitability for operating motor vehicles.

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 units of visual angle. Countless types of stimuli have been used to measure visual acuity in adults, but only two have been 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 $\frac{1}{2}$ to $\frac{2}{3}$ minutes of arc (Olzak & Thomas, 1986). By optimal conditions, we mean that the stimulus is brightly illuminated, high in contrast, presented for at least $\frac{1}{2}$ second, and viewed foveally with a well-focused eye. Changes in any of these viewing parameters cause a reduction in grating acuity.

Vernier acuity tasks require the discrimination of a displacement of one small target with respect to another. For example, one task involves distinguishing whether a vertical line segment is displaced to the left or right relative to line segment just below it. In adults, the just-noticeable offset under optimal conditions is 2 to 5 seconds of arc. 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 $\frac{1}{2}$ second, and viewed foveally with a well-focused eye.

The threshold values obtained in grating and vernier acuity tasks differ. Because the acuity limit varies from one task to another, one cannot use an acuity estimate obtained with one stimulus and task to predict the acuity for another stimulus and task. This has important implications for infant research: Specifically, one cannot use a particular acuity estimate to determine whether the pattern elements in another stimulus are visible to the infant. For example, an infant's grating acuity cannot be used in any direct fashion to determine whether the pattern elements in a schematic face are visible to the infant.

Eye movements, optics, photoreceptor properties, and postreceptor neural mechanisms all contribute to limit acuity; one factor may dominate in a given situation, but they all contribute. Thus, a strong motivation for studying visual acuity is the expectation that it will provide insight into the oculomotor, optical, anatomical, and physiological mechanisms underlying spatial vision. Psychophysical estimates of visual acuity in adults have supported this expectation (Coletta, Williams, & Tiana, 1990; Green, 1970; Williams, 1985).

There have been numerous measurements of grating acuity (the highest detectable spatial frequency at high contrast) in human infants (Figure 3.1). The displayed

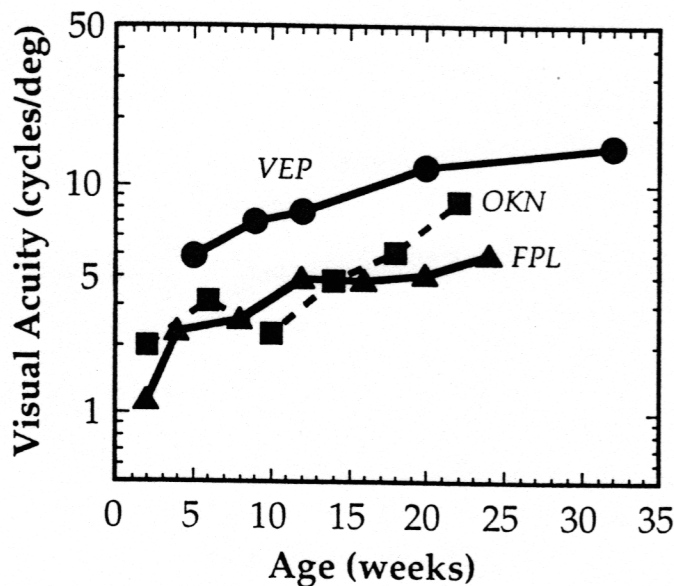


Figure 3.1 Visual acuity estimates at different ages. The highest detectable spatial frequency of a high-contrast grating stimulus is plotted as a function of age. Circles = visual evoked potential estimates from Sokol (1979); squares = optokinetic nystagmus estimates from Fantz, Ordy, & Udelf (1962); triangles = forced-choice preferential looking estimates from Allen (1978).

results were obtained using three response measurement techniques: Forced-choice preferential looking (FPL; Teller, 1979), optokinetic nystagmus (OKN; ref), and the visual evoked potential (VEP; Norcia & Tyler, 1985).¹ Two points are illustrated by this figure. First, acuity is low at birth and develops steadily during the first year. Indeed, grating acuity during the neonatal period is so low that these children would 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. We will discuss the optical, receptor, and neural factors that determine grating acuity as a function of age in the next section.

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. Indeed, the ratio of adult divided by 8-week vernier acuity is significantly greater than the corresponding ratio for grating acuity. A similar finding has

¹Forced-choice preferential looking is a behavioral technique that relies on infants' tendency to look at the more complicated of two visual targets (e.g., Teller, 1979). The infant is shown two targets, usually side by side; one side contains the signal (for example, a grating) and the other side contains the blank (a uniform field). An adult observer, who does not know which side contains the grating, makes a forced-choice judgment indicating the side he or she believes contains the grating. It is assumed that the observer will be able to judge the correct side at a greater than chance rate when the target is visible to the child. *Visual-evoked potential* is an electrophysiological technique that relies on the fact that the components of the EEG can be driven by a time-varying visual stimulus (e.g., Norcia & Tyler, 1985). The potential is recorded at the scalp. With modern signal processing techniques, the evoked potential can be recorded quite reliably in a short period of time. It is assumed that a recordable potential will be obtained when the target is able to stimulate the visual cortex. *Optokinetic nystagmus* is a behavioral technique that relies on the a reflexive eye movement that is elicited when the infant is presented repetitive pattern that moves in one direction. The eye movement consists of a slow phase in which the eyes move at about the same rate as the pattern and a fast phase in which the eyes rotate rapidly in the opposite direction. It is assumed that the child will elicit OKN whenever the pattern is visible.

emerged from VEP measurements of vernier and grating acuity (Wesemann, Norcia, & Manny, 1996). 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), but none has been confirmed by empirical observation.

Contrast Sensitivity

The contrast sensitivity function (CSF) represents the visual system's sensitivity to repetitive striped patterns; these patterns are generally sinusoidal gratings (a series of stripes with a sinusoidal variation in luminance). Before discussing research on the development of contrast sensitivity, it is useful to describe in more detail why such measurements have played an important role in the study of infant spatial vision. More rigorous discussions of this topic can be found in Banks and Ginsburg (1985) and Wandell (1995).

The utility of contrast sensitivity measures derives from linear systems analysis, an engineering technique that has played a crucial role in the analysis of a wide range of physical and biological systems. In this approach, the system under examination is thought of as a black box with an input and output. The aim is to characterize the box so that the output can be predicted for any input. In the case of visual perception, the goal is to predict the appearance (the output) for any stimulus (the input).

Linear systems analysis is based on Fourier's theorem which states that any two-dimensional, time-invariant visual stimulus can be exactly described by combining a set of sinusoidal gratings. Such gratings are specified by four parameters: spatial frequency (which is the number of pattern repetitions, or cycles, per degree of visual angle), orientation (which refers to the grating's tilt to the left or right of vertical), phase (which is the grating's position with respect to some reference position), and contrast (which is related to the difference between maximum and minimum intensities of the grating). Fourier's theorem implies that even a complex, two-dimensional visual stimulus, such as the picture of a face, can be described exactly by the combination of a set of gratings of various frequencies, orientations, phases, and contrasts.

For linear systems (technical descriptions are given in Banks & Ginsburg, 1985; Wandell, 1995), one can characterize the system's output to any stimulus by first characterizing its output to sinusoidal gratings of various spatial frequencies. In transmission through the system, the

contrast and phase of a sinusoidal grating can be altered; thus, one must estimate the input-output relationships for both contrast and phase in order to characterize the system in general. As we will see, infant work has focused to a large degree on the contrast response even though there is evidence that infants' phase response is quite immature, too.

The contrast response of the visual system is indexed by measuring the contrast sensitivity function (CSF). This function represents the minimal contrast required to detect a sinusoidal grating at different spatial frequencies. The CSF of an adult with good vision under typical indoor lighting conditions is shown in Figure 3.2. The x-axis of this plot is spatial frequency which corresponds with the number of stripes (or cycles) per degree of visual angle. (The grating pattern is becoming increasingly finer with increasing values along the x-axis.) The y-axis is contrast sensitivity which is the reciprocal of the contrast of the grating at detection threshold. (The grating pattern is becoming increasingly lower in contrast with increasing

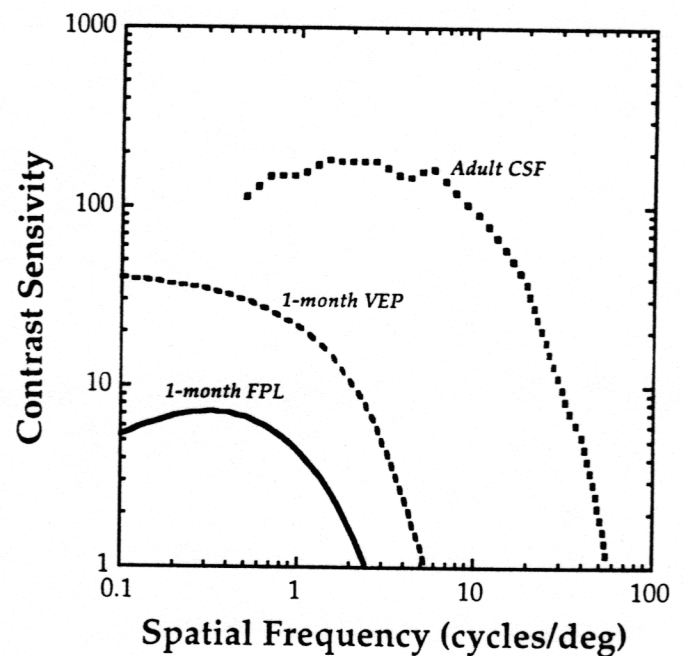


Figure 3.2 Adult and 1-month contrast sensitivity functions (CSFs). Contrast sensitivity (the reciprocal of stimulus contrast at threshold) is plotted as a function of spatial frequency (the numbers of grating cycles per degree of visual angle). The upper dotted curve is an adult CSF that was measured psychophysically. The lower solid curve is the average of 1-month CSFs, measured using forced-choice preferential looking (Banks & Salapatek, 1978). The middle dash curve is the average of 1-month CSFs, measured using the visual-evoked potential (Norcia et al., 1990).

values along the y-axis.) The curve represents the contrast sensitivities at each spatial frequency; combinations of spatial frequency and contrast that fall below the curve are visible and those that fall above are invisible. The adult CSF is bandpass with a peak sensitivity at 3 to 5 cycles/deg, 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 1/2% brighter than the dark stripes. At progressively higher spatial frequencies, sensitivity falls monotonically to the so-called high-frequency cutoff at about 50 cycles/deg; this is the finest grating an adult can detect when the contrast is 100% and it corresponds with the person's grating acuity. At low spatial frequencies, sensitivity falls as well, although the steepness of this fall-off is quite dependent on the conditions under which the measurements are made.

In summary, gratings of medium spatial frequency pass through the visual system with minimal attenuation; gratings of low and high frequency are attenuated more. Before discussing infant contrast sensitivity, we consider the optical, receptor, and neural factors that limit contrast sensitivity and grating acuity in adults.

The adult CSF in Figure 3.2 is typical for good lighting, foveal fixation, sufficiently long stimulus duration, and a well-focused eye. If the illumination is decreased, the function shifts downward and to the left (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). We can understand the high-frequency falloff of the adult's CSF by examining the optical, receptor, and retinal processes involved in spatial vision. The characteristics of these same processes also allow an understanding of how contrast sensitivity changes with illumination, the part of the retina being stimulated, and the focus of the eye. This understanding has been obtained by capitalizing on the fact that the early stages of vision can be modeled 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. Considerable information is lost in these early stages of the visual process. Indeed, 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 (including, of course, grating acuity) 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 high spatial frequencies (Banks et al., 1987; Pelli, 1990) and so has the loss that accompanies errors in the eye's focus (Green & Campbell, 1965). Given the emerging understanding of the optical, receptor, and neural mechanisms that determine contrast sensitivity in adults, the past decade has seen a number of attempts at using similar techniques to understand the development of contrast sensitivity in human infants.

Figure 3.2 also displays 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 in this area of research. First, contrast sensitivity (and grating acuity) in young infants is substantially lower than that of adults and the disparity diminishes rapidly during the first year. Second, measurements with the visual-evoked potential typically yield higher sensitivity (and acuity) estimates than do behavioral techniques.

One way to index the development of contrast sensitivity is by the lowest detectable contrast at the peak of the CSF. Contrast sensitivity at the peak of the function develops more rapidly during the first year than does visual acuity (Norcia et al., 1990). With evoked potential measurements, peak sensitivity approaches adult values by 3 months of age. Behavioral measurements exhibit a slower developmental time course.

One would think that the anatomical and physiological causes of the striking functional deficits observed during the first few months of life would have been identified, but the specific causes are still debated. Some investigators have proposed that one can explain the low contrast sensitivity and grating acuity of neonates by an analysis of 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). Let us review briefly the development of the eye and retina because large ocular and retinal

changes occur over time and they must have profound effects on the ability to see spatial patterns.

The eye grows significantly from birth to adolescence, most of the growth occurring in the first year. For instance, 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 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-deg 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 the newborn had the retina and visual brain of an adult, one would expect their visual acuity to be about 2/3 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 to 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.² 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 adult-like (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). For example, a person with a myopic refractive error (near-sightedness) can focus the eye to form a sharp retinal image for near targets, but cannot focus the eye for distant targets. Hyperopic (far-sighted) refractive errors are common in infants (Banks, 1980a; Howland, 1982). Astigmatic refractive errors (a condition in which the eye cannot be focused simultaneously for perpendicular stimulus orientations) are also common (Banks, 1980a). Infants also 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, receptor and post-receptor processes must. The retina and central visual system all exhibit immaturities at birth (Banks & Salapatek, 1983; Hendrickson, 1993; Hickey & Peduzzi, 1987; Yuodelis & Hendrickson, 1986), but there are particularly striking morphological immaturities in the fovea, particularly among the photoreceptors.

The development of the fovea is dramatic in the first year of life, but subtle morphological changes continue until at least four 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 deg at maturity. Moreover, the individual cells and their arrangements are very different at birth than they will be later on. For example, 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 that is composed of photoreceptors. The most dramatic histological differences, however, are the sizes and shapes of foveal cones. To illustrate, Figure 3.3 shows high-power micrographs of the fovea at birth, 15 months, and adulthood. In each panel, an individual cone photoreceptor is outlined for clarity. The cones' outer segments are labelled OS; the inner segments are just below the outer segments.

In mature cones, the inner segment captures light, and through waveguide properties, funnels it to the outer segment where the photopigment resides. As the light travels down the outer segment, there are several opportunities to

²The optical transfer function is the ratio of contrast in the retinal image divided by the contrast in the stimulus as a function of spatial frequency. Thus, it represents the degree to which the optics of the eye "pass" information from the stimulus to the retina. A ratio of 1 means that the retinal image contrast is the same as the stimulus contrast and therefore that the optics of the eye pass the stimulus without loss of contrast. A ratio of 0.5 means that the contrast is reduced by a factor of two in being transmitted through the eye's optics.

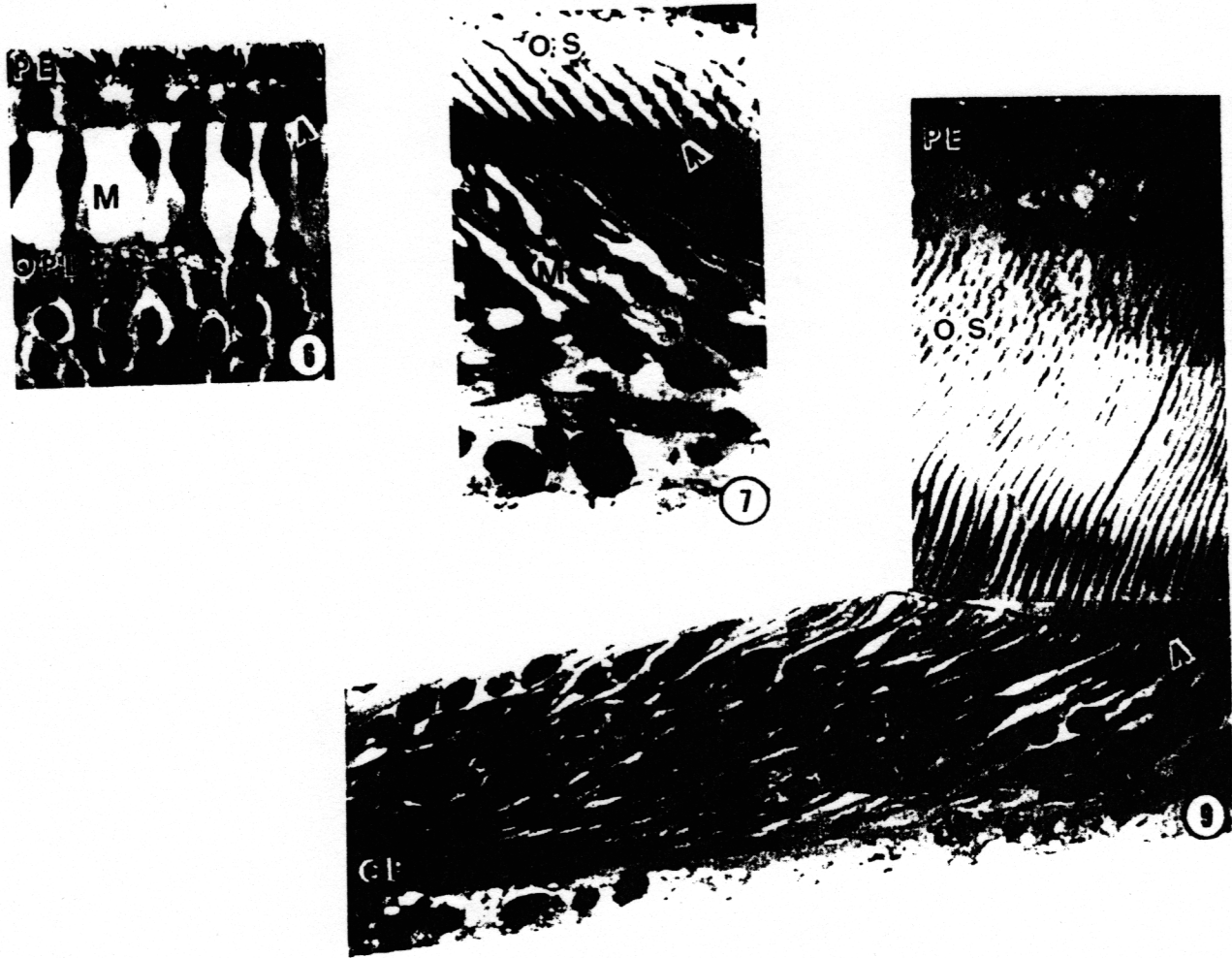


Figure 3.3 The retina near the center of the fovea at birth (#6), 15 months (#7), and adulthood (#9). The magnification is the same in each panel. An individual cone photoreceptor is outlined for clarity in each photograph. The outer segments of the photoreceptors (which contain the photopigment) are labeled OS, and the inner segments (which capture incoming photons) are just below the outer segments.

be caught by and react with photopigment molecules and thereby create visual signals that are sent through retinal circuits to the central nervous system. The micrographs reveal striking differences between neonatal and adult foveal cones. Neonatal inner segments are much broader and shorter. The outer segments are distinctly immature, too, being much shorter than their adult counterparts. All of these shape and size differences render the newborn's foveal cones less sensitive than the adult's (Banks & Bennett, 1988; Brown et al., 1987).

In order 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. Indeed, 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 each photon absorbed in newborn cones. Similar estimates were obtained by Wilson (1988, 1993). Clearly, 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 (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/deg, 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, 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. Indeed, 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). Brown (1993) has speculated that neonates' contrast sensitivity and grating acuity are actually better with peripheral than with foveal viewing, but this conclusion rests on unlikely assumptions about the connections between newborn peripheral cones and retinal neurons (Banks et al., 1991; Candy, Banks, Hendrickson, & Crowell, 1993). There is also some evidence that suggests that neonates' best acuity and contrast sensitivity is obtained with foveal stimulation. Lewis, Maurer, and Kay (1978) found that newborns could detect a narrower light bar against a dark background when it was presented in central vision rather than in the periphery. Allen, Tyler, and Norcia (1989) showed that VEP acuity is higher in central than in peripheral vision in infants as young as 8 weeks. Spinelli, Pirchio, and Sandini (1983) came to a similar conclusion. These observations suggest that the newborn contrast sensitivity and acuity estimates are manifestations of foveal and parafoveal processing

rather than peripheral processing, but more direct experimental evidence, including the recording of eye position, is needed to demonstrate this conclusively.

An important question that will be pursued vigorously in the next decade is what factors not considered in the above-mentioned 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), inefficient neural sampling (such as lack of appropriate cortical receptive fields for detecting sinewave gratings), poor motivation to respond, and so forth.

Pattern Discrimination

As mentioned earlier, the motivation for examining the development of contrast sensitivity comes from the fact that one can in principle use such measurements in combination with linear systems analysis to predict the visibility of a wide variety of patterns. Recall also that the basic stimuli involved in linear systems analysis can vary in spatial frequency, contrast, orientation, and phase. Research on infant vision has yielded a great deal of information on how contrast thresholds vary with spatial frequency (e.g., Atkinson et al., 1977; Banks & Salapatek, 1978; Norcia et al., 1990). There has been considerably less work on the ability of the immature system to discriminate stimuli that differ along these basic dimensions of pattern. Here we review briefly what little evidence exists concerning infants' ability to discriminate visual stimuli differing in contrast, orientation, and phase. To our knowledge, there have been no studies that bear directly on the ability to discriminate stimuli differing in spatial frequency.

The ability to discriminate on the basis of contrast differences is typically measured by presenting two sinusoidal gratings of the same spatial frequency, orientation, and phase, but differing contrasts. In adult experiments, the subject 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).

Contrast discrimination has also been measured in human infants. Six- to 12-week infants require much larger contrast increments than adults when the common contrast is near detection threshold; at high common contrasts, however, infants' discrimination thresholds approach 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).

The ability to discriminate patterns differing in orientation is typically measured by presenting two gratings of the same spatial frequency and contrast, but differing in orientation (e.g., vertical vs. horizontal). In adult experiments, one typically measures the smallest difference in orientation (expressed in degrees) that can be reliably discriminated. For high-contrast gratings and lines, adult observers can discriminate orientation changes of less than 1° (Thomas & Gille, 1979; Westheimer, 1981).

Sensitivity to patterns that differ in orientation has been measured in human infants using behavioral and electrophysiological techniques. Slater and Sykes (1977) reported that newborns could discriminate horizontal and vertical gratings. However, Braddick (1993) and others noted that the discrimination could have been based on differences in the perceived sharpness of the two stimuli because a significant proportion of newborns have astigmatic refractive errors (Howland & Sayles, 1985; Mohindra et al., 1978) that cause horizontal contours to be defocused relative to vertical contours (or vertical relative to horizontal). Subsequent work by Slater and colleagues (1988), however, showed more persuasively that newborns can discriminate contours differing in orientation by 90° . Other behavioral and electrophysiological work suggests that the precision of orientation discrimination improves greatly during the first few months of life (Braddick et al., 1986; Hood et al., 1992). One suspects that the immature visual system is significantly poorer at discriminating patterns differing in orientation; if so, the ability to discriminate complex visual patterns must assuredly be compromised.

Simple spatial patterns such as gratings can also differ in their spatial phase. In this context, spatial phase refers to the relative position of the spatial frequency components (the sinewave gratings) of which the pattern is composed (Piotrowski & Campbell, 1982). The importance of spatial phase is evidenced by the fact that manipulations of the phase information in a spatial pattern greatly affect 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, 1991; Rentschler & Treutwein, 1985).

To the authors' knowledge, there has only been one study of infants' ability to use phase differences to discriminate spatial patterns. Braddick, Atkinson, and Watam-Bell (1986) presented periodic patterns composed of different spatial frequency components. When the components were added in one phase relationship, the resultant was a squarewave 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 had been altered. As has been reported many times previously, 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 came rather than the pattern from which the contrasts came (Oppenheim & Lim, 1981; Piotrowski & Campbell, 1982); stated another way, the hybrid pattern that appears most face-like 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. Newborn's preferences, however, preferred the hybrid that contained the phases of the lattice and the contrasts of the face. One possible interpretation of this finding is that newborns are relatively insensitive to spatial phase, but other interpretations are possible (Badcock, 1990; Morton, Johnson, & Maurer, 1990).

The observation that young infants seem relatively insensitive to variations in spatial phase is extremely important. If it is 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).

As we have seen in the discussions of visual acuity, contrast sensitivity, and pattern discrimination, the infant visual system undergoes a dramatic change during the first few months in the ability to detect, partition, and discriminate spatial variations in light intensity coming into the eye. These abilities provide the foundations and limits for extracting information about objects. We now consider the processes by which objects and their properties are perceived.

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. The first component is *edge detection*. Edge detection involves detecting spatial variations in the optical projection. These may be intensity variations in the retinal image caused by a contour that might indicate where one object ends and another object or surface begins. They may also be discontinuities in texture, depth or motion. When we look at information for edges, we find some ambiguities in that visible contours can result from object boundaries but also from other sources, such as shadows. A second requirement, then, is *edge classification*, sorting visible contours into object boundaries as opposed to shadows, textural markings, etc. 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 object-shaped holes.

When early processes have succeeded in producing a map of visible object edges, how close are we to perceiving objects? Not very. Note that in accomplishing boundary assignment the visual system marks visible contours as bounding the surface to one side. Each time this occurs we might place a question mark on the other side. There, another surface passes behind the occlusion boundary. Where do these visible surface fragments go? How do they continue? With what other visible pieces do they link up, and what are the shapes of these linkages? These are the questions of *segmentation* and *unit formation*. A single static image raises many such complexities: more complex yet is ordinary observer motion through the environment, as well as the motions of objects. When motion occurs, the visible

fragments of objects change continuously. If the problems of unit formation can be overcome, we may be able to perceive form, that is, obtain a description of the three-dimensional arrangement of the object in space. Finally, there are perceptible properties relating to object substance: its rigidity or flexibility, surface texture, and so on.

Next we consider what is known about these components of object perception in early development.

Edge Detection and Edge Classification

What information makes edge detection possible? There are several answers, all involving discontinuities across space in some perceptible properties. First, objects tend to be homogeneous in their material composition. Parts of an 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. Texture may come from three-dimensional variations of orientation along the surface or from variations in the reflectance of the material. Another source of information comes from depth gradients. Depth values of visible points of a continuous object will change smoothly, but at object boundaries 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 are illumination changes, shadows, and so on? Similar questions apply to texture, depth, and motion variations.

There is not much direct evidence about infant edge detection and edge classification abilities. It is possible to make some inferences from the literatures on visual acuity and pattern discrimination, however. Object edges are

interesting in terms of their makeup from a linear systems perspective. At an abrupt edge, multiple spatial frequency components of identical orientation will be in phase (i.e., a transition from dark to light or vice versa will be at the same spatial position for the frequency components; Morone & Burr, 1988). Eliminating the high frequency components will reduce sharpness of the edge. For this reason, studies of grating acuity place some absolute limits on edge detection from luminance variations. One implication of newborns' poor acuity relative to adults is that their ability to process object edges must be poorer.

Above acuity thresholds, edge detection may be possible but not guaranteed. The sinusoidally varying luminance patterns used to test acuity, for example, allow adults to detect pattern variation but do not specify clear edges. Positive results in infant visual acuity tests therefore do not indicate whether infants perceive any edges as opposed to gradual variations along a surface.

Early pattern perception would seem to provide a better window into elementary edge detection. If shape of a two-dimensional (2-D) pattern is detected, one might argue, then 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. We noted that a visual pattern may be analyzed into sinusoidal luminance components. An object's edge may trigger responses in a population of cortical neurons sensitive to these components but not be represented as a single pattern feature. In short, different patterns might evoke different neural activity but not perception of edges or forms per se. This possibility is consistent with evidence we considered earlier that infants are somewhat insensitive to spatial phase information before about 8 weeks of age.

Other lines of research indirectly imply that edges and forms are perceived by newborns under at least some circumstances. Slater and his colleagues (Slater, Mattock, & 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 distance-dependent changes in the object's projected size. Shape constancy in this context refers to the perceiver's ability to detect a constant planar (2-D) shape despite variations in its three-dimensional (3-D) slant, for

example, perceiving a rectangle despite the fact that its slant in depth produces a trapezoidal retinal projection.

Later we consider the evidence for size and planar shape constancy. Here we merely note that both would seem to require some boundary perception abilities. It is hard to imagine any way to achieve constancy if the newborn's visual representation stops at V1 with a collection of activations in independent frequency channels. More likely, higher stages of processing function to some degree to localize edges of objects. To achieve constancy, projective shape or size must be obtained. Moreover, the edge must be classified as being an object edge, not a surface marking, if its orientation in 3-D space can be detected. Even boundary assignment might be implied in this case. The objects were placed in these experiments in front of more distant, frontoparallel surfaces. Assignment of the object edges to the planar form rather than the surrounding surface seems to be implied by the detection of 3-D orientation, since the surrounding surface had a different 3-D orientation.

The earliest edge classification and boundary assignment may depend selectively on a subset of information sources available to adults. For adults, surface quality differences, for example, luminance and spectral differences alone can specify object boundaries. As noted by Rubin (1915), an area whose surround differs in luminance and/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 would reach for a box of matches when it was placed on the floor but not when it was placed on a book; instead he would reach for the edges of the book. If the box slid on the book, Laurent would reach for the box. This sort of observation led to three tentative conclusions: (a) A stationary object on a large extended surface (a floor or table) may be segregated from the background; (b) a stationary object adjacent to another stationary object will not be segregated by surface quality differences; and (c) 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. *Heterogeneous* 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-olds 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. In related 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. The 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.

When in development adjacent, stationary objects come to be segregated by means of surface qualities alone, and what causes this information to become effective, remain important questions for further research.

Boundary Assignment

The question of boundary assignment involves the direction in which an edge bounds an object. Most visible object boundaries mark the edge of one object. On the other side of the boundary is another surface or object that passes behind the bounded one. Many 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 a shape rather than a hole is perceived. These two possibilities differ in terms of the direction of boundary assignment.

We noted above that early shape constancy seems to presuppose boundary assignment. If this inference is correct, then 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, 1989; Gibson, Kaplan, Reynolds, & Wheeler, 1969; Shipley & Kellman, 1994). Granrud et al. (1985) studied accretion-deletion of texture with infants of 5 months of age. They reported that infants reached more often to a surface specified to be nearer by accretion-deletion, a result suggesting that both depth order and boundary ownership. This interpretation incorporates previous findings that infants reaches tend to be directed toward object boundaries and to the nearest object in an array (von Hofsten & Spelke, 1985; Yonas & Granrud, 1985). Unfortunately, infants do not attain directed reaching until about 5 months of age, making it impossible to use this informative measure to assess possible earlier registration of boundary direction.

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, blinking the eyes, and raising of hands (Schiff, 1965; Yonas, 1981). Although some of these behaviors may not be unique to perceived approach, evidence supports the notion that some observed responses, especially blinking, indicate defensive behavior (Yonas, Arterberry, & Granrud, 1987). 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 the physical objects in the environment. We can understand the problem in more than one way. One way is to consider the implications of boundary assignment. When we indicated that perceived boundaries bound in one direction, we implied that at each perceived boundary, some unbounded object slips behind and is partly occluded. A more general way to understand the problem is to realize that most of the processing we have so far considered could take place on a two-dimensional representation (or a 2-D representation with observer-relative depths assigned to each point, the "2.5-D sketch" hypothesized by Marr, 1982). But this kind of representation will not support our knowledge of objects and spatial layout. We need to make sense of a world layered in the third dimension, in which most objects are partly occluded by other objects, and more than one object often lies along the same line of sight from the observer.

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 3-D world is projected onto 2-D receptive surfaces and also changes in the optic projections over time as the observer or objects move.

Early analyses of how problems of occlusion might be surmounted emphasized Gestalt principles of organization (Kanizsa, 1979; Michotte, Thines, & Crabbe, 1964; Wertheimer, 1923/1958). Common motion through space, simplicity of overall form, continuity of contours and similarity of surface qualities were all considered influences that could cause separate visible regions to be perceived as connected entities.

Separating Processes in Unity Perception. More recent analyses have separated the information for unity into two categories (Kellman & Shipley, 1991). One is the common motion process first described by Wertheimer (1923/1958): Things that move together are seen as connected. Some more rigorous definition of "move together" is needed. It turns out that the class of rigid motions as

defined in projective geometry, as well as a number of non-rigid 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 labeled the *edge-insensitive process*.

The other process includes in refined form some of the notions embodied in Gestalt principles, especially the principle of good continuation. It has been termed the *edge-sensitive process* because it depends on relationships of oriented edges, whether in stationary or moving arrays (Kellman, 1996; Kellman & Shipley, 1991). Hidden connections between visible areas depend on edge relationships; specifically, they appear to be governed by a mathematical criterion of *relatability* that formalizes the Gestalt notion of good continuation. Informally, relatability characterizes boundary completions as smooth (differentiable at least once) and monotonic (singly inflected). Figure 3.4 gives some examples of relatable and non-relatable 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). Evidence indicates that surface completion in occluded and illusory contexts depend on the same mechanisms (Kellman & Shipley, 1991; Kellman, Yin, & Shipley, 1995; Ringach & Shapley, 1996). Surface quality similarity affects unit formation within constraints established by boundary formation (Grossberg & Mingolla, 1985; Kellman & Shipley, 1991; Yin, Kellman, & Shipley,

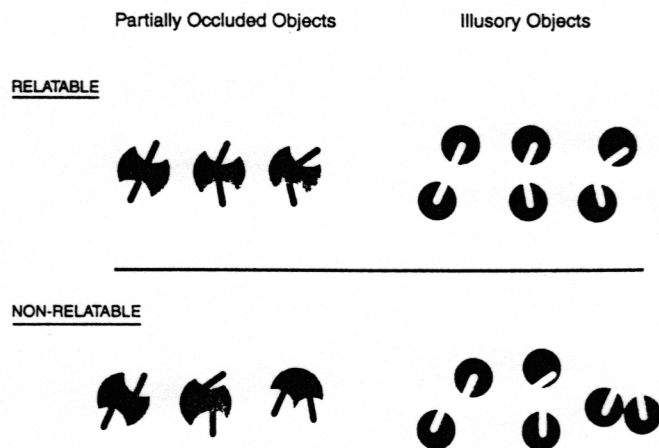


Figure 3.4 Relatable and nonrelatable edges. Connections (occluded surfaces or illusory surfaces between the two visible bars) are seen in the relatable displays, but not in the unrelatable ones.

1995). Surface quality fills in within completed boundaries, and may also spread under occlusion along the extended tangents of visible boundaries (Nakayama & Shimojo, 1992; Yin, Kellman, & Shipley, 1995).

How does unit formation get started? Understanding the processes available in early infancy and subsequent developmental changes is not only an important component of object perception but a possible window into higher visual processes, since unit formation requires contributions from the observer's system that go beyond local stimulus information.

The Edge-Insensitive Process: Common Motion.

Evidence suggests that the edge-insensitive (common motion) process appears much earlier than the edge-sensitive process. 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 generalize habituation more to an unoccluded complete object and less to an unoccluded display containing unoccluded, separate pieces.

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 whether or not 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) are 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 project and/or by changes in convergent eye movements as the object moves. The use of a variety 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 3-D space that preserve 3-D distances among object points. After habituation to a rotation display in which two visible parts rotating around the line of sight, 16-week-olds generalized habituation equally to rotating complete and broken displays (Kellman & Short, 1987a), a pattern that suggests the unity or disunity of the visible parts in the occluded display was seen as indeterminate (Kellman & Spelke, 1983). This pattern also occurred for several combinations of rotation and translation. Only when translation and rotation were combined so as to minimize any point in the motion in which the two visible parts moved in opposite directions did infants show a response pattern suggesting they perceived unity (Kellman & Short, 1987a). It appears that infants' unity perception is governed by a subset of rigid motions in which object points move in the same direction.

Motion in the Edge-Insensitive Process. 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 depends on actual object motion or on certain optical events, such as image displacement, that may be caused by either observer motion or object motion?

Buried 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? This ability is called position constancy: perceiving the unchanging positions of objects in the world despite stimulus changes due to one's own motion. If infants lack position constancy at some early stage of development, then their perceptual world might be quite bizarre. Each movement of the eyes or head might lead to impressions of objects moving as much as when objects really do move. Yet, the standard view on this question for over a hundred years has been that, given the similarities in the optical events, observers must learn to distinguish optical changes given by their own and by object motion

(Helmholtz, 1885/1925; James, 1890). A particular learning process was proposed by Helmholtz. He observed that observer-induced optical changes tend to be reversible. By moving one's head, one can make an object's image displace in one direction and then restore it to its original position by reversing the head movement. When objects move, their displacements are not in general reversible by the observer's action.

If infants cannot distinguish optical changes caused by their own and by objects' motions, then their perception of unity from motion must depend on the optical changes themselves, not uniquely on real motions of objects. The view that infant perceivers cannot distinguish real motion from observer-induced changes is not the only possible one, however. Gibson (1966, 1979) pointed out important differences between the optical consequences of observer and object motion. When an object moves, its relations to other visible objects and surfaces change. When an observer moves, certain relations among visible objects are preserved. It is possible that even young infants possess perceptual mechanisms that distinguish these cases.

Whether motion and stability can be distinguished and whether perceived unity from motion depends on one or both of them are empirical questions. Kellman, Gleitman, and Spelke (1987) took up these questions in a study of 16-week-olds. In each of two conditions, the subject'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. Test displays in each condition had the same motion characteristics as in habituation. Motion perception was assessed by comparing overall levels of looking in habituation and test

periods with earlier studies using similar moving or stationary displays. In those prior studies (with stationary observers), moving displays received markedly higher levels of visual attention.

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 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.

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).

More recent information suggests that unity may not be perceived from motion at the very beginning of life. Slater et al. (1990) replicated Kellman and Spelke's findings at 16 weeks but found different results with newborns. Newborn subjects in their experiment looked more at a complete object after habituation to an occlusion display, a pattern suggesting that the previous occluded display was perceived as containing two separate pieces. Newborns showed the same pattern of results even with larger depth separations between the occluder and the partly occluded parts (Slater, Johnson, Kellman, & Spelke, 1994).

The implications of these findings depend on what limits newborns' unity perception (Slater, Johnson, Kellman, & Spelke, 1994). One possibility is that infants begin life with an incorrect perceptual rule, assigning occlusion edges as object boundaries (Slater, Morison, et al., 1990).

This mistaken rule for parsing the world into objects might be somehow unlearned later, and rules for connecting visible parts based on common motion might be learned.

The other possibility is that newborns do not have adequate capacities to encode the crucial motion relationships. Recent evidence suggests such a limitation. Before 1 to 2 months of age, direction-selectivity of cells in visual cortex seems to be lacking, as indicated by both behavioral and electrophysiological tests (Johnson, 1990; Wattam-Bell, 1991, 1992). When a newborn views moving areas in an occlusion display, motion may be detected, but the common motion directions of the separate visible parts may not be. This might lead to the visible areas being perceived as separate, bounded fragments. The two accounts make different predictions, however, about what should be observed when directional sensitivity matures. If unity perception from common motion appears when directional sensitivity does, then it would appear that the edge-insensitive process is unlearned, awaiting only the necessary sensory inputs for its operation. Recent data suggest that the unity from motion can be found at 2 months, a finding that would tend to favor the maturational account (Johnson & Aslin, 1995).

The Edge-Sensitive Process: Unity Based on Edge Orientations and Relations. The division of unity perception into edge-insensitive and edge-sensitive process crosscuts the earlier intuitive categorization of dynamic and static information (e.g., Kellman & Spelke, 1983; Michotte, Thines, & Crabbe, 1964). Although the common motion 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. 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 (Kellman & Shipley, 1991) and kinetic illusory contours (Kellman & Cohen, 1984). In contrast to the perception of unity from common motion, unity from relationships in static displays does not appear during the first half year of life (Kellman & Spelke, 1983; Schmidt & Spelke, 1984; Slater 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.

The ineffectiveness of edge relations in specifying object unity has been found as late as 6 months of age (Bertenthal, Campos, & Haith, 1980; Schmidt & Spelke, 1984; Spelke, Breinlinger, Jacobson, & Phillips, 1993). Converging evidence comes from studies of occlusion and studies of illusory contours. For example, infants of 7 months, but not 5 months, appear to be sensitive to static and kinetic illusory contour displays (Bertenthal et al., 1980; Kaufmann-Hayoz, Kaufmann, & Walther, 1988).

Maturation, learning or some combination are the possible explanations for the later emergence of perceived unity from edge relations. Granrud and Yonas (1984) suggested that a number of 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, Yonas, Sargent, & Grant-Webster, 1993). It is possible that edge-sensitive unity perception might accompany this development. 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 boundary 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, Peterhans, & Baumgartner, 1984).

These observations are suggestive not conclusive. A clearer understanding of the roles of learning and maturation in the operation of the edge-sensitive process awaits further investigation.

Perception of Three-Dimensional Form

Knowing the functional possibilities of an object often depend on perceiving its form. Representations of form are also primary in object recognition. There are many levels of form—local surface topography, the two-dimensional projection of an object seen from a stationary vantage point and 3-D form, to name a few. Arguably, it is the 3-D forms of objects that are most important in human cognition and behavior. Whereas the particular 2-D projection from an object varies with the observer's position, the object's arrangement in 3-D space does not. Perceiving the unchanging object given changing optical information constitutes the important ability of *shape constancy*.

The origins of 3-D form perception have been disputed by perceptual theorists for several centuries. Adults perceive 3-D form perception in several ways, each of which suggests a different account of the development of 3-D form perception (Kellman, 1984). For example, 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 3-D form is a collection of 2-D views gotten from different vantage points, with any single view recalling the whole collection to mind (e.g., Mill, 1865/1965). On this account, 3-D form would develop 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 3-D form. 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 2-D views into 3-D objects make opposing developmental predictions. On the Helmholtz/Brunswik account, the rules must be acquired from many 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.

Only a few decades ago, a new and different analysis of 3-D 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 (Ullman, 1979). The idea is that perceived 3-D form results from mechanisms specifically sensitive to optical transformations. Changes in an object's optical projection over time, given by object or observer movement, can be shown by projective geometry to be quite specific to the particular 3-D structure of an object. Several theorists have proposed that human perceivers extract this kind of information using neural mechanisms specialized for this purpose (Gibson, 1966; Johansson, 1970; Shepard, 1984). Such an arrangement would make 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 3-D form involves optical transformations. This dynamic information indicates 3-D 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 3-D form from responses to particular 2-D views was developed by Kellman (1984). When an object is rotated its projection contains optical transformations over time but also might be registered as several discrete 2-D snapshots. A way to separate 3-D form from 2-D views is to habituate infants to an object rotating around one axis and test for recognition of the object (by generalization of habituation) to the same object in a new axis of rotation. For a suitably asymmetrical object, each new axis of rotation provides a different set of 2-D views, but, providing there is some rotation in depth, each conveys information about the same 3-D structure. A remaining problem is that dishabituation by infants may occur either for 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 a novel 3-D 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 3-D form was extracted from optical transformations. When habituated to one of two 3-D 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 indeed the basis of response, or whether generalization patterns might have come from 3-D form perception based on single or multiple 2-D views. In the two control groups, infants were shown sequential static views of the objects taken from the rotation sequences. Two different numbers (6 and 24) of views were used along with two different durations (2 sec and 1 sec per view); in neither static view case, however, were continuous transformations available as in the dynamic condition. Results showed no hint of recognition of 3-D form based on the static views, indicating that 3-D form perception in the dynamic case was based on optical transformations.

Later research showed that this result occurs, also at 16 weeks, with wire frame objects having no surface shading information, a finding that implicates the importance of projective transformations of edges (Kellman & Short.

1987b). Yonas, Arterberry, and Granrud (1987) showed that 3-D form gotten from optical transformations could be recognized when form information was subsequently given stereoscopically. Paradoxically, transfer does not seem to go in the other direction; that is, initial representations of 3-D form do not seem to be gotten by infants from stereoscopic depth information in stationary viewing (see below).

Motion Perspective in Form Perception. The utility of 3-D form perception from dynamic information might be rather limited if infants could perceive only objects that happened to rotate while being viewed. The projective geometry of structure from motion, however, works equally well for a moving observer passing a stationary object as for the rotating object and moving observer. Kellman and Short (1987b) tested whether infants could perceive 3-D form when they were moved in an arc around a stationary object. Different axes of rotation were created by using a single vertical axis, but altering the insertion point on the object. They found the same pattern of results as in the object motion studies: Infants appeared to detect 3-D form as evidenced by their generalization of habituation to the same object in a new rotation and dishabituation to a novel object.

Static Form Perception. Form perception from optical transformations appear to be a basic foundation of human perception. It appears early and depends on complex information, suggesting the existence of dedicated neural mechanisms that map changing 2-D projections onto 3-D object representations. Another reason for looking at 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 3-D form is a construction from stored collections of static views.

Above we described two conditions in which sequences of static views evoked no representation of 3-D form in 16-week-olds. This finding—inability to perceive 3-D form from single or multiple static views—has appeared consistently in research (Kellman, 1984; Kellman & Short, 1987b; Ruff, 1978), using real objects or photographic slides, up to an age of 9 months. The late incapacity with form from static views is perplexing given that adults easily gain 3-D form representations from single or multiple static views of objects. The one situation in which infants show some 3-D form perception from static

viewing involves recognition of 3-D forms which had previously been given kinematically (Owsley, 1983; Yonas, Arterberry, & Granrud, 1987). Perhaps this task of detecting similarity to a stored representation is simpler than developing a full 3-D object representation initially by means of static, binocular views.

Nonrigid Unity and Form. Perhaps it is obvious to say that both the concept and process of 3-D form perception are easiest to understand in the case of objects whose forms do not change, that is, rigid objects. Perception of rigid structure from motion is well understood computationally in terms of the projective geometry relating 3-D structure, relative motion of object and observer and transforming optical projections. Many objects of ordinary experience, however, do not have rigid shape. In a moving person, for example, a point on the wrist and one on the waist do not maintain a constant separation in 3-D space. Nonrigidities may be given by joints, as in animals or people, but also by flexible substances, as in a pillow that whose shape readily deforms. The possibility of perceiving or representing 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 joints and musculature, and so on. 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 non-rigid 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, evidence suggests such rules 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 non-rigid unity and form have been carried out by Bertenthal, Proffitt, and their colleagues (Bertenthal, Proffitt, & Cutting, 1984; Bertenthal, Proffitt, Kramer, & Spetner, 1987; Bertenthal, 1993). 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). Both 5- and 7-month-olds, in contrast, showed poorer discrimination with inverted than upright displays. 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 non-rigid motion relationships. Detecting and encoding motion relations may begin 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).

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

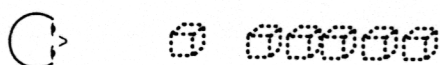
Perception of Size

An object of constant real size projects a larger image on the retina when it is close to the observer than when it is further away. Perception of constant physical size can be achieved by using the same geometry with a different starting point: 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, there may be relational variables that 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 (Gibson, 1950).

Among the most exciting developments in infant perception research over the last decade 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 5 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, and Brown (1990) tested visual preferences for pairs of identically-shaped cubes of two real sizes (5.1 cm or 10.2 cm) at different distances (23–69 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 which appeared at different distances (and varying projective sizes) across trials in the familiarization period. After familiarization, infants were shown the large and small cubes successively on two test trials. Distance was adjusted so that both test stimuli had the same projective size, and this projective size was novel. (The cube that had been presented in familiarization was placed at a distance where 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 3.5 illustrates the arrangements in familiarization and test conditions. Every subject ($n = 12$) 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). In Granrud's study, rates of habituation to sequences of

FAMILIARIZATION



TEST

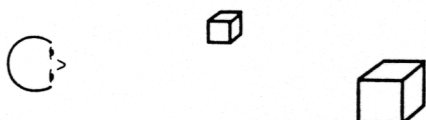


Figure 3.5 The test display in the size constancy experiment (Slater, Mattock, & Brown, 1990). Each infant was familiarized with one object [either a large (10.2 cm/side) or small (5.1 cm/side) cube] at several viewing distances. The test pair consisted of the large and small cube placed at different distances (61 cm and 30.5 cm) to produce equal projective size. Object distances in the test trials were different from those used in familiarization.

objects with varying real size were slower than habituation rates to sequences with the same array of projective sizes, but unchanging physical size.

Research on newborn size perception has not addressed directly the possible information 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. and Granrud 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 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 suggests that binocular convergence is the likely source of egocentric distance information (Kellman, 1995). Estimates of the precision of convergence vary (Aslin, 1977; Hainline, Riddell, Grose-Fifer, & Abramov, 1992; Slater & Findlay, 1975), but recent data (Hainline, Riddell, Grose-Fifer, & Abramov, 1992) and an analysis of the required precision of distance estimates needed to support size discriminations in the Slater et al. and Granrud experiments (Kellman, 1995) support this possibility.

SPACE PERCEPTION

As we have discussed, one of the more remarkable achievements of the human visual system is the ability to discern where one object ends and another begins from visual information alone. By and large, those assignments correspond with the actual boundaries of objects. However, for the perceiver to interact with objects in the visual environment, the visual system must also be able to assign them appropriate 3-D positions relative to the head and body. We now turn to this topic: that is, how does the developing visual system acquire the ability to see the spatial positions of objects in the 3-D environment?

In considering how we are able to obtain knowledge through perception, the philosopher Immanuel Kant concluded that we must bring to the task built-in (a priori) categories of space and time into which experience is organized (Kant, 1781/1902). Psychologically, understanding the origins and development of spatial perception has more nuances, as we will see. 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.

Theoretical controversy about the development of visual space perception has centered on depth perception. When we look at the human visual apparatus, it is relatively easy to see how we pick up 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. This mapping preserves information about adjacency in two spatial dimensions (up-down and left-right). The apparent problem lies in the third (depth) dimension. Nothing in the map immediately indicates how far a ray of light has travelled to get from an object to the eye.

Traditionally, it has most often been claimed that perception of 3-D space is a product of learning (Berkeley, 1709/1963; Helmholtz, 1885/1925). Before the invention of methods to study infants' perception, arguments for this view emphasized the logical problem of recovering three dimensions of space from the two-dimensional retinal image. Learning might overcome the limitation through the storing of associations between sensations of vision and touch. It was assumed that three-dimensionality was somehow more accessible through touch; thus, the problem of seeing in 3-D could be handled by retrieval of stored tactile information when familiar visual input recurred (Berkeley, 1709/1963; Helmholtz, 1885/1925; Titchener,

1910). Piaget's view 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 3-D layout (J. Gibson, 1966, 1979; Johansson, 1970). 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 3-D 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 bases. Anticipating some of these distinctions, we divide spatial perception abilities into four classes of information: Kinematic, stereoscopic, oculomotor, and pictorial. The classification reflects both differences in the nature of information and in the perceptual mechanisms at work in extracting information (Kellman, 1995; Yonas & Owsley, 1987).

Kinematic Information

For guiding action and furnishing information about the 3-D 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 in 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, 2-D cutout of a cat or tiger. To the moving observer, the transforming optic array reveals whether the object is planar or 3-D and furnishes information about relative distance and size. The mapping between the optical transformations and the 3-D 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, for example, objects and surfaces in the scene *deform* (i.e., alter their shapes) contingent on the observer's motion, a unique 3-D 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 3-D space in television, motion pictures and in virtual reality set-ups. 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). On the other hand, adults acquire much kinematic information via 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 or when the infant is carried through the environment or from self-produced head movements.

Motion-carried information is often divided into subcategories, of which we will consider three: Relative depth 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*) was discussed earlier in the section on object perception.

Accretion/Deletion of Texture

In the late 1960s, George Kaplan, James Gibson, and their colleagues discovered a new kind of depth information, a shocking achievement given that depth perception had been systematically studied for over 200 years previously (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 further object, the elements on the nearer surface remain visible whereas those on the farther 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 transformations occur when the motion is given by a moving object rather than a moving observer. This kind of information has been shown to be used in adult visual perception, both to establish depth order and shape, even when no other sources of information are available (Andersen & Cortese, 1989; Kaplan, 1969; Shipley & Kellman, 1994).

Shape perception from accretion-deletion of texture was studied by Kaufmann-Hayoz, Kaufman, and Stucki (1986). They habituated three-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 three months, we cannot tell much about perceived depth order from this study. That accretion-deletion does specify depth order at 5 to 7 months is suggested by a different study (Granrud 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. Both groups showed modestly greater reaching to areas specified as nearer by accretion-deletion than to areas specified as farther.

It has been suggested (Craton & Yonas, 1990) that ordinary accretion-deletion displays actually contain two kinds of information. Besides 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. Evidence suggests that 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 often retract their heads, raise their arms, and blink (Ball & Tronick, 1971; Bower,

Broughton, & Moore, 1970). Not all of these responses, however, indicate perception of an approaching object (Yonas, Bechtold, Frankel, Gordon, McRoberts, Norcia, & Sternfels, 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 1–4 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 blinking 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 that it does so reliably from about one month of age (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 farther object. Comparing two such objects or points defines the classical depth cue of motion parallax. Gibson (1950, 1966) argued that perceptual systems might use relative velocities of many points, that is, that 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 (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 does function quite early, but these suggestions have been based on indirect evidence (Walk & Gibson, 1961; Yonas & Owsley, 1987). Gibson and Walk (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 14-month-old infants were reported by von Hofsteden, Kellman, and Putaansuu (1992). Subjects moved back and forth while viewing an array of three vertical bars. If motion perspective operates, the observer contingent motion should indicate that the middle rod is furthest from the subject. (See Figure 3.6.) 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 0.32 to 0.16 deg/sec 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. In other words, the results do not show that the optical changes were taken to indicate depth. It is interesting that the experiments with these contingent optical changes found sensitivity to velocities an order of magnitude below those found in studies of motion thresholds, using noncontingent motion and stationary observers (see below). Further research is needed, however, to determine whether this enhanced sensitivity results from encoding the relative motions into depth relations via motion perspective.

Stereoscopic Information

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 available 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 (binocular disparity) is only 5 to 15 sec of arc (Westheimer & McKee, 1980). A 5 sec disparity would translate into detection of a 1.4 mm depth difference between two objects at a distance of one meter. A prerequisite for precise computation of disparity 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. Points at roughly the same distance as the fixated point will project to corresponding retinal locations, thus, having the same angular separation and direction from the fovea on each of the two eyes.³ Points more distant than the fixation point will have *uncrossed disparity*. The visual direction of such a point will be more to the

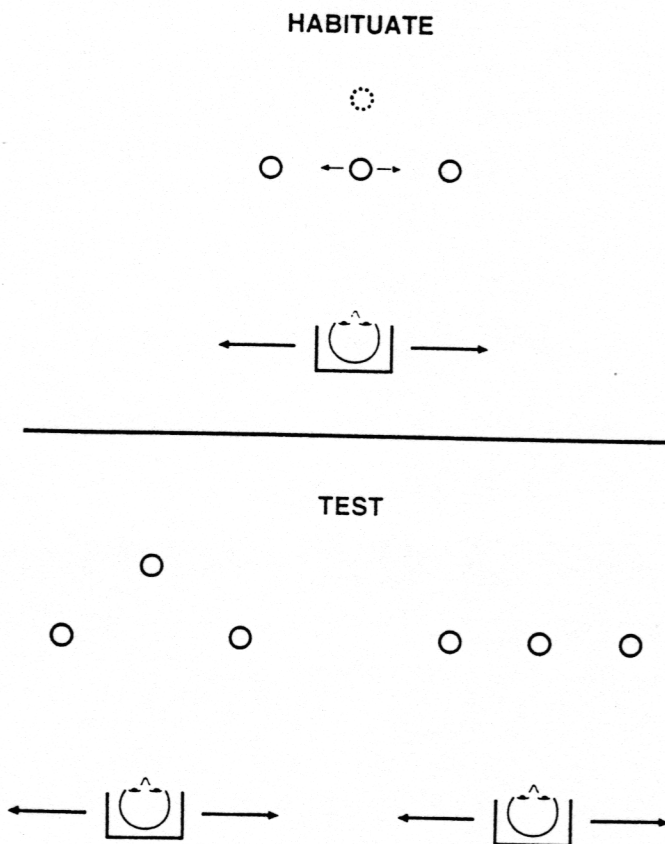


Figure 3.6 Displays used in motion parallax experiment (Von Hofsteden, Kellman, & Putaansuu, 1992). *Top*: Moving observers were habituated to a linear array of rods (top view shown) in which the center rod moved in phase with the observer. The dotted line indicates the virtual object specified by motion parallax. *Bottom*: The two test arrays pictured were shown after habituation.

³The positions of objects that stimulate corresponding retinal locations actually lie on a circle that contains the fixation point (the place where the two foveas are directed) and the centers of the two eyes. This circle is called the Vieth-Muller Circle. Objects inside this circle create crossed disparity and those outside the circle create uncrossed disparity.

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 directions of these points will be more leftward in the right eye than in the left.

Development of Stereoscopic Depth Perception

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 it suggests that stereoscopic depth perception arises on average 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 which 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, Birch, & Gwiazda, 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. 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, Birch, and Gwiazda (1980), for example, found that subjects who showed clear preferences for vertical line displays containing horizontal disparity showed no such preferences when the displays were rotated 90 deg to give 34 min of vertical disparity (this condition produces binocular rivalry for adults). Fox, Aslin, Shea, and Dumais (1980) observed that infants did not track a moving object specified by very large disparities which do not signal depth to adults. They found instead that infants reliably looked away from such displays. The different reactions by infants to different magnitudes of disparity might be expected if only some disparities produce perceived depth. On the other hand, the result shows that disparities per se can affect infants' fixation. Other research supports the conclusion that by 4 to 6 months, binocular information affects infants' spatial behavior (Gordon & Yonas, 1976; Granrud, 1986). Granrud's (1986) research suggests that binocular disparity (as opposed to convergence alone) is important: Disparity-sensitive infants showed substantially better reaching accuracy than disparity-insensitive infants of a similar age.

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, Birch, and Gwiazda (1980) reported that thresholds change over 3 to 4 weeks from greater than 60 min to less than 1 min 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 on line. 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. Two forms of evidence suggest that the onset of stereopsis is not dependent on improvements in visual acuity (grating acuity).

First, when both acuity and disparity sensitivity are measured longitudinally in the same subjects, little or no change in grating acuity is found during the period in which stereopsis appears (Birch, 1993). Although this evidence is consistent with the hypothesis that these two aspects of vision are not causally related in development, we should point out that infant acuity and stereopsis tests generally do not have high reliability; obviously, low measurement

reliability would give the appearance of a low correlation between the age-related improvement in acuity and stereopsis when there in fact might be a significant correlation.

Second, a different method pointing toward the same conclusion comes from a study by Westheimer and McKee (1980). Adult subjects 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. Recent reassessments of the development of convergence (Hainline, Riddell, Grose-Fifer, & Abramov, 1992) indicate 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, Birch, & Gwiazda, 1980).

Given the above 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.

Oculomotor Information

Oculomotor information is based on two kinds of muscular adjustments that attune the eyes to targets at different distances. The observer's eyes *accommodate* by changing the thickness of the lens (thereby changing refractive power) to attain a clearly focused image, and the two eyes converge by turning to fixate (i.e., center on the fovea) the same point in both eyes. At least since Berkeley's (1709/1910) *Essay toward a New Theory of Vision*, it has been suggested that information from receptors in the muscles that accomplish accommodation and convergence might provide information about the distance of a viewed target from the

observer. This notion is plausible in that both adjustments are distance dependent. The nearer a viewed target, the greater the thickness of the lens and the turning inward of the eyes needed to achieve sharp focus and foveation respectively.

Accommodation

Research on adult perceivers has produced varied opinions about the status of accommodation as a depth cue. At best it seems to be a weak cue (Hochberg, 1971). For reasons that are somewhat complex (and not particularly relevant here), direct tests of accommodation have tended to produce negative results. Using indirect measures, however, such as the effect of accommodation on perceived size, there is reason to believe that accommodation influences perceived distance when targets are placed no more than 2 to 3 meters from the observer (e.g., Wallach & Floor, 1971).

In human infancy, accommodative responses vary somewhat with target distance but are not very accurate until about 12 weeks of age (Banks, 1980b; Braddick, Atkinson, French, & Howland, 1979; Hainline, Riddell, Grose-Fifer, & Abramov, 1992). No studies, however, have indicated whether accommodation provides depth information for infant perceivers.

Convergence

Some evidence indicates that convergence provides distance information to adult perceivers under at least some circumstances (von Hofsten, 1976; Wallach & Floor, 1971). As with accommodation, the geometry of convergence limits its effectiveness to near space, that is, within 2 to 3 meters from the observer. To equal the same convergence angle difference between two targets differing by 1 cm in depth at about 30 cm from the observer, targets at 3 meters would have to be separated by almost 1.5 meters! Thus, the precision of convergence information drops off rapidly with distance.

Early research on infant convergence suggested that achievement of appropriate convergence by young infants younger than about 5 months may occur but is quite variable (Aslin, 1977; Slater & Findlay, 1975). These assessments may have been limited by a number of methodological difficulties in precisely measuring convergence in infant subjects (Aslin, 1977). Hainline et al. (1992) reported results based on paraxial photorefractive techniques. With targets at varying distances between 25 and 200 cm, infants as young as 26 to 45 days (the youngest

group tested) converged with almost adultlike accuracy. A complex question about these results is what information could produce accurate convergence in infants so young? Binocular disparities cannot be the information for convergence, given that disparity sensitivity emerges later. Convergence in adults can be triggered by accommodation, but for infants, accurate convergence seems to appear before precise accommodation. At least two possibilities remain (Hainline et al., 1992). If only a single target (or few targets) appear in each visual field, foveating the target in each eye may drive convergence. Or, convergent eye movements might occur to maximize correlated firing of separate cortical units driven by the two eyes that are sensitive to similar retinal locations. Available evidence does not permit a choice between these possibilities (Hainline et al., 1992).

Only one study (von Hofsten, 1977) has taken up directly the issue of convergence as depth information in infancy. Using convergence-altering spectacles, von Hofsten found that 5-month-olds' reaching behavior changed appropriately with convergence information. Several lines of indirect evidence suggest that convergence plays a role in early size constancy, as we considered earlier, and in perception of motion and stability (see below).

Pictorial Depth Information

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 utilized 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 3-D 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 such 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 3-D scenes offering information than 2-D representations.)

Ecologically, the pictorial cues to depth are diverse, but a number 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, it is obvious that 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* (Gibson, 1950). If a surface is assumed to be made up of physically uniform or stochastically regular tokens (pebbles, plants, floortiles, 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, simply 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, for example. Misleading cases of pictorial depth information are not too 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 (Yonas, Arterberry, & Granrud, 1987; Yonas & Owsley, 1987). For brevity, we consider only two examples: interposition and familiar size. The developmental course of other pictorial cues that have been studied, such as linear perspective and shading, appears to be quite similar.

Interposition

The depth cue of *interposition*, sometimes called overlap, specifies relative depth of surfaces based on contour junction information. To a first approximation, 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) 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 there were no contour junctions 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 experiment, the interposition display was compared to the indeterminate control display and in a second experiment, the interposition display was compared to the control display having separated areas. In both experiments, 7-month-old infants reached reliably more often to the leftmost ("nearest") part of the interposition display than to the leftmost part of the control displays. Five-month-olds showed some tendency to reach more to the leftmost 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 they are equivocal or negative about its availability at 5 months of age.

Familiar Size

Perhaps the clearest example of learning effects in space perception is 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 perspective, 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 objects unfamiliar to the subjects before the experiment. Two pairs of objects were used. 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 subjects 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 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.

A decade 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. What is not yet clear is what causes the appearance of pictorial depth perception around the midpoint of the first year. That various pictorial cues appear 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). Recent 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 they put it, this result is compatible with the idea that "... pictorial depth perception may have ancient phylogenetic origins, rather than being a product of enculturation." A key to this interpretation is that the timing fits the rough ratio of 1:4 in terms of time after birth in

chimps and humans that fits the maturation of numerous other abilities. (In other words, a function that matures at 4 weeks in chimpanzees 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 advance, 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 or not.

Further research will be 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.

COLOR VISION

The study of the development of color vision has been one of the most active research areas in infant perception during the past decade. Here we set the relevant background to the issues that have been examined, review recent work on the ability to discriminate on the basis of differences in wavelength composition, and review work on the development of color constancy.

Certain psychophysical observations in adults have proven to be strong indicators of the properties of the underlying physiological mechanisms and this is particularly the case in the study of color vision. Even though the experimental paradigms used in color vision may seem obscure, they are generally designed to provide significant insight into underlying mechanisms. For this reason, we devote some time in this section to describing basic features of mature color vision before we review the infant literature.

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 a broad band of wavelengths tend to be less saturated. We will refer to visual discriminations on the basis of differences in hue and/or saturation as *chromatic discriminations* and discriminations on the basis of differences in brightness as *achromatic discriminations*.

What advantage does color vision offer? There is no definitive answer, but chromatic information probably aids object segmentation and recognition in a number of everyday situations. 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). Finally, it can aid the object segmentation process. For example, it can be difficult to determine whether a change in luminance in the retinal image is caused by a shadow falling across a uniform piece of material or is caused by a change in the material. A shadow generally yields a change in brightness without a change in hue whereas a change in material generally yields both. Thus, color vision may allow the perceiver to distinguish changes in the retinal image caused by shadows from other causes.

The first stage of the visual process—the photoreceptors—is the first important stage in color vision. The adult visual system, of course, has four types of photoreceptors, one type of rod and three types of cones. The cones are active under daylight viewing conditions and subservise color vision; rods are active under quite dim illumination. We will consider cones only in the remainder of 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 particular cone types are responsible for the perception of different hues and this is simply 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 infer the wavelength composition of the stimulus. Therefore, the existence of only three cone types imposes a profound limitation and leads directly to the *trichromacy* of adult color vision.

Photoreceptor characteristics cannot be the whole story because the subsequent stages of the visual process must preserve wavelength information to allow 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. Part of the interest in the behavioral study of infants arises from the possibility that they will lead to similar insights concerning the development of color mechanisms. We will return to this point at the end of this section.

Development of Spectral Sensitivity and Hue Discrimination

The most basic question to ask about the development of color vision is: 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 rule out brightness artifacts, one needs to know the relationship between wavelength and brightness for the individual under examination. This relationship is characterized by the *spectral sensitivity function* which plots the reciprocal of light intensity at threshold as a function of wavelength. The spectral sensitivity function manifests the sensitivities of M and L cones; S cones do not contribute to spectral sensitivity.

Infants' spectral sensitivity curve under daylight viewing conditions (favoring cones over rods) has been measured behaviorally and electrophysiologically (Dobson, 1976; Maurer, Lewis, Cavanagh, & Anstis, 1989; Moskowitz-Cook, 1979; Peeples & Teller, 1975; Teller & Lindsey, 1993). Even at 4 weeks of age, sensitivity varies with wavelength in a fashion similar to spectral sensitivity in adults. There is a tendency for infants' sensitivity to be relatively greater at short wavelengths (e.g., violet and blue), but this is probably a simple consequence of the less dense pigmentation of the lens and macula early in life (e.g., Bone, Landrum, Fernandez, & Martinez, 1988).

The general similarity of adult and infant spectral sensitivity curves suggests the presence of normal M and L cones early in life. However, the observation that M and L cones are present is not sufficient evidence that infants can distinguish lights on the basis of wavelength composition. To demonstrate this convincingly, one must show that infants can discriminate on the basis of hue alone. To do so, one must rule out brightness artifacts and two strategies have been successfully employed.

The studies have presented two stimuli differing in hue (e.g., red and green) and looked for a systematic response 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. Oster (1975) and Schaller (1975) used this strategy, but different response measures, to demonstrate hue discrimination in 8- and 12-week 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 will explain it in some detail. They too 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 can discriminate on the basis of hue alone.

Thus, three reports in 1975, using different techniques, provided the first convincing evidence that 8- to 12-week-olds can make chromatic discriminations. Young infants must have at least some rudimentary form of chromatic vision.

Infants less than eight weeks of age do not consistently demonstrate the ability to discriminate stimuli that differ in hue only, but older infants make such discriminations quite reliably (Peeples & Teller, 1975; Teller, Peeples, & Sekel, 1978; Hamer, Alexander, & Teller, 1982; Packer, Hartmann, & Teller, 1984; Varner, Cook, Schneck, McDonald, & Teller, 1985; Clavadetscher, Brown, Ankrum, & Teller, 1988; Allen, Banks, & Scheffrin, 1988). Here we consider three sorts of hue discriminations—Rayleigh, tritan, and neutral-point—because they are particularly interesting theoretically.

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. Peeples and Teller (1975) and Teller et al. (1978) used a neutral-point test to examine 8-week-olds' color vision. They examined both white-on-white luminance discrimination and discrimination of a variety of chromatic targets from white. The colors of the test targets and background are represented in Figure 3.7, 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 symbols. Eight-week-olds did not discriminate yellow, yellow-green, one green, and some purples from white; these are represented by the open symbols. Thus, 8-week-old infants seemed to exhibit a neutral zone running from short wavelengths to yellow and green. Teller et al. (1978) argued from these results that 8-week-olds may have deficient S cones (in color parlance, that they have tritanopia or tritanomalous trichromacy).

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 et al. (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. Allen et al.

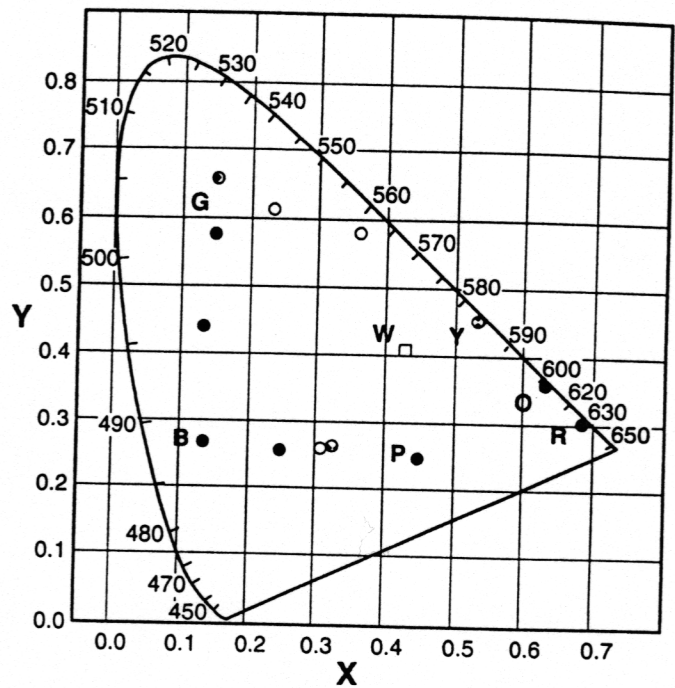


Figure 3.7 The stimuli used in neutral-point experiments (Peeples & Teller, 1975; Teller et al., 1978). Subjects in both experiments were 8-week-olds. The format of the figure is the CIE Chromaticity diagram, which allows one to plot chromatic stimuli differing in hue and saturation. Saturated colors are represented at the exterior of the diagram, and unsaturated colors toward the middle. The right corner of the diagram (labeled 700) 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 (labeled 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.

(1988) and Clavadetscher et al. (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.

Rayleigh discrimination tests involve the discrimination of 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 et al. (1982) and Packer et al. (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. This is 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. also found a significant effect of target size. Twelve-week-olds were able to make Rayleigh discriminations with 4- and 8-deg targets, but not 1- and 2-deg targets. These results imply that early color vision differs from that of color-normal adults perhaps due to an absence of M and/or L cones or to an inability of post-receptoral circuits to compare M and L cone signals.

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.

Several experiments by Adams and colleagues (Adams, Maurer, & Davis, 1986; Maurer & Adams, 1987) appear to show better hue discrimination performance at comparable ages than the studies reviewed above. However, the experiments used between-subjects designs so there was no assurance that luminances were equated for each individual child. Furthermore, they used a more lenient statistical criterion than the studies reviewed above, so direct comparisons of the outcomes are difficult. More recently, however, Adams, Courage, and Mercer (1994) used a within-subjects design and an efficient behavioral procedure to assess neutral-point discriminations in newborns. They reported that the majority of newborns were able to discriminate broadband red from white and that 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). They suggest that efficient procedures might reveal chromatic discrimination capabilities at younger ages.

In sum, there are no rigorous demonstrations that the majority of infants 4 weeks of age or younger make hue discriminations with the possible exception of discriminating red from white. The paucity of positive evidence is consistent with the hypothesis that human neonates are generally color deficient. Younger infants' hue discrimination failures may be due to the absence or immaturity of different cone types or because of immaturities among post-receptoral chromatic channels. Banks and Bennett (1988) have called this the *chromatic deficiency hypothesis*. There is, however, another possibility that was raised

initially by Banks and Bennett (1988) and elaborated by others (Allen, Banks, & Norcia, 1993; Banks & Shannon, 1993; Brown, 1990; Teller & Lindsey, 1993). Perhaps neonates have a full complement of functional cone types and the requisite neural machinery to preserve and compare their signals, but their overall visual sensitivity is simply too poor to allow them to demonstrate their chromatic capabilities. Similarly, older infants may exhibit reliable chromatic discrimination because of increased visual sensitivity. For the purposes of this hypothesis, we define visual sensitivity as the discrimination performance of a visual system limited by optical and photoreceptor properties plus a general post-receptoral loss. This hypothesis has been called the *visual efficiency hypothesis* (Allen et al., 1993) and the *uniform loss hypothesis* (Teller & Lindsey, 1993).

The primary difference between these two explanations of the development of infant color vision can be quantified in the following way. 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) 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 chromatic deficiency hypothesis predicts that the ratio of luminance discrimination threshold divided by chromatic discrimination threshold will decrease with increasing age. That is, luminance and chromatic thresholds may both become lower with age, but chromatic thresholds change more. The visual efficiency or uniform loss hypothesis predicts that the ratio of luminance threshold divided by chromatic discrimination threshold is constant with age. That is, luminance and chromatic discrimination 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 predict the poor Rayleigh and neutral-point discriminations of neonates.

Recently, several investigators have tested the chromatic deficiency and visual efficiency hypotheses empirically: unfortunately, no clear consensus has yet emerged. The trick 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.

Allen et al. (1993) and Morrone, Burr, and Fiorentini (1993) used VEPs and optimal spatiotemporal stimuli to examine luminance and Rayleigh discriminations at different ages. The stimuli consisted of two spatial sinewave gratings of equal contrast: one produced by modulating a saturated green stimulus (thus creating a green/black grating) and the other by modulating a saturated red (creating a red/black grating). The two sinewaves were added in counterphase (the bright red bars of one being positioned in-between the bright green bars of the other). Allen and colleagues and Morrone and colleagues then varied the ratio of red and green luminances in order to measure sensitivity for pure luminance variations and for pure chromatic variations. When the red luminance was zero (or green luminance was zero), the sinewave was an isochromatic green/black (or red/black) pattern with a variation in brightness only. When the red and green luminances were the same, the sinewave was an isoluminant pattern with a variation in hue only. The two groups of investigators measured contrast sensitivities for the various ratios in color-normal adults and in infants. The chromatic deficiency hypothesis predicted that the ratio of luminance threshold divided by chromatic threshold would increase with age and visual efficiency hypothesis predicts that the ratio would be constant with age. As expected from either hypothesis, the lowest thresholds were observed when either the red or green luminance was zero (these are luminance threshold measurements) and the highest thresholds were obtained when the red and green luminances were the same (when the grating was isoluminant). Allen et al. (1993) found that the ratio of thresholds was indeed constant from 3 weeks of age to adulthood, a finding that is consistent with the visual efficiency hypothesis. However, Morrone et al. (1993) reported that the ratio of thresholds increased with age, which is consistent with the chromatic deficiency hypothesis.

More recently, other investigators have examined the same issue using other response measures. Teller and colleagues (Teller & Lindsey, 1993; Teller & Palmer, 1996) used an ingenious OKN technique and obtained data consistent with the visual efficiency hypothesis. Brown, Lindsey, McSweeney, and Walters (1995) used a similar technique with similar results. Kelly, Borchert, and Teller (1995) used a technique similar to Allen et al. (1993) and observed a small increase with age in the luminance/chromatic threshold ratio. Thus, most of the current data is consistent with the visual efficiency hypothesis that young infants' inability to make behavioral discriminations that rely on M and L cones is due to generally poor

visual sensitivity rather than to deficits among chromatic mechanisms *per se*. The causes of the differences in results among some of these studies remain to be determined. Human neonates appear to have functional M and L cones and the post-receptor neural machinery to preserve and compare their signals.

We now turn to tritan discriminations that isolate the functioning of S cones. Varner et al. (1985), Allen et al. (1988), and Clavadetscher et al. (1988) reported that few 4-week-olds and most 8-week-olds demonstrate the ability to make a tritan discrimination. Banks and Bennett (1988) and Banks and Shannon (1993) showed that the visual efficiency hypothesis cannot predict the poor tritan discrimination performance on infants less than 4 weeks of age. This theoretical finding implies that young infants may well have a tritan color defect; in particular, they may have dysfunctional or insensitive S cones or perhaps the post-receptor blue/yellow opponent mechanisms do not develop for a couple of months. This prediction failure does not affect the interpretation of the Rayleigh discrimination experiments because they do not involve S cones.

In summary, the predictions of the visual efficiency hypothesis are consistent with the pattern of Rayleigh and neutral-point discriminations observed by Teller and colleagues. Moreover, research reports from three groups (Allen et al., 1993; Brown et al., 1995; Kelly et al., 1995; Teller & Lindsey, 1993; Teller & Palmer, 1996) have shown empirically that the chromatic information required to make a Rayleigh discrimination is transmitted to the cortex of infants as young as 3 weeks of age. Consequently, discrimination failures observed among the youngest children and for small targets among the 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 are inconsistent with the tritan discriminations observed by Varner et al. (1985), Allen et al. (1988), and Clavadetscher et al. (1988). Therefore, young infants may in fact possess some form of color anomaly involving a deficiency among S cones.

Color Constancy

The wavelength composition of light reaching the eye from a reflecting surface depends not only on the properties of surfaces but also on the light illuminating the surface.

Thus, light reflected from a surface that is perceived as "white" can have a predominance of long wavelengths (e.g., yellow and red) when illuminated by sunlight at noon or can have relatively more short wavelengths (e.g., blue) when illuminated by fluorescent indoor lights. Even though the light reaching the eye can vary in this fashion, we usually do not perceive a significant change in the color appearance of the surface itself. This property of being able to perceive a surface's color despite changes in the spectrum of light illuminating the surface is called *color constancy*. The adult visual system exhibits color constancy for the relatively small variations in illumination that occur with natural lighting. There are numerous theories of color constancy (D'Zmura & Lennie, 1986; Maloney & Wandell, 1986; Marimont & Wandell, 1992), but it is as yet unclear which method or methods is employed by the mature visual system.

Dannemiller and Hanks (1987) and Dannemiller (1989) have examined the development of color constancy. In both cases, infants were presented test objects that were constructed of different sorts of reflecting material. The test objects were also illuminated by lights with different wavelength compositions. Dannemiller (1989) showed that 20-week-olds generalized habituation in a fashion consistent with the presence of color constancy. Specifically, when these infants were exposed to objects under one illuminant, they generalized habituation to the same objects viewed under a different illuminant, but did not generalize habituation to new objects viewed under the same illuminant. In other words, their behavior was consistent with discrimination based on changes in the objects themselves and not with changes in the wavelength composition of the light reaching the eye from the objects. The younger, 9-week-old infants did not exhibit this behavior. They showed a novelty preference when the objects remained the same but were viewed under a different illuminant. These findings suggest that color constancy, at least in a rudimentary form, can be demonstrated in the first half year of life. We hope that more experimental effort is devoted to this fascinating topic.

MOTION PERCEPTION

Processes of visual perception and action seem inextricably linked. To locomote safely through space and respond effectively to events require detailed information about the environment's spatial and temporal structure. Elaborate

systems for acquiring such information exist only in organisms with complex action systems, and in many species, vision is the best source of this information. From these considerations alone, we may suspect that motion plays an important role in visual perception. We may intuit, for example, the relatively modern idea (Gibson, 1966; Johansson, 1970) that seeing while moving—the pickup of information over time—is basic to vision, rather than an annoying complexity added onto the decoding of static snapshots of scenes. Earlier we considered ways in which motions of objects and observers offers high-fidelity information about persisting properties of the environment such as spatial layout and object form. Here our emphasis is on the perception of change: moving objects, their trajectories, speeds, and collisions with surfaces and other objects.

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; Gibson, 1966).

In the case of passive (i.e., nonself-produced) observer motion, relations in optic flow and/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. Earlier we mentioned 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. Subjects 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).

Sensitivity to Motion

Early research on infant visual motion perception found that motion strongly attracts infant orientation and attention (Fantz & Nevis, 1967; Haith, 1983; Kremenitzer, Vaughan, Kurtzberg, & Dowling, 1979; White, Castle, & Held, 1964). In recent years, progress has been made in analyzing the limits and probable mechanisms of motion sensitivity.

Directional Selectivity

The ability to detect motion direction is one of the most basic and important perceptual capacities, but one whose development has not been much studied until recently. 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 deg/sec patterns and 90 days for 20 deg/sec 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, he or she 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 to 15 weeks of age. The younger infants (8–11 weeks) could tolerate only about a .25 deg of visual angle displacement (frame duration was 20 msec) whereas 14- to 15-week-olds showed a d_{max} of about .65. (The value for adults is about 2 deg 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 min of visual angle per second may be detected as motion, as may faster motions up to 15 to 30 deg/sec, at which blurring or streaking occurs (Kaufman, 1974). Estimates of the slowest velocity to which infants respond have varied. Volkman and Dobson (1976) used checkerboard patterns (check size = 5.5 deg) and found a moving display to be clearly preferred to a stationary one by 2- and 3-month-olds for a velocity as slow as 2 deg/sec. One-month-olds showed a weaker preference. Using rotary motion displays, Kaufmann, Stucki, and Kaufmann-Hayoz (1985) estimated thresholds at about 1.4 deg/sec at one month and .93 deg/sec at 3 months, also using a visual preference technique.

More recent studies designed to distinguish various possible mechanisms by which moving patterns might be detected (see below) 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 deg/sec for 16-week-olds and about 2.3 deg/sec for 20-week-olds. For vertically moving gratings, Aslin and Shea (1990) found velocity thresholds of about 9 deg/sec at 6 weeks dropping to 4 deg/sec 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 deg/sec from 2.0 deg/sec, but not from 2.5 deg/sec.

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 0.32 deg/sec, but not 0.16 deg/sec. Subjects 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. Likewise, 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 modulation or flicker rate. This flicker rate depends both on the velocity of the pattern and on its spatial frequency (cycles per deg). Now consider preferential attention to such a stimulus over a non-moving 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 stimulus is 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 was not directly addressed 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 subjects 6 and 12 weeks of age. Evidence for velocity-sensitive mechanisms was also reported by Dannemiller and Freedland (1989). 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.

CONCLUSION

We close with a few general observations. Not too long ago, infant visual perception was a topic dominated mostly by speculation and inference. Over the past thirty years, laboratory research with human infants has shed much new light on the starting points of vision and its development. The developmental courses of basic visual sensitivities to pattern, motion and color are reasonably well understood. Likewise, we have gained some understanding of perception of functionally important aspects of the environment, such as objects, spatial arrangements and events. These achievements have already produced far-reaching changes in our conceptions of both perception and infant development. The idea that reality must be constructed from sensory fragments under the guidance of touch or action (Berkeley, 1709/1963; Piaget, 1954) is incorrect. Meaningful perception begins from innate foundations, and much of its improvement over the early weeks of life comes from maturation of central and peripheral mechanisms.

We have touched upon some generalizations that describe early patterns of visual development. Weakness or absence in neonates of sensitivity to basic stimulus variables, such as orientation, phase and motion direction, suggest immaturity of cortical visual mechanisms, a situation that changes markedly by 6 to 8 weeks (Johnson, 1990; Kleiner & Banks, 1987; Wattam-Bell, 1991). Many of the earliest appearing abilities to perceive objects and space involve information carried by motion, such as the use of optical transformations in perceiving object approach or 3-D form. The primacy of kinematic information may reflect the relatively early maturation of temporal processing or it may indicate the reliance of early perception on information sources of highest ecological validity (Kellman, 1993).

Yet no simple generalization encompasses the nuances of visual development. Even where visual competence begins early, infants' abilities are far worse than adults'. Refinements of various abilities follow different time courses, paced by particular courses of maturation. Some abilities, such as pictorial depth perception and 3-D form perception from static views, do not appear at all until the second half-year of life. Their origins remain unclear and may involve learning.

Further progress in understanding the characteristic pace and sequencing of visual abilities will require a deeper understanding of processes and mechanisms. One can look upon the state of research over the past several decades as a highly successful descriptive phase in infant perception. We know when many abilities emerge, what precision they have and what information they depend on. Testing hypotheses about the use of specific perceptual computations and how these are carried out neurally stand out as challenges for future research.

ACKNOWLEDGMENTS

We thank Bob Siegler for helpful comments.

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