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The Development of Visual Surface Perception: Insights Into the Ontogeny of Knowledge

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The more the eyes have seen, the more the mind sees.
—Bernard de Fontenelle

William James (1890/1950) described the task of psychology as "looking into our minds and reporting what we there discover" (p. 185). Although our methods are more advanced today than they were in James' time (his quote described introspection), our goal remains the same: to describe and explain mental activities such as attention, perception, memory, concepts, thinking, and so forth. One important strategy in meeting this goal is to investigate properties of the visual system. Visual and visual-motor areas occupy a large part of the primate cortex (see Fig. 4.1), and it follows that much of our mental activity is visually based. Studies of the visual system have a relatively long history, and much is known about visual processing in a variety of species, including humans (Crick, 1994; Zeki, 1993).

Central to a complete description of the human visual system is an interdisciplinary approach, encompassing empirical work with both humans and other species as well as computational models of visual function. An important part of this description can be found in studies of visual development. Systematic research on visual development in human infants began about 40 years ago, with the pioneering studies of Robert Fantz (1961, 1963). Fantz discovered that infants often show visual preferences, looking longer at some stimulus patterns relative to others. Fantz (1964) also found that infants' interest usually declined with repeated presentations of the same

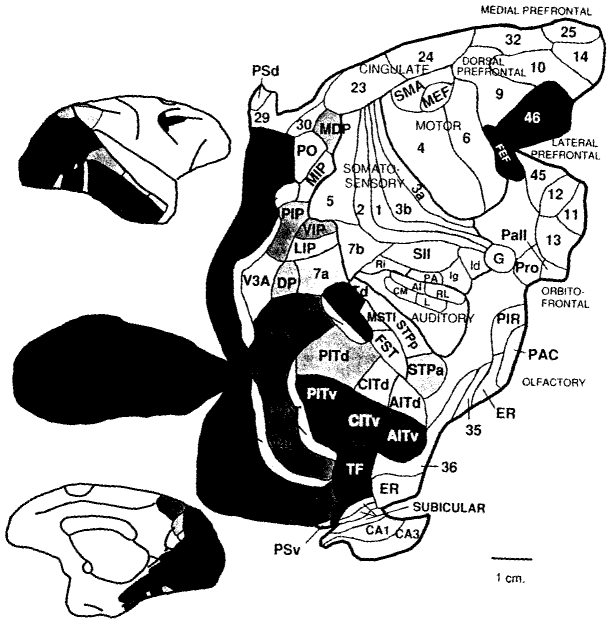


FIG. 4.1. Map of cortical areas in the macaque monkey. Shaded portions indicate visual areas. Top left: outer surface of the right hemisphere. Lower left: inner surface of the right hemisphere. Center right: the surface is "flattened" to show the proportionality of various areas. Note the relatively high ratio of visual to nonvisual areas, underscoring the importance of vision to the animal's functioning. *Note.* From "Distributed hierarchical processing in the primate cerebral cortex" by D. J. Felleman and D. C. Van Essen, 1991, *Cerebral Cortex, 1*, 1–47. Copyright 1991 by Oxford University Press. Reprinted with permission.

stimulus. Subsequent research refined Fantz's methods (e.g., Fagan, 1970) and led to more sophisticated paradigms such as the habituation/dishabituation method. This and related designs capitalize on the tendency of infants to look longer at stimuli that are unusual or unexpected (Spelke, 1985), and their use has revealed a wealth of perceptual and cognitive competencies in infancy (for reviews, see Johnson, 1997; Needham, Baillargeon, & Kaufman, 1997; Slater, 1995). Since that time, there have been important advances in our knowledge of visual function in the first year. One general pattern that has emerged from this research is that low-level visual attributes, such as

contrast, contour, and motion, are often accessible to infants within a few months after birth (see Atkinson, 1984). In contrast, many high-level functions, such as veridical perception of objects' physical properties (e.g., solidity, occlusion, causality, support, inertia, and gravity), seem to emerge later in the first year (see Baillargeon, 1994).

Researchers have often considered the development of object perception and knowledge in the context of the nature–nurture debate: whether a particular ability or skill is rooted in our genetic inheritance or arises from exposure to the environment. Most would agree that the strong form of this choice is unrealistic, and that we are a product of interactions of nature and nurture (Gottlieb, 1997; Oyama, 1985). Nevertheless, the nature–nurture dichotomy remains central to developmental psychology and continues to provide an impetus for debate (e.g., Spelke & Newport, 1998). The present chapter reports a body of research that may shed light on controversies surrounding the contributions of nature and nurture to development. The question under investigation involves the development of perception of partly occluded objects. Evidence from a variety of my studies indicates that, in many displays (generally simple depictions of objects against a background), young infants appear to perceive objects veridically.

My research is geared toward discovering the time course and underlying mechanisms of development of perception of visual surfaces in depth (cf. the "2½ D sketch" of Marr, 1982; Nakayama, He, & Shimojo, 1996). This approach acknowledges surface representation as an intermediate link between low-level visual processing (e.g., coding of image contrast, color, and depth) and high-level visual cognition (e.g., object recognition, physical reasoning, and visuomotor control). An advantage of this approach is that my results dovetail well with (and, in turn, inform) some of what is known about surface and object perception in other primates, whose visual systems are understood more clearly than our own (Felleman & Van Essen, 1991). The approach also makes it possible to sidestep the issue of infants' object knowledge to focus on what might be a more tractable problem: development of the visual representation of surfaces. It will become clear, however, that studies of surface perception may have important implications for theories of the development of object knowledge.

The value of this departure from more traditional questions of cognitive development can be found by considering the nature of visual surface representation. Surfaces appear to be constructed by the visual system from the coding of border ownership (i.e., which boundary belongs to which surface), perceptual completion of hidden surfaces, and placement of surfaces in their respective depth planes (Nakayama et al., 1996). Some of these low- and intermediate-level processes are based on known neurophysiological mechanisms, unlike higher level cognitive processes such as object recognition or physical reasoning. Veridical perception of object surfaces underlies virtually

all of our everyday visual and visuomotor tasks. Furthermore, many rapid, automatic visual functions seem to operate on explicit surface representations (e.g., perceptual segregation and shape recognition of transparent surfaces has been found to occur after only 60-ms exposure; Watanabe & Cavanagh, 1992). Because surface segregation is such a fundamental task, and because the mature visual system seems geared toward rapid surface perception, one might expect veridical surface representation to be available early in human ontogeny. My experiments focus on this question.

The evidence from these surface perception studies seems to deny a strong role for sophisticated object perception skills at birth. However, there is rapid improvement in infants' perception of segregated surfaces, such that before the middle of the first postnatal year, infants appear to respond to many object displays as do adults (although there are some important and provocative differences). The precise mechanisms of development remain unknown, but I discuss computational and neurophysiological models of object perception that may provide insights into this problem.

THE INFANT'S VISUAL WORLD

Infants are born with no experience of patterned visual input. What is the nature of the infant's experience when he or she first encounters the visual world? Acuity, contrast sensitivity, and color sensitivity are poor at birth (Banks & Bennett, 1988; Slater & Johnson, 1998). Nevertheless, the neonate's visual system is organized such that infants are born with certain visual preferences, many of which have been identified: Patterned stimuli are preferred to nonpatterned stimuli, moving to stationary stimuli, high contrast to low contrast, three-dimensional to two-dimensional stimuli, and others (Slater, 1995). There remains disagreement as to the level of functioning of the visual system at birth (Banks & Shannon, 1993; Slater, 1995), but it is clear that infants are born with at least the rudiments of visual skills and organization. How do veridical surface and object perception emerge?

Young Infants' Perception of Object Unity

One way in which infants' surface perception has been investigated is with the use of displays of partly occluded objects. Figure 4.2A depicts a display in which two aligned rod parts undergo common lateral motion above and below a box. To most adults, this display gives rise to an unambiguous percept of a single, partially hidden object behind a second, occluding surface (i.e., adults perceive the partly occluded object's unity). How do young infants perceive an arrangement of surfaces? One possibility is that they may respond

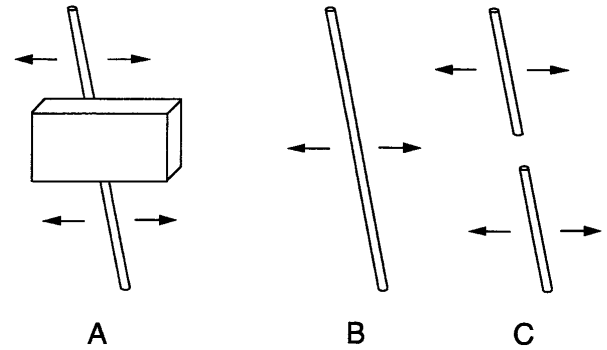


FIG. 4.2. Displays presented to young infants in surface perception studies. A. Rod-and-box display in which two visible rod parts are aligned and undergo common lateral motion. Adults report perceiving a single, partly occluded surface (the rod) behind an occluder (the box). B and C. Complete and broken rod test displays, respectively. After habituation to A, 4-month-old infants often look longer at C than at B, indicating that C is relatively more novel. This implies that a complete rod was perceived behind the box in the rod-and-box display (after Kellman & Spelke, 1983).

as do adults, perceiving two objects, one of which is partly occluded. It is also possible that infants might respond only to those surfaces that are directly visible, in which case three objects would be perceived rather than two. A third possibility is that infants would find such a display ambiguous, perhaps if they are unable to infer the hidden region of the rod, or if there is insufficient visual information in the display to allow an interpretation to emerge. (In fact, each of these possibilities obtains depending on the type of display and the age group.)

Kellman and Spelke (1983) assessed perception of object unity with a habituation paradigm. Infants were first shown a three-dimensional rod-and-box display, such as that shown in Fig. 4.2A, until habituation of looking occurred. The infants then viewed test displays consisting of a complete rod (Fig. 4.2B), or a broken rod, two rod parts separated by a visible gap (Fig. 4.2C). Given the tendency of young infants to prefer novel stimuli relative to familiar stimuli after habituation (Bornstein, 1985), the test display that elicited the most interest was thought to be more novel relative to the habituation display. In general, preference for the broken rod test display indicates perception of the rod's unity in the rod-and-box habituation display. After habituation, the 4-month-olds in this study showed a strong overall preference for the broken rod. This preference was unlikely to be due to an

inherent preference for the broken rod because infants in a control group, who were habituated to a rod-and-box display in which only the top part moved, showed no posthabituation preference. These results provide evidence that 4-month-olds perceive object unity at least under some conditions.

Kellman and Spelke (1983) were interested in the visual cues used by young infants to segregate visible object surfaces; they employed rod-and-box displays to gauge the role of "Gestalt" cues in 4-month-olds' perception of object unity. Gestalt psychologists espoused the view that organization of visual scenes proceeds according to the tendencies of neural forces to maximize the featural goodness of a scene via principles such as good form, common fate, similarity, and good continuation of surfaces and edges in the array (Koffka, 1935). Some past research has favored the hypothesis that young infants are not proficient at using a range of Gestalt cues in perception of object layout. For example, Spelke, Breinlinger, Jacobson, and Phillips (1993) found that, at 9 months of age, infants were only weakly sensitive to similarity, good form, and good continuation in perceiving objects. Kellman and Spelke reported that 4-month-olds did not respond to similarity, good form, and good continuation, but were sensitive to common fate (i.e., common motion). Recently, however, Needham (1998) obtained evidence that 4.5-month-olds attend to similarity in perception of object segregation (for reviews of the development of infants' surface segregation later in the first year, see Needham, 1997; Needham et al., 1997).

Kellman and Spelke (1983; Kellman, Spelke, & Short, 1986) went on to explore more closely the visual cues with which infants perceptually segregated the rod-and-box surfaces by observing 4-month-olds in several conditions, some of which are depicted in Fig. 4.3. The top row of Fig. 4.3 shows object arrangements in which 4-month-olds appeared to perceive the unity of the visible surfaces above and below the occluding box, as indexed by posthabituation preference for the broken object. Note that in addition to lateral motion of the rod (Fig. 4.2A) vertical motion and motion in depth also supported perception of object unity (Figs. 4.3A and 4.3B, respectively). Even if the visible surfaces were dissimilar in appearance (Fig. 4.3C), they seemed to be perceived as belonging to a single object if they moved together. In contrast, the bottom row of Fig. 4.3 shows surface arrangements in which 4-month-olds did not seem to perceive object unity, as indexed by a lack of posthabituation preference. In a stationary display (Fig. 4.3D), or displays in which only the box moved (Fig. 4.3E) or all three surfaces moved together (Fig. 4.3F), unity was apparently not perceived. Thus, common motion of the partly occluded object's visible surfaces, relative to a stationary occluder, appears to specify object unity to 4-month-old infants (Kellman & Spelke, 1983; Kellman et al., 1986). Collinearity of the rod parts (Fig. 4.3D) and surface appearance (i.e., similarity; Fig. 4.3C) seem not to contribute strongly to this process.

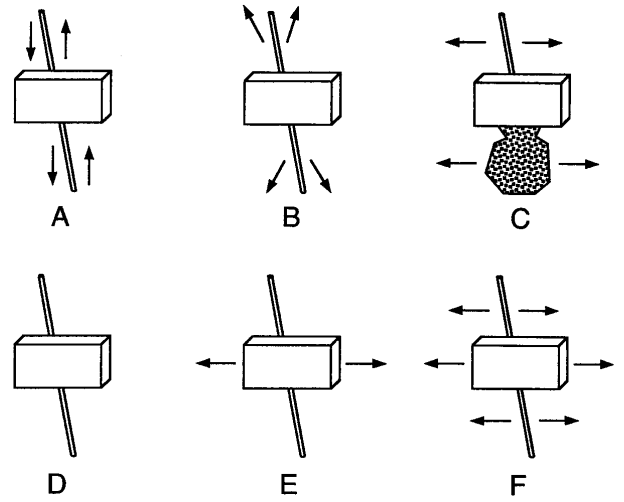


FIG. 4.3. Displays employed assess the visual cues used by 4-month-olds in perception of object unity. In A and B, two aligned rod parts move vertically, and back and forth in depth, respectively. In C, a rod part and a surface dissimilar in appearance undergo common lateral motion. In D, all surfaces are stationary. In E, the box moves in front of a stationary rod. In F, all surfaces undergo common lateral motion. The infants appeared to perceive the unity of the far surfaces only in A, B, and C, suggesting that common motion of two surfaces leading behind a stationary occluder is the primary cue supporting perception of object unity in 4-month-olds (after Kellman & Spelke, 1983).

Visual Information in the Three-Dimensional Rod-and-Box Display

Consider the visual information present in the three-dimensional (3D) rod-and-box display depicted in Fig. 4.2A. Like most real-world scenes, a variety of cues was available that may have contributed to perception of object unity.

Three-Dimensional Depth Cues

The depth difference between the rod, box, and background was specified by self-produced motion parallax (given by small movements of the head), binocular disparity (the slight difference in views to the two eyes of objects and scenes), and oculomotor cues (accommodation of the eyes' lenses and

convergence of the two eyes' lines of sight). By 4 months of age, infants are sensitive to small amounts of motion parallax (von Hofsten, Kellman, & Putaansuu, 1992), and many 4-month-olds demonstrate stereopsis (Birch, Gwiazda, & Held, 1982; Fox, Aslin, Shea, & Dumais, 1980). The contributions of accommodation and convergence to young infants' depth perception are unclear at present, although both systems are operational by 4 months of age (Aslin, 1993).

Accretion and Deletion of Texture

The rod and box were presented against a pegboard background. As the rod moved back and forth, it progressively covered and uncovered the background texture (the pattern on the pegboard). Accretion and deletion of background texture serves as a powerful depth cue for adults (Gibson, Kaplan, Reynolds, & Wheeler, 1969) and infants as young as 3 months of age (Kaufman-Hayoz, Kaufman, & Stucki, 1986).

Common Motion

The two rod parts moved together as the box remained stationary, constituting an example of the Gestalt cue, common fate (Koffka, 1935). We saw earlier that common motion, more so than other cues, was claimed to support young infants' perception of object unity (Kellman & Spelke, 1983; Kellman et al., 1986). This finding is not fully corroborated by my research program (see "Edge Orientation Studies" discussed later) and others (e.g., Eizenman & Bertenthal, 1998).

Interposition of Rod-and-Box Edges

At the point of intersection of the rod parts and the top and bottom edges of the box, occlusion (the rod parts extending behind the box) was specified by *T junctions* (one upright and the other inverted), so called because the box edge formed the top of the T and the rod edge formed the stem. T junctions in visual scenes usually indicate interposition of one surface behind another (Cutting & Vishton, 1995; Gibson, 1950; Nakayama et al., 1996). Sensitivity to interposition and T junctions as cues for depth was reported to emerge between 5 and 7 months of age (Granrud & Yonas, 1984), but younger infants were found not to perceive unity if T junctions specified two rod parts in front of a box, suggesting earlier sensitivity to these cues (Kellman & Spelke, 1983; Slater et al., 1990).

Configurational Information

The rod edges were collinear or aligned. Thus, the configuration of the rod parts' edges was consistent with the connectedness of the rod's visible surfaces. Kellman and Shipley (1991) used the term *relatable* to denote an

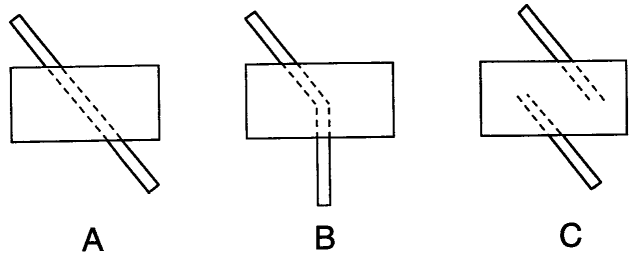


FIG. 4.4. Rod-and-box arrangements illustrating alignment and relatability. Two edges are termed *relatable* if they would meet, behind an occluder, at an angle greater than 90° (here shown by the dotted lines). A. Two rod parts that are both aligned and relatable. B. Two rod parts that are relatable but not aligned. C. Two rod parts that are neither aligned nor relatable. See Kellman and Shipley (1991) for details.

arrangement of partly occluded surfaces in which the edges would meet at an obtuse angle (i.e., greater than 90°) if extended behind the occluder. By definition, if edges are aligned, they are relatable, but not all relatable edges are aligned (see Fig. 4.4). Configuration of object edges and surfaces is an important cue for infants' perceptual segregation.

Surface Appearance (Texture, Luminance, and Color)

The wooden rod was painted black, the wooden box was tan (unpainted), and the pegboard background was white with black dots. Differences in the surface textures, and either luminances or colors, or both, may have contributed to their perceptual segregation by the Kellman and Spelke (1983) 4-month-olds; evidence in support of this possibility is presented later.

Models of Young Infants' Perception of Object Unity

Spelke (1990) noted that any viable mechanism for segmenting the visual array must ascertain the boundaries of adjacent objects, the complete shapes of partly occluded objects, and the continued existence of objects that are no longer visible. Since the Kellman and Spelke (1983) theoretical formulation of infants' perception of object unity, Kellman (1993, 1996; Kellman & Shipley, 1991) has advanced a more precise model of the development of unit formation. Kellman's two-process account proposed that perception of object unity is driven exclusively by common motion in infants younger than 6 months of age. Only a primitive (or edge-insensitive) process is operational at this time, which specifies the unity, but not the form, of the hidden region.

The primitive process does not take account of other potential contributing cues, such as edge orientation. After 6 months of age, a rich (edge-sensitive) process also operates, which takes account of edge orientation and specifies form as well as unity. In addition to the studies discussed previously, Kellman's (1993) model derives support from a recent finding that not until 8 months of age do infants appear to infer the form of the hidden region of a partial occlusion display (Craton, 1996).

Recent research conducted by my colleagues and me indicated that this two-process account does not fully explain young infants' perception of object unity. It appears that in addition to common motion, other kinds of visual information contribute to young infants' veridical object segregation, such as depth cues, illusory contours, edge orientation, surface configuration, and surface color (discussed in the next section). To account for these results, we have proposed a threshold model (Johnson, 1997; Johnson & Aslin, 1996) stipulating that perception of object unity depends on both the visual information available in a particular display and the readiness of the infant to attend to this information (which may vary depending on age). That is, veridical object perception occurs when sufficiency of visual information is matched by efficiency of perceptual and cognitive skills. There does not seem to be a single cue that uniquely supports unit formation. Rather, object unity and other surface attributes appear to be multiply specified to young infants, and performance is highly age-dependent (cf. Eizenman & Bertenthal, 1998; Needham et al., 1997). The model is discussed in more detail in subsequent sections.

Kellman's (1993, 1996) claim that young infants rely exclusively on motion-based cues provided clear predictions about the conditions under which object unity will be perceived in occlusion displays. My initial investigations were motivated by a desire to test some of these predictions, based on the hypothesis that given the richness of visual information in a scene even as simple as a rod-and-box display, infants might make use of a variety of cues in this and other surface segregation tasks. Each cue examined is described in turn in the next section.

All studies described in the next section employed the following methodology. Infants were first habituated to a computer-generated display that depicted a rod behind an occluding (or transparent) box. Infants then viewed two test displays with the box removed, presented three times each in alternation (for six test trials). One test display resembled the habituation display at a proximal level (e.g., the visible rod portions, above and below the box). The other test display resembled the habituation display at a distal level (e.g., what an adult might expect to see if the box were to be removed). Each test display was similar to the habituation display in terms of rod motion and background. Preference for the proximal display (e.g., a broken rod) was taken as evidence that the infants perceived the habituation display in

like manner to adults—that is, as a single surface (the rod) partly occluded by another surface (the box). (In all experiments, a control group was included to assess baseline preferences for either of the two test displays. In no case was such a preference observed in any of our studies.)

TESTING INDIVIDUAL CUES IN YOUNG INFANTS' SURFACE PERCEPTION

This section describes a body of research that has systematically explored 4-month-olds' use of visual cues to perceive surfaces in depth. The research strategy employed the following logic: If a group of infants shows a reliable posthabituation preference for one of two test displays after habituating to a particular occlusion display, this suggests that the infants segregated the displays into their constituent surfaces based on the visual information available (Kellman & Spelke, 1983). By varying this information across conditions, it is possible to establish which cues were and which were not used by young infants in this process, as well as the relative strengths of the contribution of individual cues.

Depth Cues

Three-Dimensional Depth Cues

I began my investigations of infants' surface perception by asking whether three-dimensional depth cues are necessary for young infants' perception of object unity (Johnson & Náñez, 1995). We predicted that we would replicate the Kellman and Spelke (1983) results with two-dimensional displays for three reasons. First, based on Kellman's (1993) two-process account of unit formation, we hypothesized that because common motion was available, 4-month-olds' perception of object unity would obtain in a two-dimensional display. Second, adults perceive apparent depth in two-dimensional displays despite the ability to perceive display elements as coplanar due to lack of binocular disparity (thus precluding the possibility of actual occlusion). Third, not all 4-month-olds would be expected to be sensitive to disparity as a cue for depth (Birch et al., 1982).

Four-month-olds were habituated to a two-dimensional, computer-generated rod-and-box display (Fig. 4.5A). Like the Kellman and Spelke (1983) display, our display contained two rod parts moving left and right, above and below an occluding box, against a textured background. Other details of methodology were as similar to the Kellman and Spelke study as possible. The infants showed a consistent preference for the broken rod after habituation, suggesting that they responded to the apparent unity of the rod parts

FIG. 4.5. Displays used to investigate the role of depth cues in young infants' perception of object unity. A. 2D rod-and-box display with background texture. B. 2D rod-and-box display without background texture. Infants appeared to perceive the unity of the rod in A, but not B, suggesting that depth cues are important in the surface segregation process (Johnson & Náñez, 1995).

in the two-dimensional rod-and-box display. This experiment indicated that three-dimensional depth cues are not necessary for young infants' perception of object unity, and established the feasibility of using computer-generated displays to investigate questions of infants' perceptual segregation of surfaces.

Accretion and Deletion of Background Texture

I went on to ask about the role of another potential depth cue—accretion and deletion of background texture (Johnson & Aslin, 1996). It might seem unclear why one would predict that accretion and deletion of the far (background) surface would affect perception of the unity of the rod's parts behind the near (box) surface. Our rationale was based on the fact that veridical surface segregation involves perception of the relative depths of all display elements, without which perception of object unity may be precluded (Nakayama & Shimojo, 1990; Nakayama, Shimojo, & Silverman, 1989). We reasoned that accretion and deletion of texture might contribute to this process, and we habituated a group of 4-month-olds to a rod-and-box display in which the rod parts moved together but there was no background texture (Fig. 4.5B). The infants preferred neither of the test displays, suggesting that, in contrast to infants who viewed the display with background texture (Fig. 4.5A), these infants were not able to segregate the rod-and-box surfaces effectively perhaps because of an insufficiency of depth cues.

Interestingly, 4-month-olds' segregation of surfaces in the object unity task can occur in the absence of accretion and deletion of texture, as demonstrated by Slater et al. (1990, Experiment 4). Infants in that study viewed real three-dimensional rod-and-box displays against a matte white background and subsequently looked longer at a broken rod than at a complete

rod. It seems likely that the added depth information from three-dimensional depth cues (stereopsis, self-produced motion parallax, and perhaps accommodation and convergence) supported segregation of surfaces in that display.

Edge Sensitivity: The Case of Illusory Contours

Kellman (1993, 1996) argued that infants younger than 6 months of age do not respond to edge information in perception of object unity; that is, young infants are edge insensitive. However, findings of young infants' perception of illusory contours would suggest some degree of edge sensitivity. For example, Ghim (1990) reported that after habituation to a dark square against a light background, 3- and 4-month-olds looked less at an illusory square (Fig. 4.6A) relative to a display in which the inducing elements (the ¾ circles) were arranged in different orientations (Fig. 4.6B).

Many illusory contour displays involve both modal and amodal completion (Petry & Meyer, 1987). *Modal completion* refers to perception of a coherent (but illusory) surface in front of another, whereas *amodal completion* refers to perceptual completion of the far surface. In the case of the illusory square of Fig. 4.6A, perception of the square is an example of modal completion. Perception of four partly occluded circles comprises amodal completion. Ghim (1990) provided evidence of modal completion in the infants she observed. Amodal completion is evident in perception of object unity, which implies completion of the rod's surface behind the box (Johnson & Náñez, 1995; Kellman & Spelke, 1983). Thus, young infants appear to be capable of both kinds of perceptual completion.

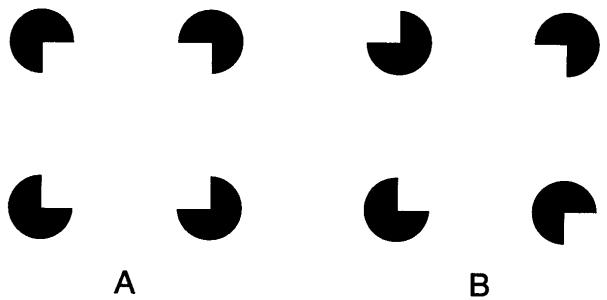


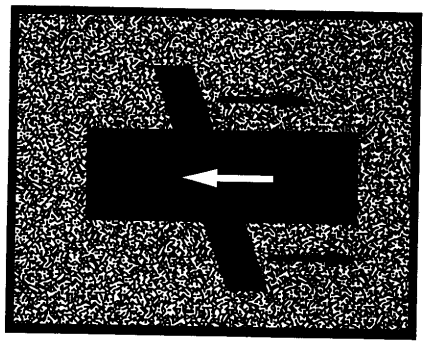
FIG. 4.6. Displays used to explore young infants' perception of illusory contours (Ghim, 1990). Three- and 4-month-old infants appeared to perceive a square shape in A, but not in B, suggesting that edge-sensitive mechanisms are available to young infants.

However, it is unknown whether infants' abstraction of the two-dimensional square shape in Ghim's (1990) study of illusory contours was accompanied by perception of the apparent depth ordering of the individual surfaces (the square in front of the inducing elements), such as reported by adults (Kanizsa, 1979). Indeed, it is unclear whether the infants perceived separate surfaces at all in this two-dimensional display. It is possible that shape perception occurred in the absence of perception of occlusion. To address these concerns, we conducted two studies in which we asked whether 4-month-olds' perception of surfaces in depth could be specified by illusory contours (Johnson & Aslin, 1998). If so, this would imply that operational edge-sensitive mechanisms contribute to processes of both modal and amodal completion in young infants.

In the first study, we showed a group of 4-month-olds a display in which a black rod and black box moved laterally out of phase against a background composed of a random-dot texture (Fig. 4.7A). After habituation to this display, the infants saw test displays consisting of black broken and complete rods and reliably preferred the broken rod. Although the relative depth ordering of the rod and box was not specified in the occlusion display (because there were no T junctions), it appears that the contribution of the illusory contours in the display was strong enough to support perception of the rod parts' unity.

In the second study, we employed a display in which surface boundaries were specified by kinetic illusory contours (illusory contours given by motion; see Kellman & Cohen, 1984). This display consisted of a sparse random-dot texture rod and box presented against a sparse texture background (Fig. 4.7B). Boundaries at the top and bottom edges of the rod parts and box were given by motion shear of nearby surface and background dots (note that there were no texture elements at the edges themselves—thus the edges were not specified by discontinuities in luminance, color, or depth, as is usual in real-world scenes). Boundaries at the left and right edges of the rod parts and box were made available by accretion and deletion of background texture elements as the surfaces moved back and forth. Like the vertical edges, these horizontal edges were not physically specified. After habituation to this display, the infants preferred the broken rod. Therefore, as in the previous experiment, it appears that the available illusory contours provided sufficient information to evoke perception of bounded, segregated surfaces in depth.

These studies confirm the existence of edge-sensitive mechanisms in young infants. Such mechanisms contribute to the detection of surface boundaries that are visually underspecified in processes of both modal and amodal completion. (I recently obtained evidence that infants as young as 2 months of age perceive illusory contours [Johnson, 1998]. Thus, edge sensitivity may characterize even very young infants.)



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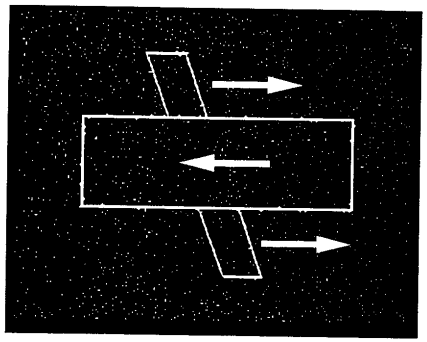

B

FIG. 4.7. Displays used to explore young infants' segregation of surfaces whose boundaries were specified by illusory contours (Johnson & Aslin, 1998). Infants seemed to perceive segregated surfaces in depth in both displays, implying both modal and amodal completion of illusory shapes. (Note: arrows are shown here for illustrative purposes only, as is the outline in B.)

Edge Orientation

We continued our explorations of infants' edge sensitivity with occlusion displays containing surfaces whose edges were misaligned at the point of intersection with the occluder. If young infants are sensitive to edge orientation, perception of object unity might be disrupted under these conditions.

Misaligned Edges

This prediction was tested with a display in which two rod parts, above and below an occluding box, would be misaligned if they were to meet behind the occluder, as seen in Fig. 4.8A (Johnson & Aslin, 1996). Note that although the rod parts were misaligned, they were relatable according to the Kellman and Shipley (1991) criterion (i.e., if extended behind the occluder, they would meet at an obtuse angle). In addition, the rod parts underwent common motion. Thus, both young infants and adults would be predicted to perceive object unity in this display—infants because of common motion and adults because of common motion plus relatability (i.e., adults should perceive relatable edges as connected; see Kellman & Shipley, 1991). After habituation to this display, a group of 4-month-olds viewed broken- and complete-rod test displays. The former consisted of two rod parts that corresponded to the visible portions of the rod in the habituation display (two misaligned, disparate rod parts) and the latter to a connected, bent rod.

The infants demonstrated no consistent posthabituation preference, implying that they relied on edge orientation in perception of the rod parts' unity—in the absence of edge alignment, the infants did not seem to perceive the edges as belonging to a single surface. This study provides further evidence that 4-month-olds are edge sensitive. (Interestingly, the responses of a group of adults who viewed the misaligned rod display cast further doubt on the contribution of relatability to unit formation. Adults were asked to judge whether they thought the rod parts were connected, and the results indicate that they found the display ambiguous with respect to unity.)

Nonaligned Edges

The likelihood that 4-month-olds attend to edge configuration in perception of object unity was corroborated with an occlusion display in which the rod parts were neither aligned nor relatable (Fig. 4.8B), but again underwent common motion (Johnson & Aslin, 1996). Test displays consisted of two disjoint rod parts that corresponded to the visible rod surfaces in the habituation display and a connected, crooked rod. In this case, the infants preferred the complete rod, indicating that the rod parts in the habituation display had been experienced as disjoint objects (as reported by the adults

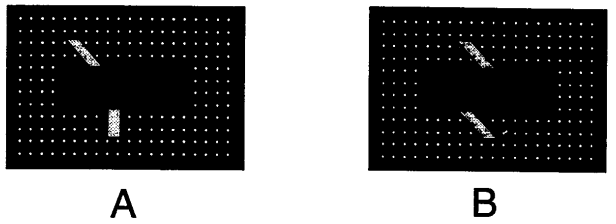

FIG. 4.8. Displays used to gauge the role of edge orientation in young infants' perception of object unity (Johnson & Aslin, 1996). A. Misaligned rod and box. B. Nonaligned rod and box. The results indicate an ambiguous percept of the rod's unity in A, and perception of disjoint objects in B, implying that orientation is fundamental to young infants' perception of the unity of edges leading behind an occluder.

in our experiment). In this case, edge orientation may have contributed even more strongly to the infants' percepts than did common motion.

Smith, Johnson, Spelke, and Aslin (1996) considered an alternative explanation for this finding, asking if the infants' preference for the complete crooked rod (after habituation to the display with the nonrelatable rod parts) may have been due to the presence of novel features not present in the broken rod. Specifically, there were two angles in the complete rod test display. It may have been that the infants who were habituated to the display depicted in Fig. 4.8B looked longer at the complete rod because of these novel features. We tested this possibility with an occlusion display in which the visible rod parts each contained an angle (Fig. 4.9A) and each test display contained four angles (Figs. 4.9B and 4.9C). (We were careful to ensure that, at the intersections of the rod parts and the box, the orientations of the rod parts closely matched those in the nonrelatable rod parts display employed by Johnson & Aslin, 1996.) The infants preferred the complete rod after habituation (replicating Johnson & Aslin, 1996), indicating, again, perception of nonrelatable rod parts as disjoint objects.

In a second experiment, we asked if the addition of three-dimensional depth cues would contribute to perception of the zig-zag rod's unity. Given the cue conflict in the two-dimensional display, it might be that extra information in favor of the rod's placement in a depth plane farther than the box is critical. That is, such placement information would lead the infants to overcome the nonrelatability of the rod parts' edges and thus perceive them as connected. We found that three-dimensional depth cues did seem to effect a change in performance: There was no consistent posthabituation preference (thus, the infants appeared to move from perception of disjoint objects toward perception of unity, although unequivocal evidence of perception of unity was not obtained). We interpreted these findings as evidence for 4-

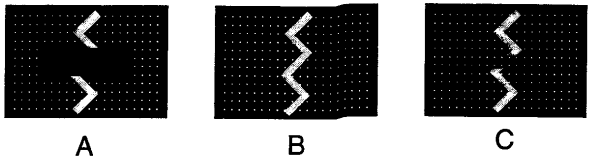

FIG. 4.9. Displays used to further explore the role of edge orientation in young infants' perception of object unity (Smith et al., 1996). A. Rod-and-box display in which the edges of two crooked rod parts are not relatable behind the box. B and C. Complete and broken crooked rod test displays. Note that both test displays contain four angles, and thus it would be unlikely that the presence of angles as a novel feature would attract the infants' attention more to one test display than the other. The infants looked longer at B than at C, suggesting perception of disjoint rod parts.

month-olds' reliance on both edge alignment and depth cues in segregating the rod-and-box surfaces.

The results discussed in this section imply that alignment, rather than relatability, supports both infants' and adults' perception of object unity. When surfaces are not aligned, they are not perceived as unified, even in the presence of cues that might be expected to indicate unity, such as common motion and three-dimensional depth cues. This raises the question of why infants perceived object unity in a display in which the edges of visible surfaces were not aligned (Kellman & Spelke, 1983, Experiment 6), as depicted in Fig. 4.3C. Smith et al. (1996) noted that the outer edges of these surfaces were not aligned, but the orientations of the surfaces were consistent with unity if their major axes were to be smoothly extrapolated behind the occluder. Thus, Smith et al. proposed that axis alignment, rather than edge alignment, contributes to young infants' perception of object unity.

Surface Configuration

Configuration of the Occluder: Integration of Visual Information Over Space and Time

The display used by Smith et al. (1996) contained a cue that might potentially contribute to infants' perception of the rod parts' unity: the global configuration of the rod's surface. The fact that each visible rod part was oriented in two orthogonal orientations may lead an observer to perceive a partly occluded zig-zag shape behind the occluder (see Fig. 4.9A). Nevertheless, the responses of the infants who were habituated to this display argue against the global configuration as contributing in an important way to perception of object unity.

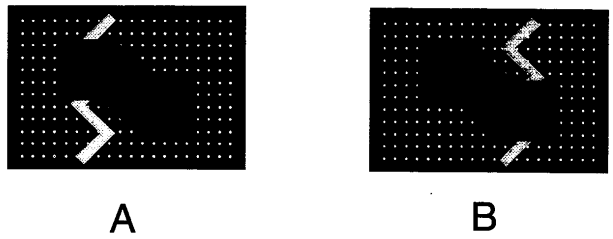

FIG. 4.10. Two frames from a display used to investigate surface (occluder) configuration and young infants' perception of object unity (Smith et al., 1996). In A, the rod is at its far leftmost position as it translates laterally behind the occluder. In B, the rod is in its rightmost position. As the rod moves, the relatability of its edges (and therefore its unity) is revealed over time as the center angles of the rod become progressively visible. The infants looked longer at a broken rod after habituation to this display, indicating perception of the rod parts' unity. This was most likely accomplished via spatiotemporal integration of information for unity.

This does not necessarily mean, however, that infants are unable to take advantage of surface configuration in perception of object unity. Smith et al. (1996) conducted a third experiment in which the shape of the occluder was changed such that any static view of the display revealed nonrelatable edges (as in the first two Smith et al. experiments). However, integration of the outermost views of the rod's translation revealed the oblique alignment of the edges of the crooked rod's center portion (Figs. 4.10A and 4.10B). After habituation to this display, the 4-month-olds in this study looked longer at the broken-rod test display, suggesting that they perceived the rod as connected. This study provides evidence that infants as young as 4 months of age are capable of spatiotemporal integration or integration of visual information across space and time (cf. Arterberry, 1993; Van de Walle & Spelke, 1996).

Configuration of the Partly Occluded Object: The Role of Good Form

In the Smith et al. (1996) first experiment, edge alignment appeared to take precedence over object configuration in specifying unity. Recently, I continued exploring this issue by considering the different kinds of configuration that might be made available in an occlusion display. The Smith et al. zig-zag rod might have been too complex a shape for 4-month-olds to complete when occluded without the extra information imparted by edge alignment revealed over time.

Locally Misaligned Object Edges. The role of good form in young infants' perception of occlusion was assessed with a partly occluded ring, as depicted in Fig. 4.11A (Johnson, Bremner, Slater, & Mason, 1999). Note that at the points of intersection of the ring and occluder, as shown in Fig. 4.11B, the outer tangents of the ring's edges would meet at an angle of approximately 162° if interpolated behind the occluder, as in the Johnson and Aslin (1996) misaligned relatable rod display (Fig. 4.8A). On the basis of the misalignment of these edges, therefore, it would not be expected that 4-month-olds perceive the ring as a unified, coherent object. However, the ring provides additional information for unity from the Gestalt cues of closure and good form (i.e., symmetry and simplicity). Thus, at a local level (the ring–occluder intersection), the ring display is similar to the Johnson and Aslin display, but at a global level (the ring's configuration), it contains extra information that might be expected to favor perception of unity. After habituation to a partly occluded ring, the infants viewed a broken ring (akin to the letter C) and a complete ring. There was a slight, but nonsignificant, preference for the broken ring, suggesting that the infants may not have been able to take full advantage of the extra visual information provided by the global configuration of the ring in perception of the complete object.

However, recall the proposal that, for young infants to disambiguate an occlusion display, a certain threshold level of information must be exceeded. Given that young infants have been found to be limited in the effectiveness of their scanning of visual displays (Bronson, 1990, 1991), some of the infants in this study may not have sampled the display appropriately (e.g., the infants may not have scanned the entire circle). (Large individual differences in 4-month-olds' scanning efficiency were reported by Freeseman, Colombo, & Coldren, 1993.) Thus, sufficient visual information for disambiguation of

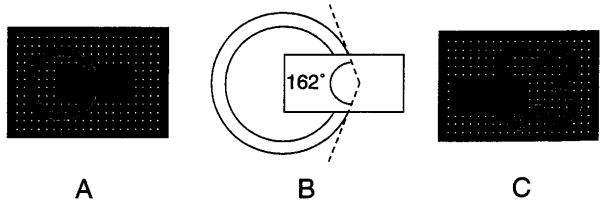

FIG. 4.11. Displays used to explore the role of configuration of partly occluded objects and young infants' perception of object unity (Johnson et al., 1999). A. Ring-and-box display. B. The tangents of the outer edges of the ring would meet at an angle of 162° if extended, the same angle as the misaligned rod edges employed by Johnson and Aslin (1996). C. Cross-and-box display. In small displays, but not large displays, the infants appeared to consistently respond to the unity and coherence of the ring and cross. See text for details.

the partly occluded ring display may not have been obtained during habituation. To address this question, a second group of 4-month-olds was presented with a partly occluded ring display in which the size of the display elements was reduced to help ensure that more of the display would be scanned during habituation. (The large ring subtended 13.3° visual angle vs. the small ring's 9.1°; the height of the box in the large ring display subtended 4.5° vs. 2.9° for the box in the small ring display.) The size reduction was expected to allow the infants to extract more information in support of unity (i.e., the ring's configuration). This prediction was confirmed: There was a significant preference for the broken ring after habituation to the small ring display.

Locally Nonaligned Object Edges. Further confirmation of the contribution of global object configuration to perception of unity was provided by conditions that applied a similar logic to the Johnson and Aslin (1996) nonrelatable rod condition. As seen in Fig. 4.11C, the two nonrelatable rod parts were incorporated into a partly occluded cross shape. In like manner to the previous study, at the local level, these rod parts were not aligned and thus might be perceived as disjoint objects. At the global level, they might be perceived as part of a partly occluded object. In a large cross display (15.6° across), there was no strong evidence of perception of the cross's unity in the habituation display. In contrast, the infants appeared to perceive unity in a small cross display (11.0° across). These findings imply that young infants attend to global object configuration, as well as edge and surface orientation, in determining the unity of partly occluded objects, and that limitations in scanning effectiveness may inhibit expression of this ability under some circumstances.

Common Fate (Synchronous Change)

Motion is a powerful cue for perceptual object segregation for both adults (Gibson, 1979; Gibson et al., 1969) and infants (Arterberry, Craton, & Yonas, 1993; Kellman, 1993). Kellman and Spelke (1983) stressed the importance of common motion to infants' perception of object unity. It might be, however, that perception of the rod's unity depends not on common motion per se but on the presence of synchronous change in the visible rod parts. This cue includes, but is not restricted to, motion. We asked whether synchronous change as a cue for object unity generalizes to domains other than change in position (common motion) by presenting infants with rod-and-box displays in which the visible rod parts underwent changes in color or brightness (Jusczyk, Johnson, Spelke, & Kennedy, 1999).

Two groups of 4-month-olds were shown 1 of 2 two-dimensional rod-and-box displays in which the visible portions of the rod gradually and repeatedly changed color from red to blue. In one display, the rod parts

underwent two kinds of synchronous change: common motion accompanied by common color change. In the other display, the rod parts underwent a common color change but remained stationary. The infants appeared to perceive the rod parts' unity in the moving color-change display, but not in the stationary color-change display. These results suggest that color change does not provide sufficient visual information to support object unity in this age group, casting doubt on the generalizability of synchronous change as a contribution to this process.

Nevertheless, it is possible that nonmotion synchronous change in conjunction with additional cues might support unity perception, as might be predicted from the threshold model. That is, it might be that the addition of three-dimensional cues would exceed the threshold required for perception of the rod parts behind the occluder. This was tested with a three-dimensional color-change rod, in which small red and blue lights were embedded in a Plexiglas rod. The red lights were dimmed as the blue lights were brightened, and vice versa, repeatedly and gradually. Even with the addition of three-dimensional depth, however, the responses of the infants did not indicate unity perception.

We went on to ask whether the color change employed in these stationary rod conditions may have been too subtle or slow for the infants to pick up. To assess this possibility, the red lights in the three-dimensional rod were flashed on and off. Again, the infants did not appear to respond to unity. In a final experiment, we investigated whether the negative results of the previous experiments stemmed from a failure to use the changes as information for object unity or from a failure to detect the synchronous changes in color or brightness. Four-month-olds were habituated to the three-dimensional rod alone, the red lights flashing at either a fast or slow rate. Test displays consisted of broken and complete rods that flashed at either the fast or slow rate. Both groups looked longer during the test at the faster flash rate, regardless of the rod's form, suggesting that 4-month-olds are able to detect color change and flash rates of the kinds used in the color-change displays. Regardless of the conditions we have tested, common motion appears to be the only kind of synchronous change that consistently supports perception of object unity in this age group.

Luminance and Color

Differences in texture, luminance, and color between objects or background, or both, are not necessary for 4-month-olds' segregation of rod-and-box surfaces because infants at this age successfully perceived object unity in displays in which all surfaces (rod, box, and background) were covered with similar random-dot textures (Johnson & Aslin, 1998). Does this imply that such cues are not used by infants at this age in surface-segregation tasks?

We explored this question with transparency displays (Johnson & Aslin, 1999). The display depicted in Fig. 4.12 consisted of a rod and box against a textured background. To adults, the box appeared transparent—the center of the rod and the background dots were visible through the box's surface. The rod appeared light gray, the box a darker gray against the black background, and the overlapped region of the rod a medium gray. The rod and box moved laterally out of phase. We reasoned that if young infants are able to use these differences in luminance to veridically segregate the rod-and-box surfaces (i.e., as opaque and transparent surfaces, respectively, as did adults in our experiment), then they may expect the rod to be a single luminance (light gray) behind the box. Thus, they were predicted to demonstrate a preference for a rod in which the top and bottom regions were light gray (we termed this the *overlapped* rod) over a single luminance (or *solid*) rod after habituation to the transparency display. This prediction was not confirmed—there was no consistent posthabituation preference.

It remains unclear, however, whether other kinds of visual cues will support transparency perception in 4-month-olds. We tested this possibility with a color display in which a translucent yellow box covered the center of a red rod. The center of the rod appeared orange when seen through the translucent box. Again, the rod and box moved out of phase. In this case, the infants looked longer at an overlapped (red-orange-red) rod than at a solid red rod. We replicated this finding with displays in which the box appeared blue when overlapping a yellow rod, followed by appropriate test displays. These studies indicate that 4-month-olds appear to attend to color

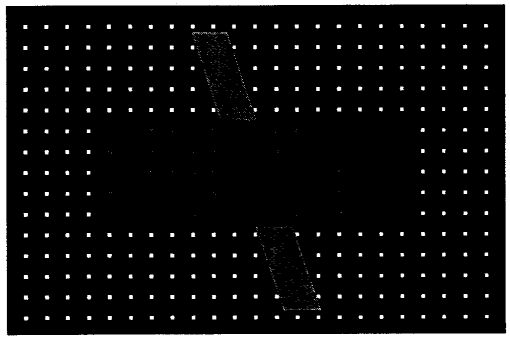

FIG. 4.12. Transparency display used to investigate the roles of luminance and color in young infants' surface segregation (Johnson & Aslin, 1999). When the display was achromatic, the infants did not seem to segregate such a display into its constituent components. However, in color displays, the infants responded as if they perceived the display as consisting of a transparent box in front of an opaque rod.

differences between visible surfaces and use such information to veridically segregate the surfaces into their respective depth planes. It remains unclear why the infants appeared to perceive transparency in the color displays, but not in the achromatic displays. The roles of other potential cues (such as motion and surface configuration) in infants' transparency perception also are not known at present.

Summary

The results of the experiments described in this section suggest that young infants rely on multiple sources of visual information in perceiving surfaces, as do adults (Cutting & Vishton, 1995; Gibson, 1950; cf. Needham et al., 1997). Three- and two-dimensional depth cues, motion, the orientations and configurations of edges and surfaces, and color all specify the arrangements of surfaces in depth to infants; however, young infants do not respond to all object displays in like manner to adults. In the absence of sufficient visual information, infants' ability to veridically parse object scenes into constituent surfaces breaks down.

A Theoretical Description of the Results: The Threshold Model

Past accounts that posit a single or dual process underlying unit formation (Kellman, 1993, 1996; Kellman & Spelke, 1983) do not appear to characterize adequately the majority of the recent findings. At this time, the best account for these results may be the threshold model, which posits that surface segregation is possible only when there is sufficient visual information and when the observer possesses adequate perceptual skills to pick up this information (Johnson, 1997; Johnson & Aslin, 1996). What is sufficient information for veridical surface perception at a particular age might not be sufficient for younger infants with less mature perceptual and cognitive skills.

We drew inspiration for our model from studies of adult visual perception. First, Nakayama and Shimojo noted that perceptual completion of one surface behind another depends on two subprocesses—namely, depth placement and contour ownership (Nakayama & Shimojo, 1990; Nakayama et al., 1989). That is, the observer must ascertain relative depth ordering of surfaces in a display and determine whether the edges of surfaces that appear to lead behind the occluder are likely to be joined behind it. If either subprocess is disrupted, then the partly occluded surface will not be experienced as complete behind the occluder. Second, Ramachandran's (1988) utilitarian approach to surface perception likens visual skills to a bag of tricks, which is opportunistic in its functioning. That is, a variety of visual information is available in the structure of the light that is reflected from object surfaces (Gibson, 1979), and human observers are adept at using these cues, separately or together, in veridical perception of object layout.

The threshold model is necessarily only descriptive at present because there remains insufficient evidence from infant studies to permit detailed explanations of early object perception and its development. Moreover, it would be desirable to obtain independent assessments of young infants' sensitivity to individual visual cues in tasks other than perceptual surface segregation. However, the utility of the model can be found both in its predictions, some of which were discussed earlier, and within links to other theoretical approaches, some of which are presented subsequently. There is another important set of predictions drawn from the threshold model that concerns the emergence of object perception discussed in the following section.

THE DEVELOPMENT OF SURFACE PERCEPTION: EMPIRICAL FINDINGS

Evidence for Innate Knowledge?

Kellman and Spelke (1983) maintained that their findings of perception of object unity in 4-month-olds constituted evidence for innate knowledge: "Humans may begin life with the notion that the environment is composed of things that are coherent, that move as units independently of one another, and that tend to persist, maintaining their coherence and boundaries as they move" (p. 521). Spelke (1990, 1994) has since proposed that the earliest kinds of object perception are tantamount to processes of reasoning in accord with certain fundamental physical principles. One of these is the principle of cohesion: Objects that move together tend to be connected (Spelke & Van de Walle, 1993).

These speculations prompted Slater et al. (1990) to habituate neonates to rod-and-box displays followed by paired broken- and complete-rod test displays. In contrast to the 4-month-olds observed by Kellman and Spelke (1983), the Slater et al. neonates preferred the complete rod. (Slater et al. were careful to conduct control studies to rule out alternative accounts of these results, such as an inability to distinguish the number of visible rod parts or a posthabituation familiarity preference.) Slater et al. suggested that the neonates they observed only responded to what was directly visible in the scene, failing to make the perceptual inference necessary to posit the hidden portion of the rod.

The Development of Perception of Object Unity: Evidence From Infants

The Slater et al. (1990) results cast doubt on the likelihood that mechanisms responsive to object unity are operational at birth, but leave open the question of how it is that perception of object unity emerges in young infants. This

issue was addressed by Johnson and Náñez (1995), who presented 2-month-old infants with the rod-and-box display depicted in Fig. 4.5A. We asked if perception of object unity might emerge by 2 months of age, in which case we expected their responses would echo those of our (and Kellman and Spelke's) 4-month-olds—a posthabituation preference for the broken rod. It was also possible that perception of object unity emerges after this time, in which case we expected the 2-month-olds would respond in like manner to neonates in preferring the complete rod. The responses of the 2-month-olds were intriguing, in that they were unlike either 4-month-olds or neonates: There was no consistent posthabituation pattern. We interpreted this result to indicate that perception of object unity may emerge within the first several months after birth, but may not be fully formed by 2 months of age.

However, the threshold model notes that younger infants' perceptual skills may be underdeveloped relative to those of older infants. It might be that with additional visual information for the existence of the hidden portion of the rod, 2-month-olds would respond to unity. This was accomplished in two ways (Johnson & Aslin, 1995). In one condition, the box height was reduced; in the second and third conditions, gaps were placed strategically in the box such that portions of the rod were visible as it passed back and forth (Fig. 4.13). (At no time in either of the latter two conditions was the entire rod visible.) In each of these three conditions, the infants looked longer at a broken test rod relative to a complete rod, as had 4-month-olds with less perceptual support (Johnson & Náñez, 1995). Thus, the infants appeared to perceive the rod parts' unity, providing support for the threshold model's predictions.

An important aspect of these results is the implication that infants' ability to perceive object unity emerges between birth and 2 months of age. On the basis of the Johnson and Aslin (1995) finding, however, we conjectured that neonates may perceive object unity, but this ability was not expressed in the

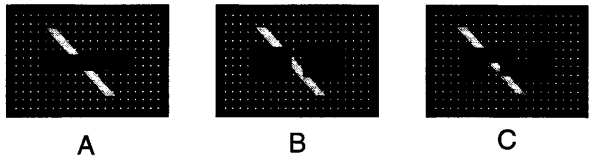

FIG. 4.13. Displays used to assess 2-month-olds' perception of object unity (Johnson & Aslin, 1995). In each display, more of the rod was visible than had been available in previous experiments (Johnson & Náñez, 1995). The 2-month-olds appeared to perceive object unity in each of these displays, implying that the extra information provided in terms of rod visibility was attended to by the infants.

infants observed by Slater et al. (1990). Neonates might require more visual information to perceive object unity than was provided in the Slater et al. display (i.e., the threshold of visual information required by neonates may not have been achieved). We tested this possibility by presenting neonates with object unity displays that were richer in visual cues than had been provided by Slater et al. First, we increased the depth difference between the rod and box (Slater, Johnson, Kellman, & Spelke, 1994). Next, we added increased depth, background texture, and reduced box height to the cues from the Slater et al. (1990) original displays (Slater, Johnson, Brown, & Badenoch, 1996). (These original cues were rod motion, color and luminance differences between rod, box, and background, and alignment of rod parts.) With the exception of alignment, neonates previously have been found capable of discriminating each of these cues. If this extra information were used by the neonates, we would expect them to prefer the broken-rod test display or at least have a reduced preference for the complete rod. Interesting, the neonates observed in these two studies showed remarkably similar performance to those tested by Slater et al. (1990): There was a strong and consistent preference for the complete rod.

The Slater et al. (1994, 1996) results suggest that the neonates did not take advantage of the extra available visual information to perceive the rod's unity (thus, the threshold model's prediction was not supported). These results have important implications for theories of the development of object perception: Neonates do not appear to be invested with skills underlying veridical surface perception. How do such abilities emerge in infancy? This question is discussed in the next section.

THE DEVELOPMENT OF SURFACE PERCEPTION: THEORETICAL CONSIDERATIONS AND HYPOTHESES

I have presented evidence that, at birth, infants' skills at veridical surface perception are limited. Little is known about the precise mechanisms of development of surface and object perception, but it is clear that the first few months after birth see rapid improvements in such abilities. I noted previously that the threshold model promises to identify important theoretical links to other approaches that might help explain the emergence of surface and object perception in infancy. Two such approaches seem particularly illuminating. First, I discuss recent insights from computational modeling of developmental processes underlying object perception. Following this is a brief survey of neurophysiological mechanisms subserving visual perception, including a consideration of how these mechanisms might address the problem of the development of surface perception in accord with the threshold model.

The Development of Perception of Object Unity: A Computational Model

One important tool with which to explore questions of perceptual and cognitive development is computational (connectionist) modeling. Such techniques have been successful in modeling a range of developmental phenomena (see Elman et al., 1996). Computational models consist of networks of several layers of interconnected processing nodes designed to learn through interactions with a specific environment created by the modeler. A network develops a representation of the environment (either in the connection weights or as a pattern of activation across a bank of nodes) by extracting the statistical regularities (patterns that tend to recur) in the environment. Computational models can provide rigorous accounts of development because the time course and nature of learning can be captured and made explicit. If a particular ability can be acquired by a simulation, the implication is that, in principle, preexisting knowledge is not a prerequisite for the development of that ability. (Instead, computational models are characterized by built-in constraints such as the architecture of the network, learning rules, and how the input is encoded.) Moreover, it is possible that humans, given appropriate learning mechanisms and the means to detect and encode environmental structure, acquire the ability in the absence of inherent knowledge.

Recently, Mareschal and I (1998) modeled the development of perception of object unity. The simulation we designed inhabited a simple "world" in which unified and disjoint objects moved past and behind an occluding screen. The model was initially endowed with the ability to extract surface motion, common motion of two disjoint surfaces, texture deletion and accretion, T junctions, and edge alignment from the simulated visual environment. The model also possessed a short-term memory, such that when an object became occluded, a trace of that object's representation remained. The model learned to associate (with a supervised Hebbian learning rule) the presence of certain visual cues and the appearance of a single unified object or two disjoint objects; it was tested throughout its development on events similar to those used when testing infants (e.g., Johnson & Aslin, 1996).

Four events were randomly presented to the model during training, consisting of either one object or two aligned objects moving across the model's environment. Objects were presented against a background either with or without texture. In each event, the objects were initially fully visible and then moved behind an occluder and out the other side. The model quickly learned (within 10 presentations) to associate relevant cues with appropriate single-object versus two-object responses for episodes when the objects were visible. The model was periodically presented with events in which an object only appeared behind an occluder (i.e., it was never fully visible), and the model's predictions regarding the object's unity were recorded.

Interesting, early in training, the model incorrectly classified occlusion events as consisting exclusively of two objects, as did human neonates (Slater et al., 1990, 1994, 1996). With further training, the model responded appropriately on tests where the object's unity was ambiguously specified (misaligned and nonaligned rod parts). At the end of learning (approximately 2,000 presentations), the model responded in the same way as adults, as reported by Johnson and Aslin (1996). As expected, the nature of the training environment (i.e., the cues that were made available) was critical in determining performance. So, too, was the model's memory: With a low memory value, the model was unable to perceive the objects' unity. A second model endowed with a layer of hidden units and a backpropagation learning algorithm showed superior performance, demonstrating that the networks' architectures and learning mechanisms strongly impact the development of representations. (These are avenues that await exploration in future modeling and experimental work with infants.)

The success of these models has important implications for the development of perception of partly occluded objects in infancy. Although the models were not intended to precisely emulate young infants' visual proficiency or development, it is clear that, given the right starting conditions, development of perception of object unity does not necessarily require any level of preexisting object knowledge. (Neonates can distinguish between one- and two-object displays and between figure and ground, but these perceptual skills are probably not best characterized as object knowledge given neonates' limitations in perception of object unity.) Rather, object unity may be a characteristic of the environment that is embodied in repeated patterns of stimulation in a reliable and predictable fashion. Given the visual skills to pick up these regular patterns, and the means to form associations between them, perception of object unity may be acquired in humans via interactions with the environment. For a fuller account of this process in humans, we next consider some of what is known about the neurophysiological functioning of the visual system.

The Neurophysiology of Vision

Over the past several decades, evidence from anatomical and physiological studies involving monkeys and cats, and clinical studies involving humans with cerebral lesions, has converged in establishing that the visual system is organized hierarchically (DeYoe & Van Essen, 1988; Felleman & Van Essen, 1991; Van Essen, Anderson, & Felleman, 1992; Zeki & Shipp, 1988). From the retina, the visual processing stream proceeds via the lateral geniculate nucleus (part of the thalamus) to the visual cortex. Over 30 cortical areas are devoted to visual or visuomotor function (Felleman & Van Essen, 1991; see Fig. 4.1). Different attributes of the visual scene (such as form, color,

and motion) are processed in these discrete, anatomically segregated (although richly interconnected) areas.

In general, areas that are lower in the processing stream contain cells that code for visual features common to a wide variety of objects in the world, whereas cells in areas that are located higher in the hierarchy code for more specific features. For example, Area V1, the initial visual area in the cortex (i.e., lowest in the cortical processing stream), contains some cells that respond best to orientation, others to motion, and still others to wavelength (see Zeki, 1993). Some parts of the inferotemporal cortex (near the top of the processing stream) contain cells that are maximally responsive only to distinctive stimulus configurations, such as faces (Desimone, 1991), bodies (Wachsmuth, Oram, & Perrett, 1994), and complex geometrical shapes (Tanaka, 1993). Cells in visual areas nearer the center of the hierarchy code for visual features that are of intermediate specificity, such as context-dependent color (processed by area V4) and motion (processed by area MT), although many neurons here may have multifunctional properties (Schiller, 1996).

There is no indication at present that the highest visual areas are the seat of awareness and consciousness (see Crick, 1994; Crick & Koch, 1990b). Nor is there strong evidence for highly specific cells that maximally fire in response to one and only one stimulus (Barlow, 1972). How, then, does the visual system distinguish between different objects?

The Neurophysiology of Object Perception

It may be that the answer lies not in the firing of single cells, but rather with the patterns of synchronous firing of assemblies, or networks, of cells across the hierarchy (Crick & Koch, 1990a; Engel, König, Kreiter, Schillen, & Singer, 1992; Phillips & Singer, 1997; Singer, 1993, 1994). On this temporal coding view, a visual stimulus in the environment that is the object of attention activates a constellation of feature detectors throughout the visual system. Individual stimuli tend to activate unique cell assemblies, the global activity of assemblies' subcomponents binding together stimulus features to impart a stable percept of distinct, coherent objects. The glue that binds together unique object representations is the synchrony of neuronal discharges in the various visual areas.

Evidence in favor of temporal coding comes from demonstrations that synchronized responses in spatially separate regions of the cat visual cortex (e.g., cells that fired preferentially to a particular orientation) corresponded to specific pattern features (Gray, König, Engel, & Singer, 1989), becoming associated with the coding of stimulus position, orientation, motion, and binocularity in visual areas 17 and 18 (Eckhorn et al., 1988). In addition, evidence was recently obtained for synchronization of neurons in visual and parietal cortex, and parietal and motor cortex, in cats engaged in a visuomotor response task (Roelfsema, Engel, König, & Singer, 1997). Synchronized oscillatory firing of cells within and across layers in V1 was also observed in monkey visual cortex (Livingstone, 1996). In all these studies, synchrony among cell assemblies was not observed when the animal was off task. (However, some researchers have reported difficulty in obtaining consistent synchronized responses among cortical areas, suggesting that synchrony in the cortex is an epiphenomenon of subcortical activity; see Ghose & Freeman, 1992, 1997; Kiper, Gegenfurter, & Movshon, 1996; cf. Singer & Gray, 1995.) Synchrony has also been adopted by some computational modelers as a way to link related inputs. For example, von der Malsburg and Buhmann (1992) incorporated Gestalt laws of perceptual organization into a model of surface segregation, unifying discrete processing units into circuits via synchronized oscillation. Hummel and Biederman (1992) utilized synchronized oscillatory activity across individual nodes as a way of parsing object scenes into their constituent parts and then binding features into coherent objects. Shastri and Ajjanagadde (1993) described a model that employed synchrony between nodes in a simulation of the human capacity to retain large amounts of knowledge in memory.

How can the temporal coding hypothesis speak to questions of the development of surface perception? In particular, is there a correspondence between temporal coding and the threshold model, which seems to provide a useful description of young infants' responses to surfaces in depth?

A Threshold for the Development of Surface Perception?

Consider the task of the observer who is presented with a partly occluded rod (e.g., Fig. 4.2A). Although this is not necessarily a familiar object, the mature visual system binds together the two rod parts such that adults report a percept of a unified object immediately and without effortful reflection. The ubiquity and facile nature of the process masks an intricate and complicated set of components that work together to impart our experience of a stable, object-filled environment. A variety of visual areas are engaged when attending to a partly occluded rod, including cells that code the rod parts' motion, alignment, color, luminance, surface texture, and distance behind the occluder (i.e., cells tuned to binocular disparity). The precise neural mechanisms underlying perception of object unity are unclear, but the temporal coding hypothesis suggests that the rod parts are perceptually bound due in part to the synchronized responses of cells in these active visual areas. In rod-and-box displays with fewer cues (e.g., a stationary rod), fewer visual areas may be directly involved, yet adults may still readily perceive unity. However, individual areas in the infant's visual system may not yet be as finely tuned to surface characteristics as they are in adults. Moreover, there is likely a higher degree of internal noise that imposes limitations on

efficient neural transduction in the young infant's cortex, which may restrict, for example, contrast sensitivity and other low-level functions (Skoczenski & Aslin, 1995; Skoczenski & Norcia, 1998; cf. Banks & Bennett, 1988). Therefore, cell circuitries in infants analogous to those in adults may be engaged to some extent by a particular display, yet the totality of their responses may be insufficient to activate a veridical percept of a partly occluded surface. To explore this possibility more fully, evidence from other domains, relevant to development of the human visual cortex, must be considered.

Development of the Visual Cortex and Surface Perception

How does the visual cortex develop? There is some direct evidence concerning development of the cerebral cortex in humans (e.g., Conel, 1939–1967), but little is known about the relation between visual cortical development and improvements in object perception. However, evidence from object recognition and other visual processing in monkeys and cats may provide insights into our inquiry of the emergence of surface and object perception in human infants.

As noted previously, the inferotemporal cortex (IT) has been implicated in a variety of object recognition tasks, and many cells in adult IT are characterized by a high degree of stimulus selectivity. Rodman (1994) described several studies with infant macaque monkeys indicating that stimulus selectivity in IT is present by 5 weeks of age. (This does not necessarily indicate that such specificity is prewired—the visual system of macaques develops rapidly—even faster than that of humans. Nor should stimulus selectivity in infant macaque IT necessarily be taken to imply the existence of similar mechanisms in human infants, direct evidence for which is not presently available.) Rodman noted that there are both important similarities and important differences in response characteristics of IT cells in infant and adult macaques. As well as stimulus selectivity, cells in infant macaque IT share similar receptive field properties to those in adults—like adult IT cells, they respond to stimuli over a broad area of the visual field. However, the responses of infant macaque IT cells are consistently weaker, and latencies are more variable and often longer. Rodman speculated that these differences may be due in part to lower overall metabolic activity of infant cells. Consistent with this finding, Hawken, Blakemore, and Morley (1997) described rapid perinatal improvements in the functioning of individual cells in the parvo- and magnocellular processing streams in the infant macaques' lateral geniculate nucleus—a subcortical visual structure. The greatest rate of change occurred in the first 2 months after birth, before which time there was poor sensitivity to contrast, motion, and spatial resolution perhaps due to a general sluggishness of response. In human infants, Chugani and Phelps (1986) reported greater metabolic activity in subcortical visual structures before 5 postnatal weeks, relative to visual cortex and other cortical areas, which became more active after 3 months.

In addition to changes in metabolic activity of the cells, Rodman (1994) suggested other factors that contribute to visual development in macaques. First, patterns of connectivity undergo considerable development, most prominently in the pruning or scaling back of "exuberant" connections between IT and other areas (cf. Greenough, Black, & Wallace, 1987). Second, neural myelination is not uniform across the cortex—IT cells seem to lag behind other visual areas. Third, specificity of circuitry emerges, with the differentiation of neurotransmitters exclusive to particular functions (such as formation of visual object memories).

Singer (1995) reviewed a body of research that supports a view of visual development stressing both experience-independent and experience-dependent processes. Experience-independent visual abilities are manifested by the fact that many neurons in cat V1 possess their characteristic orientation selectivity at birth (Hubel & Wiesel, 1963). Shatz (1992) recounted groundbreaking studies exploring the developmental neurobiology of the visual system before birth. Normal postnatal functioning of visual structures such as the lateral geniculate nucleus and V1 appears to be critically dependent on the activity of cells that constitute the inputs to these areas during fetal ontogeny (i.e., retinal ganglion cells and the LGN, respectively), well before the infant is exposed to patterned visual stimulation.

In contrast, a visual experience-dependent mechanism underlies the completion of ocular dominance columns in V1, which forms the basis for sensitivity to binocular disparity as a depth cue (Held, 1993). When the two eyes are prevented from functioning in tandem during a critical period soon after birth in monkeys and eye opening in kittens, stereopsis in adult animals is precluded (LeVay, Stryker, & Shatz, 1978; LeVay, Wiesel, & Hubel, 1980). The development of cortical substrates subserving more sophisticated visual functions, such as surface perception, may require synchronized firing of cell assemblies during ontogeny: As Shatz (1992) stated, "cells that fire together wire together" (p. 64).

These changes provide tantalizing possibilities for theorizing about human infants. It may be that veridical surface perception in young infants is challenged by limitations in the responses and coordination of individual cortical visual areas. On this view, improvements in surface perception are brought about by the tuning (i.e., increases in response specificity) of cell assemblies that fire together during presentation of visual stimuli—early in development, synchronization of these cortical assemblies is less precise and more differentiated. Improvements in the tuning of cell assemblies are partly a function of visual experience. This account is speculative, yet it is consistent

with the human developmental, computational, and animal models presented earlier. Clearly, more interdisciplinary research is needed to more fully explore the development of object perception and the binding problem.

Is Object Knowledge Innate?

Earlier I described the Kellman and Spelke (1983) claim that a limited form of object reasoning is innate in humans. At first glance, the evidence presented here does not support such a position. These studies do not necessarily impugn nativist views, however, in part because there is not a single, universally accepted definition of what constitutes an innate ability.

Elman et al. (1996) defined *innateness* as constituting "those behaviors which, given the normal experiences encountered during development, are universal across a species" (p. xiii). Spelke and Newport (1998) noted that "knowledge that is inherent in the mind might emerge either early or late in development and be either invariant or subject to change, and abilities abstracted from experience might be either universal or variable across cultures" (p. 275). By these definitions, perception of object unity may be innate: As far as we know, all adults with normal visual systems experience the world of objects as composed of bounded, coherent entities that maintain their shape and boundaries under conditions of partial occlusion. Moreover, all adults received visual experience during development in an environment filled with solid, coherent objects, whose characteristics were reliably specified in the structure of reflected light (see Gibson, 1979).

A more precise definition of innateness would incorporate specific roles for experience in the developmental domain of interest. In the case of the development of visual surface perception, the role of experience is as of yet unknown. Some low-level visual skills are present in neonates, and are therefore experience-independent. It seems likely that the conditions for improvements in the extraction of visual information relevant to veridical surface perception are also present at birth, and that surface perception awaits development after some period of visual experience. Because patterns of cortical interconnectivity appear to be selected by experience in accord with the probabilities of exposure to various stimulus classes (Singer, 1995), it might be that the experience of viewing moving objects in the first few months after birth is critical to veridical surface perception.

Is surface perception synonymous with object knowledge? I think the answer is no. Object knowledge seems to require more reasoned, reflective cognitive activity than does surface perception. The rapidity and automaticity with which surface perception occurs in the adult imply a lower neurophysiological locus than higher level cognitive tasks; in fact, surface perception provides the input on which visual cognition relies (Nakayama et al., 1996). Given that veridical surface perception only becomes available after birth, there seems to be little indication that object knowledge per se is inherent in the mind of neonates.

FUTURE DIRECTIONS

A fuller account of the development of surface perception requires more data from infant, computational, and animal studies. Remaining questions include:

- *What is the role of attention in the development of object perception?* Ontogenetic improvements in sampling of the optic array may be central to the emergence of veridical surface perception (Johnson, 1997). This can be assessed with studies of object perception that use an eye tracker to record scanning patterns over the course of the experiment.
- *Can individual differences in one or more measures of oculomotor development inform us about the mechanisms underlying infants' surface perception?* This question is perhaps best addressed with longitudinal studies of infant object perception, of which there are none currently reported in the literature. Individual differences in infant visual behavior have been interpreted to reflect fundamental information processing and learning abilities, as well as to predict cognitive functioning in childhood (Coldren & Colombo, 1994; Colombo, 1993; Freeseman et al., 1993). Therefore, such studies with young infants might prove particularly illuminating.
- *Are there one or more cortical or subcortical bottlenecks that limit young infants' surface perception?* An example of a cortical bottleneck is limitations in motion discrimination that have been observed in infants younger than 8 weeks of age (Wattam-Bell, 1991, 1996; but see Laplante, Orr, Neville, Vorkapich, & Sasso, 1996). This has been interpreted to indicate a limitation in the functioning of area MT, which is involved in motion processing (Johnson, 1990). Spelke and Newport (1998) noted that such a limitation implies that neonates' failure to perceive object unity may reflect an inability to capture the common motion of the rod parts, which is critical to older infants' performance (Kellman & Spelke, 1983). Examination of this potential bottleneck, and others, might elucidate future theorizing about the development of surface perception, which relies on a vaiety of visual cues.

A second, more generalized bottleneck can be found in the neural noise intrinsic to young infants' visual functioning (Skoczenski & Aslin, 1995; Skoczenski & Norcia, 1998). At present, it is unclear precisely how neural noise might impact the development of surface perception. However, the effects of neural noise can be incorporated into future computational models of infants' surface perception to gauge the influence such noise might have during development. Modeling efforts might also benefit from a considera-

tion of low-level limitations, such as optical and photoreceptor immaturities (Banks & Bennett, 1988).

• *Are limitations in infants' surface perception characteristic of other primate visual systems?* A recent report that an adult chimpanzee perceived object unity (Sato, Kanazawa, & Fujita, 1997) invites speculation concerning how animal studies might inform questions of the development of surface perception in humans. Such research facilitates the generation of experiments that would not be possible with human infants. For example, monkeys can be raised under unusual visual circumstances, and tested as adults on surface perception tasks, to explore the impact exerted by experience during visual development on mature performance. Moreover, surgical intervention to compromise the functioning of various visual areas, in addition to recording from specific visual sites during testing, can enlighten us regarding the contribution of these areas to veridical surface perception.

What about other species? Recent avian studies provided conflicting results concerning birds' completion of partly occluded figures (Lea, Slater, & Ryan, 1996; Regolin & Vallortigara, 1995; Sekuler, Lee, & Shettleworth, 1996). Therefore, at this time, it remains unclear whether work with nonprimates can provide useful information regarding the development of surface perception in humans.

CONCLUSIONS

I have presented evidence concerning the development of surface perception between birth and 4 months of age, arguing that veridical surface segregation is a sine qua non of object knowledge. The strength of this approach to perceptual development lies in its greater precision relative to some other object perception paradigms. That is, because these questions invoke less sophisticated cognitive skills than those involved in, say, physical reasoning tasks, it might be possible to identify more precise developmental mechanisms due to recent advances in complementary methodologies such as computational modeling and neuroscientific approaches, which can provide important insights into low- and mid-level perception and its development.

In summary, by 4 months of age, infants attend to a variety of sources of visual information when segregating surfaces in depth. Neonates do not seem adept at these tasks, although by 2 months of age, infants are able to veridically perceive surfaces in depth under some conditions. These findings, in conjunction with past research, support a view of human visual development that proposes that infants are born equipped with visual sensitivity (i.e., some low-level visual skills), rapidly develop visual perception (i.e., construction of segregated surfaces in depth), and then, more gradually, amass a number of cognitive skills constituting visual cognition (i.e., responses to objects' physical properties). Whether object knowledge is innate depends on one's definition of what constitutes an innate ability, and therefore this question cannot be definitively answered by our research. However, very young infants' responses to object displays reveal fundamental limitations in their surface perception skills.

This account of the development of surface perception stresses the importance of both experience-independent and experience-dependent mechanisms. The experience-independent mechanisms are evinced by visual attention at birth, which is often geared toward contour and motion (Slater, 1995). The experience-dependent mechanisms that undergo development might involve processes such as changes in synaptic strengths and increased synchronization of the firing of neurons in various visual areas in response to environmental stimulation (Bailey & Kandel, 1995; Shatz, 1992). These two kinds of mechanisms may combine in their contributions to the shaping of the visual system during development because object edges and object motion provide critical information for surface segregation, and both kinds of cues are central to young infants' (and adults') object perception.

ACKNOWLEDGMENTS

The author's research has been supported by NIH grants EY-07125 and HD-07748 and ESRC grants R000221813 and R000237093. I wish to express sincere thanks to Dick Aslin, Jim Dannemiller, Bill Graziano, Amy Needham, Wayne Shebilske, Brad Sheese, and Alan Slater for thoughtful comments and suggestions concerning an earlier draft of this chapter. Thanks are especially extended to the many parents and infants who participated in the research.

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PROGRESS IN INFANCY RESEARCH, VOLUME 1

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2000 LAWRENCE ERLBAUM ASSOCIATES, PUBLISHERS
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