CHAPTER

1

Development of Perceptual Organization

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When newborn infants first look at their surroundings, do they perceive a radically different world from older children and adults, or is their perceptual world organized in ways fundamentally like our own? As infants and children grow and learn about objects, events, and scenes, do these developments change the organization that they perceive in their surroundings, or is perceptual organization constant over human life?

Theories of the development of perceptual organization can be distinguished by the answers they offer to these questions. One class of theories embraces *the continuity thesis* and proposes that the processes by which adults organize scenes into units are constant over human postnatal development. Although newborn infants sense the world with lower acuity, perceive as novel scenes that are familiar to us, and fail to appreciate the functional properties of many categories of objects, they organize their surroundings in fundamentally the same ways as adults. A second class of theories embraces *the discontinuity thesis* and proposes that processes of perceptual organization change fundamentally over development. Most proponents of the discontinuity thesis attribute these changes to learning: Children's ability to organize scenes into units develops by virtue of their encounters with scenes and objects. On this view, experiences with objects lead to qualitative changes in how objects are perceived.

The continuity and discontinuity theses cast strikingly different perspectives on the infancy period. If infants perceive the same objects and scenes as older children and adults, then infants may learn from their encounters with objects and people. An infant who views an adult eating a grapefruit with a spoon, for example, might learn about functional properties of these objects (spoons are manipulable, grapefruits are edible) and about actions that apply to them (spoons are grasped by the hand, grapefruit is chewed in the mouth). Learning during infancy might be useful later in development, because infants will be learning about the very entities—utensils, fruits, people—that older children and adults perceive and think about. If the discontinuity thesis were correct, in contrast, the things that infants learned would be of little use later in development. Imagine, for example, that infants perceived no people, food, or spoons but only momentary arrays of visible surfaces. Because adults' actions are directed to whole objects, not to the visible parts of surfaces, infants would be unable to represent actions such as eating grapefruit with a spoon in a useful way. Anything that infants learned from this event (e.g., that silvery surfaces tend to move into contact with shiny yellow surfaces) would need to be relearned later, when the child's perceptual experience shifted from a focus on visible surfaces to a focus on objects, allowing the child to realize that it is spoons (whether silver or not), not silvery surfaces (whether spoons or not) that carry food.

Ample evidence reveals that infants do learn about the world from birth: In the first days of life, they come to recognize faces (Bushnell, Sai, & Mullin, 1989), develop a distinctive preference for the sound of their own language (Mehler et al., 1988), and gain short-term familiarity with repeatedly presented visual scenes (Friedman, 1972). One might expect, therefore, that evolution would favor the emergence of perceptual mechanisms that parse faces, sounds, and scenes in the same general ways as those of the older child and the adult, in accord with the continuity thesis. Contrary to this expectation, all the evidence from studies of infants has appeared to support some version of the discontinuity thesis. Because infants' actions on objects undergo marked changes with development, Piaget (1954) and his followers proposed that there are radical changes in perception and representations of objects over infancy. Because infants' perception of a variety of simple visual displays also appears to undergo considerable changes, students of perceptual development have also proposed qualitative changes in object perception over infancy (e.g., Cohen, DeLoache, & Strauss, 1979; Spelke, Vishton, & Hofsten, 1994; but cf. Kellman, 1993). If any of these proposals are correct, then the learning capacities revealed in infants could not contribute the development of knowledge until they, or other processes, first brought structure to the infant's perceptual world.

In this chapter, we take a new look at the evidence for developmental changes in perceptual organization. Although infants' reactions to particular visual displays undergo real and compelling developmental changes, we believe these changes can be reconciled with the continuity thesis. Developmental changes in perceptual abilities, we suggest, stem from gradual, continuous increases in the precision of object representations, not from qualitative changes in its underlying processes.

To focus our review, we consider just one aspect of perceptual organization: the construction and extrapolation of object contours in 2-dimensional visual displays and in 3-dimensional scenes. We begin by discussing infants' perception of partly occluded objects—an area that has been interpreted to provide evidence both for continuity and for discontinuity in object perception. Then we discuss what may be the strongest evidence for discontinuity in infants' perceptual organization, from studies of developing perception of "illusory contours."

PERCEPTION OF PARTLY OCCLUDED OBJECTS

Amodal completion is a perceptual phenomenon in which contours are perceived or inferred despite their absence in the retinal projection (Michotte, Thines, & Crabbe, 1964). For example, adult observers perceive Fig. 1.1a as a triangle partly hidden behind a human finger. Adults appear to extrapolate the contour smoothly behind the occluding finger in accord with the Gestalt principle of "good continuation." Note that despite the visual system's principled extrapolation of the visible contours, it is possible that the contours change direction and that the removal of the finger would reveal a polygon of a different shape (Fig. 1.1b). Although the visual information in Fig. 1.1a is consistent with either a triangle or the complex polygon, the visual system favors the former. When the visible contours of a partly occluded object do not accord with the principle of good continuation, an indefinite perception results. For example, observers do not perceive a compelling, complete form behind the occluder in Fig. 1.1c. As these observations indicate, the relative alignments of the visible contours of a partly occluded object have a large effect on adults' perception of the object's unity, whether or not the contours evoke a familiar object.

The notion of good continuation has been formalized mathematically and tested in psychophysical experiments with adults. Whenever two or more spatially disjoint contours can be joined by a smooth, monotonic curve (i.e., a curve that does not inflect between convexity and concavity) observers tend to perceive the contours as connected (Kellman & Shipley, 1991), and the long edge that they form appears to pop out of a larger array of randomly oriented edges (Field, Hayes, & Hess, 1993). When these contours cannot be smoothly joined with such a curve, they are not perceived as be-

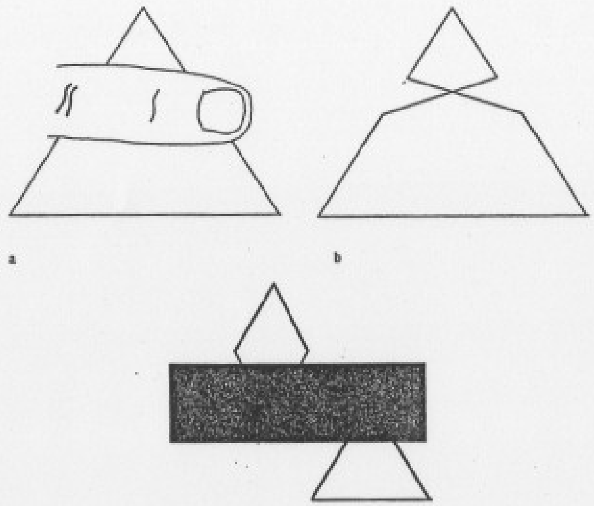

FIG. 1.1. Some partial occlusion displays (after Michotte et al., 1954).

longing to the same object and a line of such contours does not pop out of an array (Kellman & Shipley, 1991; Field et al., 1993).

Since the 1980s, the development of these organizational phenomena has been studied with infants by means of preferential looking methods. In these studies, infants are presented repeatedly with an occlusion display until their interest in the display (as reflected by their spontaneous looking time) declines. Then the occluder is removed and infants are presented with two test displays that both match the visible areas of the original display and show complete or incomplete objects. Numerous experiments, with control conditions in which the critical objects and changes in objects are directly visible, reveal that infants tend to look longer when a test display presents a new object than when it presents an object from the original display (see Johnson & Aslin, 1996; Kellman & Spelke, 1983; Needham, 1994; Slater et al., 1990).[1] This novelty preference therefore serves to assess infants' perception of the similarity between each test display and the original occlusion display.

[1] Bogartz and Shinskey (1998) recently introduced a different method for studying infants' perception of partly occluded objects, in which a smaller number of infants view a larger number of test displays with a single test trial of each type. Their method does not provide evidence for any novelty preferences, either in control conditions where the critical objects are fully visible or in an experimental condition in which an object first is occluded. It is not clear why infants fail to show novelty preferences in their experiments. Because of the absence of such preferences with fully visible displays, however, these experiments do not shed light on infants' perception of partly occluded objects.

Early experiments using this method presented 4-month-old infants with a stationary object whose center was hidden behind a horizontal occluder. After habituation to a partly occluded rod or triangle, infants looked equally long at a complete object and at an incomplete object composed of the two segments that were visible above and below the occluder in the habituation display (Kellman & Spelke, 1983; Fig. 1.2a). These results provide evidence that infants perceived no definite, connected object behind the occluder, despite the alignment of the visible contours of the rod and the symmetry and closure of the triangle. The findings suggested that infants fail to use configural cues such as good continuation to determine object unity.

In further experiments, infants were presented with the occluded rod undergoing lateral translatory motion behind the occluder during habituation. In contrast to the studies with stationary objects, 4-month-old infants showed a strong preference for a translating incomplete rod at test, relative to a translating complete rod (Johnson & Aslin, 1996; Jusczyk, Johnson, Spelke, Kennedy, & Smith, 1997; Kellman & Spelke, 1983; Slater et al., 1990; Fig. 1.2b). This looking preference implies that the incomplete rod was less familiar to infants than the complete rod, and thus that infants perceived the partly occluded rod as connected behind the occluder. Because the two rod displays differed only in their completeness, this preference in turn

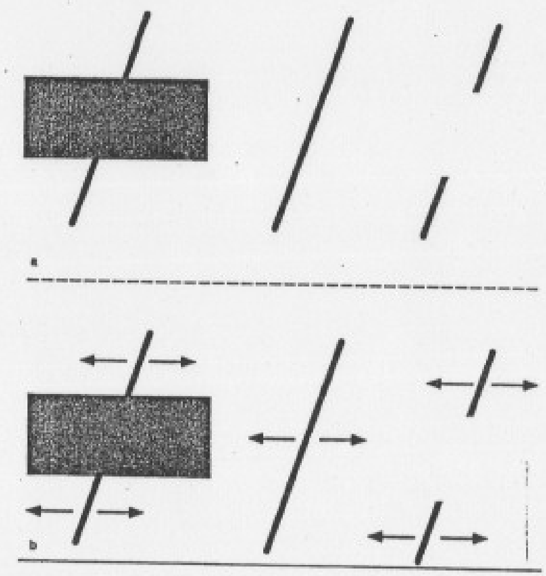

FIG. 1.2. Displays used in studies of infants' perception of partly occluded objects. Part a shows stationary rods; Part b shows translating rods (after Kellman & Spelke, 1983).

suggests that the common motion of the rod ends served as an indication of object unity. Infants' reliance on motion information to determine object unity is a good strategy given the physical laws governing object motions: Because most nonliving objects do not interact at a distance, two surfaces that move together are not likely to be separated by empty space. If two object segments visible above and below an occluder move together, therefore, those parts are likely to belong to the same object (Kellman, 1993).

Similar experiments have shown that these results generalize to 3-dimensional solids (Schmidt, 1985) and to flat, regularly textured, and/or colored surfaces (Johnson & Náñez, 1995; Termine et al., 1987; Schwartz, 1982; Slater et al., 1990). Experiments presenting different patterns of motion revealed that translation of the rod either vertically or in depth supports perception of a unified object (Kellman, Spelke, & Short, 1986), and that the object must move relative to the infant: Movements of the retinal projection due to observer motions do not yield perception of object unity (Kellman, Gleitman, & Spelke, 1987). The finding that motion specifies object unity for 4-month-old infants therefore appears quite robust, leading investigators to propose that motion provides infants' only information about objects (Kellman & Shipley, 1991; Kellman & Spelke, 1983; Spelke, 1990).

More recent studies suggest, however, that infants also are sensitive to configural cues such as the alignment of object parts and similarity of surfaces, especially when information from those cues appears within displays of moving objects. Using 2-dimensional video-displayed stimuli, Johnson and Aslin (1996) explored the role of contour alignment in 4-month-olds' perception of partly occluded objects. Infants were shown a center-occluded rod with misaligned visible ends that translated laterally behind a rectangular occluder (Fig. 1.3a). After habituation, infants looked longer at a complete rod (consisting of the two previously visible ends and a middle segment connecting them) than at two disjoint rod ends. This longer looking suggests that infants did not perceive the partly occluded rod ends as a single object despite their common motion. In a follow-up study using connected and incomplete test displays with equal numbers of corners (Fig. 1.3b), infants again preferred the complete rod over the broken rod, confirming that the differential recovery of looking time was due to the connectedness of the complete rod rather than to the presence of corners per se (Smith, Johnson, Spelke, & Aslin, 1996). These findings suggest that infants used both motion and alignment as information about object unity (see Johnson & Aslin, 1996). When two cues for determining object unity conflict (i.e., when alignment appears to specify two objects while motion specifies one) infants perceive two distinct objects rather than a unified object that continues behind the occluder.

The conflict between these recent results and earlier work may result from differences in the degree of depth information present in the displays: In 2-dimensional displays, infants may segment the surfaces differently than

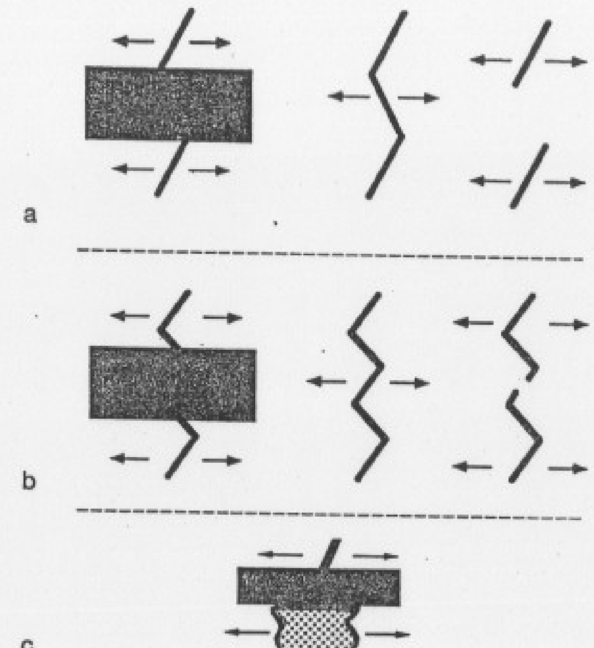

FIG. 1.3. Displays used in studies of the effects of motion and contour alignment on infants' perception of partly occluded objects (top, after Johnson & Aslin, 1996; middle, after Smith et al., 1996; bottom, after Kellman & Spelke, 1983).

they segment 3-dimensional displays. With 3-D displays, additional information about the depth of objects is available from accommodation and convergence and from motion parallax caused by the movement of the infant's head. Thus, infants' failure to perceive the misaligned, commonly moving rod ends as connected could arise from a relative poverty of depth information.

One experiment reported in Kellman and Spelke (1983) is consistent with this suggestion. Infants were presented with a moving, center-occluded compound object composed of a rod and polygon (Fig. 1.3c). After familiarization, infants looked longer at the incomplete test display, suggesting that they perceived a connected object in the occlusion display. Because the edges of the surfaces in the occlusion display were not aligned, this finding suggests that only motion influences the perceived unity of 3-dimensional displays. This possibility prompted a further study using 3-dimensional solid analogs to the zig-zag displays shown in Fig. 1.3b. Four-month-old infants again were habituated to a partly occluded zig-zag rod and then were shown a complete rod and a broken rod at test. Under these conditions, infants showed no consistent pattern of preference for either of the test displays (Smith, Johnson, & Spelke, in preparation). In contrast to results with 2-dimensional displays, infants here appeared to form no determinate perception of object unity: They did not see the occlusion display either as a single unified object or as two distinct objects.

This finding suggests that richer depth information makes the misalignment of an object's edges less salient or compelling than it is in 2-dimensional displays. Nevertheless, the misalignment must be detected by the infants, because they otherwise should have perceived a connected object in the habituation display and shown a clear test preference for the broken rod. It appears that the addition of 3-dimensional depth cues has tipped infants toward the perception of object unity, but not far enough to completely override the conflicting misalignment of the rod ends.

Why then do infants perceive the rod-polygon display (Fig. 1.3c) as a single object? In this moving, 3-dimensional display, the edges of the rod and polygon are misaligned, but infants perceive this partly occluded object as unified. The contrast between infants' perception of the rod- polygon and zig-zag displays suggest that perception of object unity depends more on the alignment of the axes of orientation of an object than on the alignment of its outer contours (see Tse, 1999). Although the outer contours of the rod-polygon would not meet if smoothly extended, the surfaces bounded by these contours would meet. Planned experiments will test this possibility.

Because the abovementioned experiments were conducted with 4-month-old infants, they raise questions about the origins of these abilities. By 4 months of age, infants may have accumulated enough experience with partly occluded objects to learn that when visible surfaces are aligned and move together, they belong to the same object. Initial results with neonates were consistent with the hypothesis that the abilities underlying the perception of object unity develop during the first 4 months. After habituation to a partly occluded rod, neonates consistently look longer at a complete rod than at a broken rod, providing evidence that the partly occluded display was not perceived as unified (Slater et al., 1990; Slater, Johnson, Brown, & Badenoch, 1996; Slater, Johnson, Kellman, & Spelke, 1994). Furthermore, Johnson and Náñez (1995) reported that 2-month-old infants showed an equal preference for the complete and broken test displays after habituation to a center-occluded rod. This finding suggests that there is an intermediate stage of object perception between birth and 4 months.

What events take place during this intermediate period? It is possible that qualitative changes occur in infants' perceptual organization. For example, mechanisms for grouping commonly moving surfaces or for extrapolating surfaces behind occluders may become functional between birth and 4 months. Alternatively, such mechanisms may be functional throughout development, but infants' perceptual systems may increase in sensitivity and precision. Older infants therefore may be better able to *detect* the common motion of surfaces that are separated in the visual array.

Research by Johnson and Aslin (1995) and Kawabata, Gyoba, Inoue, and Ohtsubo (1999) supports the latter possibility. Johnson and Aslin (1995) found that narrowing the height of the occluder at points along the path of a laterally translating rod improved 2-month-old infants' performance in a partial occlusion study. Contrary to the infants in Johnson and Náñez' (1995) study, these infants preferred the broken rod at test. Most dramatically, Kawabata et al. (1999) found that by presenting a moving high-contrast grating of repeating bars rather than a single bar, even 3-week-old infants perceived the grating to continue behind the occluder. Both grating contrast and occluder size were critical for this perception, as 3-week-old infants failed to perceive the complete grating when the occluder was widened as the grating narrowed. These findings provide evidence that these infants perceive the unity of an object or pattern over partial occlusion. The change in performance that occurs as an infant matures over the first 4 months appears to stem primarily from increases in sensitivity to motion and spatial contrast over a spatial gap. These findings support the continuity thesis.

In addition to the configural cue of contour alignment, adults also make use of the similarity of surface color, texture, and pattern in perceiving object unity. For example, adults readily perceive the dots in Fig. 1.4a as arranged in a triangular configuration despite the presence of the intermingled crosses. Similar elements tend to be grouped together. How do these surface relationships influence infants' perception of partly occluded objects?

In most of the object displays discussed thus far, the visible portions of the display have been similar in appearance and have shared such attributes as color, texture, and shape. Because the single exception—the rod and polygon display of Kellman and Spelke (1983)—was perceived as connected, some investigators concluded that young infants do not use the configural cue of surface similarity in perceiving object unity (Kellman & Shipley, 1991; Kellman & Spelke, 1983). As in the case of contour alignment, however, this conclusion was premature. There is now evidence that infants do exploit differences in surface appearance in determining object unity, especially when objects are presented in motion.

Experiments by Needham (1997) provided evidence that infants use dissimilarities in surface color, pattern, and shape to perceive object boundaries. Although most of Needham's experiments focus on infants' perception of the boundaries of fully visible, adjacent objects, one line of research focused on perception of center-occluded objects. In one experiment (Needham, 1994; Needham, Baillargeon, & Kaufman, 1998), 4-month-old infants were shown a display in which two boxes were visible to the left and

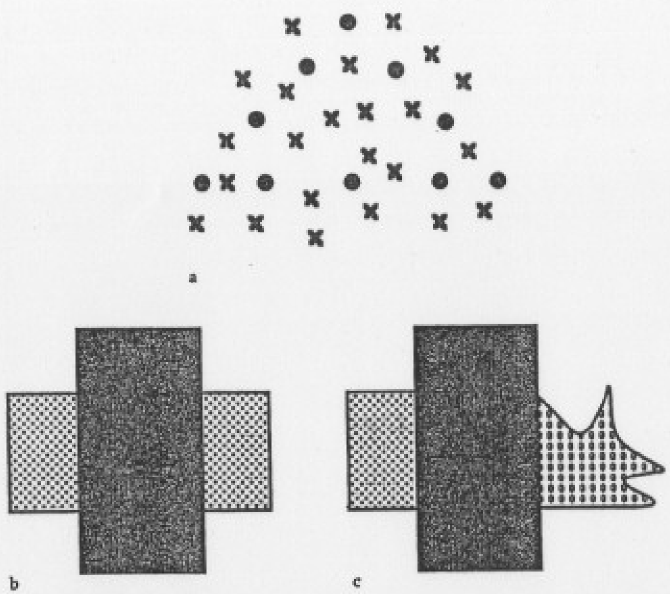

FIG. 1.4. Displays used in studies of effects of surface texture and similarity on perceptual grouping and object perception (parts b and c, similar and dissimilar boxes, adapted from Needham et al., 1998).

right of a nearer object that partly occluded them. In one condition, both boxes were red and rectangular (Fig. 1.4b); in a second condition, the left box was red and rectangular but the right box was green and irregularly shaped (Fig. 1.4c). Perception of the connectedness or separateness of the boxes was tested by comparing infants' looking time to events in which a hand moved one of the boxes and the other box either moved with it (implying a connection between the boxes) or remained at rest (implying no connection). Infants in the first condition showed an equal preference for the move-together and move-apart events, suggesting that they had no determinate perception of the unity or separateness of the boxes. In contrast, infants in the second condition looked longer at the test display in which the red and green surfaces moved together. This looking pattern provides evidence that infants had formed an expectation, based on the dissimilar appearance of the two surfaces, that these surfaces belonged to two distinct objects.

Four sets of findings nevertheless suggest strong limits to infants' use of surface color and texture similarity to perceive objects. First, infants fail to use the common colors and textures of stationary, center-occluded objects to perceive their unity (Kellman & Spelke, 1983; Slater et al., 1990). Second, infants perceive the unity of a moving, center-occluded object just as

strongly when its visible surfaces differ in color and texture as when they are the same color and texture (Kellman & Spelke, 1983). Third, recent studies provide evidence that infants fail to use common *changes* in the color and texture of stationary, center-occluded objects to perceive their unity (Jusczyk et al., 1997). In these studies, infants viewed either 3-dimensional displays or 2-dimensional videotaped displays containing a moving or stationary center-occluded object. In all the displays, the object changed brightness and color throughout the study, either suddenly or gradually, at various rhythms. Infants were very interested in these changes, as judged from their long looking times to the displays. They also dishabituated to a broken object test display when the object in the occlusion display had appeared in motion. When the occluded object was stationary, however, infants looked equally at the test displays with complete and incomplete objects. Although the synchronous color and brightness changes drew infants' attention, those changes failed to specify a connected object.

Fourth, further studies by Needham (1997) showed that infants fail to use similarities and dissimilarities in the colors and textures of objects to perceive the boundaries of two adjacent objects under certain conditions. Infants were presented with two adjacent objects of contrasting colors and textures and misaligned edges. In one set of conditions, the objects were angled such that the place where they touched was hidden. Perception of the boundary between the objects again was assessed by observing infants' looking times to events in which a hand pulled one object and the other object either remained at rest or moved with it. Infants looked equally at the two test events, suggesting that they failed to perceive the boundary between the objects.

What accounts for this pattern of findings? The analyses of 2-month- old infants' failure to respond to the common motion of surfaces by Johnson and Aslin (1995), discussed earlier, suggests an answer. Infants may have the same propensity as adults to group surfaces of common colors and textures into single units. With development, however, infants may become better able to detect when two surfaces are similar and when they are not, especially when the surfaces are separated by a gap in the visual field. It is noteworthy that in all cases where infants have failed to respond to the similarity of two surfaces, the border between the surfaces has been hidden, either behind a separate occluding object (e.g., Jusczyk et al., 1997) or behind an occluding surface of one of the two objects (e.g., Needham, 1997). Following the logic of Johnson and Aslin (1995), therefore, infants should successfully use surface similarity to specify object boundaries when the area of occlusion is reduced or eliminated.

Recent research by Needham (1997) confirmed this prediction. Needham presented infants with the same displays of adjacent objects as in the earlier studies, with one change: The objects were rotated so that the point at which they touched was directly visible. In this condition, infants looked longer at the test event in which the hand pulled one object and both objects moved together, providing evidence that they perceive the two objects as separate units. Studies of infants' reactions to surface similarity therefore suggest continuity in the mechanisms of object perception over development, with an increase in sensitivity to the information on which those mechanisms operate.

We believe that these studies favor the continuity thesis for the perception of partly occluded objects. Although early results seemed to indicate that infants relied on dynamic information alone and neglected configural information in perceiving object unity, more recent studies suggest that infants are able to use all the sources of information used by adults, including motion, contour alignment, and surface similarity. Where infants' perceptions are less clear than those of adults, this difference appears to reflect infants' lower sensitivity to these sources of information. Developmental changes in perception of partly occluded objects may stem more from increases in sensitivity than from qualitative changes in processes of visual organization.

PERCEPTION OF ILLUSORY FIGURES

Illusory figures provide a second test case for examining the development of perceptual organization in infancy. Illusory contours are edges and lines that are perceived across areas where there are no luminance differences to indicate a contour. The illusion is created by the careful positioning of inducing elements, which are themselves luminance-defined figures perceived as being partly occluded by the illusory edge. Because illusory contours are experienced as real contours differing in brightness from their surroundings, the completion of the illusory figure is a case of modal completion (in contrast to amodal completion in partial occlusion displays). If the inducing elements are arranged slightly differently or rotated so that their gaps are not aligned, the display radically changes character, no longer creating an illusion. Illusory figures are useful for studying perceptual organization precisely because they exist only in the relationship between the inducing elements, and this allows for the creation of comparison figures that are highly similar in their local components but very different in global form.

The first illusory figure was introduced by Schumann (1900/1987), who made two important observations: The illusory figure appears to have sharp edges that cut across an area of homogeneous luminance, and the figure itself appears to be brighter than the background on which it appears. Schumann's discovery went unheralded for over half a century, until

Kanisza (1955/1987) developed an illusory figure that was so perceptually salient, it sparked an explosion of research that has continued to the present day (Fig. 1.5a). The Kanisza triangle consists of three circles (inducing elements), each with a trisection removed, oriented as if at the corners of a triangle. This display is perceived clearly by most adults as a central white triangle, brighter than the background, resting atop three complete black circles (Kanisza, 1955/1987).

There are several types of illusory contour displays, of which the most commonly studied are edge-induced displays and kinetic displays. In edge-induced illusory figures like the Kanisza triangle, the inducing elements are figures in themselves, perceived as objects (discs) that are partially occluded by an overlaying object (the triangle). The gaps in the inducing discs mark the corners of the occluding triangle, and illusory edges are perceived to span the open area between the discs, despite the absence of luminance changes in this part of the display. In kinetic illusory figures, the illusion is created over time by the progressive permutation of inducing elements. Kinetic illusory contours typically are created on computer displays in which the boundaries of stationary inducing elements on a solid background are altered, consistent with occlusion by a rigid object the same color as the background. This type of kinetic display leads to the perception of an illusory object that progressively covers and uncovers portions of the inducing elements (Kellman & Cohen, 1984; Fig. 1.5b).

When adults are presented with illusory figures such as the Kanisza triangle, they typically observe four characteristics. The illusory triangle appears to be occluding portions of the inducing discs, whose edges are perceived as complete circles behind the triangle. The illusory triangle appears to be closer in depth than the discs it occludes. The edges of the triangle seem to be clearly defined across the gaps between the discs, despite the absence of luminance differences. And finally, the illusory triangle appears to be brighter than the background on which it appears. Research into adult perception of illusory figures has focused on the relative importance of each of these characteristics, as well as the stimulus variables that affect the overall strength of the illusory figure.

Psychophysical research has revealed several factors that affect the strength of the illusion, and here we find similarities to the factors that influence perception of partly occluded objects as well. Early research suggested that the size of the inducing elements affected the salience of the illusory figure, and that illusions subtending smaller visual angles were less compelling (Dumais & Bradley, 1976). However, more careful psychophysical study has determined that the critical variable is the ratio of the amount of edge that is specified by the inducing element (the supported edge) to the size of the gap (the unsupported edge; Shipley & Kellman, 1992). Thus the relative amount of edge that is not specified and must be

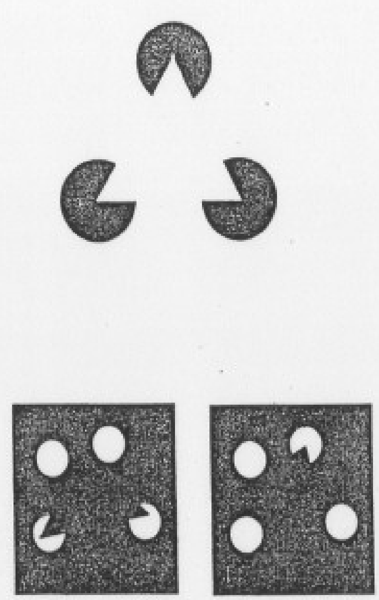

FIG. 1.5. Displays evoking perception of illusory contours in adults (after Kanizsa, 1955/1987; Kellman & Cohen, 1984).

modally interpolated by the observer has an impact on whether an illusory figure is seen and how powerful the illusion is.

Early illusory contour displays employed simple regular forms both as inducing elements and as illusory figures (e.g., Fig. 1.5a), but later studies determined that neither the figure nor the inducing elements need be simple or regular to produce the illusion (Kellman & Shipley, 1991). Regardless of their shape, however, the discontinuities in the inducing elements must be "relatable" in order for an illusory figure to appear (Kellman & Shipley, 1991). As in the case of partial occlusion displays, these discontinuities are relatable if a smooth, monotonic curve can be interpolated between them. When the elements' gaps are not relatable, no illusion is perceived, and the display appears to consist of the inducing elements alone. The common conditions on relatability for illusory contour and partial occlusion displays suggests that perceptual organization depends on similar processes in these two situations (Kellman & Shipley, 1991).

In addition to edge length ratios and edge relatability, numerous other factors have been found to influence perception of illusory contour displays, and studies attempting to specify these factors and their interrelations precisely have yielded conflicting results (see Lesher, 1995; Parks, 1986, for reviews). From the adult research, it has been impossible to find a

single necessary component for the perception of illusory figures. Indeed, it appears increasingly unlikely that there is one unitary explanation for all illusory figures. This impasse provides a powerful reason for investigating the development of perception of illusory contours in infants, to examine the origins and emergence of the perception of their various characteristics. When infants first begin to see these illusions, we may ask what factors influence their perception and what other perceptual processes and capacities emerge at that time. In this way, we may shed light on the basic mechanisms giving rise to perception of illusory contours at any age.

In contrast to the wealth of research with adults, little research has focused on how infants perceive illusory figures as a means of understanding their genesis in visual processing. Nevertheless, a number of investigators have asked when infants first perceive illusory contours, and their findings suggest paths for future research to follow.

The question of when infants begin to perceive the illusion in illusory figure displays is simple to pose but difficult to resolve. Trieber and Wilcox (1980) examined how very young infants perceive a Kanisza triangle. One- to four-month-old infants were habituated to an illusory triangle and then were tested with three comparison displays: a real triangle, a nonillusory display composed of the same inducing elements rotated so that their gaps were not aligned, and an unrelated shape with the same amount of total contour (Fig. 1.6a). Results showed that infants dishabituated to the unrelated shape but transferred habituation to both the real triangle and the nonillusory display. These results suggested that infants note a similarity between the real triangle and the illusory figure, but the fact that they also perceived a similarity between the illusory triangle and the nonillusory display suggests that they may have responded to the triangular configuration of the inducing elements rather than to any perceived illusory triangle. Infants' lack of differential responding to the illusory and nonillusory triangular displays of inducing elements weakens the interpretation that young infants perceive illusory figures in the same manner as adults.

Bertenthal, Campos, and Haith (1980) advanced the study of infants' perception of illusory figures by asking whether 5- and 7-month-old infants can distinguish an illusory figure from a pair of nonillusory displays composed of the same inducing elements in the same global positions. Their central display presented an illusory square, evoked for adults by four inducing discs with a single quadrant removed, arranged as if at the corners of a square with their gaps facing centerward. Nonillusory comparison displays were created by rotating either two or four of the inducing elements outward, so that the inducing elements were symmetrically arranged into the same square configuration without creating any illusion (Fig. 1.6b). The cleverness of this comparison is that if one attends solely to the orientation of the local elements in the different displays, there is the same amount of

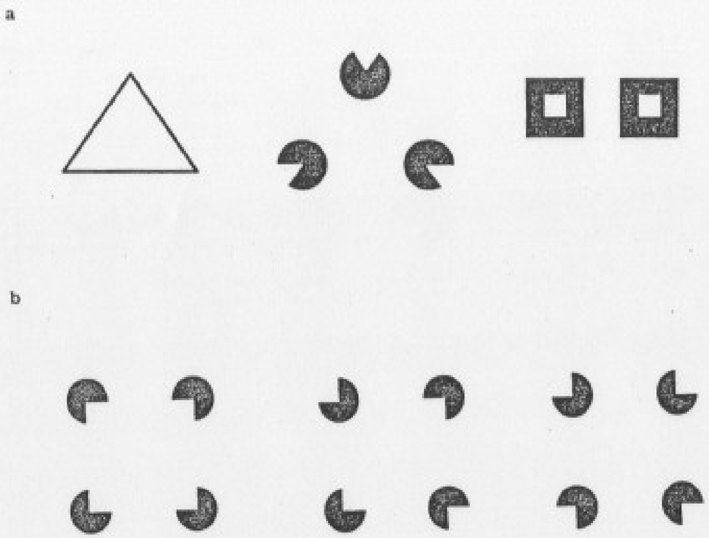

FIG. 1.6. Displays used in studies of infants' perception illusory contours (after Trieber & W[illegible], 1980; Bertenthal et al., 1980).

difference between the illusory display and the nonillusory display with two rotated elements as between the two nonillusory displays with two versus four rotated elements. Following habituation to one of the displays, infants were tested with the other two displays. If infants responded only to local elements, then habituation to the two-element rotated display should have generalized equally to the four-element rotated display and to the illusory contour display, and the reverse. If infants responded to the global configuration of these elements as do adults, then habituation to either nonillusory display should have been followed by greater dishabituation to the illusory display, and the reverse.

In their experiment, 7-month-old infants dishabituated to a change from the illusory figure to a nonillusory display, but not from one nonillusory display to the other. These findings provided evidence that the infants responded to the global configuration of the display rather than simply the orientation of the individual inducing elements. Five-month-old infants' attention showed a trend in the same direction, but their looking patterns were less consistent. The authors interpreted these findings cautiously to suggest that older infants attended to the global configuration of the illusory display and treated it differently from other configurations of the same elements.

Bertenthal et al. (1980) stopped short of claiming that infants perceived the illusory form in their experiments, because this stronger interpretation requires the elimination of alternative explanations in terms of lower level sensory processing. In particular, the illusory square figure used in the experiments contains a central, open area that could be distinguished from the nonillusory displays on the basis of low-spatial frequency information alone, irrespective of perception of the illusory figure. Bertenthal et al. (1980) suggested that the solution to this problem is to create a nonillusion comparison display in which the inducing elements retain the same orientation but are misaligned. This study has not yet been attempted.

A further study of young infants' perception of illusory figures used the logic of Bertenthal et al. (1980) with a paired-comparison visual preference procedure. Ghim (1990) habituated 3- and 4-month-old infants to an illusory square or 1 of 3 nonillusory shapes (produced by rotating 2 or 4 of the inducing elements) and then tested infants' discrimination of the other displays with a paired preferential looking paradigm. Infants were found to discriminate the illusory display from some of the nonillusory displays but not from other nonillusory displays. The reasons for the discrepancies among responses to the nonillusory displays were never fully explained. Because the infants did consistently treat all the nonillusory displays as indistinguishable from one another, however, Ghim's findings suggest that the successful discriminations depended on detection of some aspect of the global organization of the illusory figures.

To our knowledge, only two studies have examined whether infants perceive illusory figures in kinetic displays. The first study examined how 5- and 8-month-old infants generalize habituation between real squares, disconnected corner elements, and a variety of kinetic illusory square displays. Kaufmann-Hayoz, Kaufmann, and Walther (1988) habituated infants to either a real stationary square or a set of four disconnected right angle elements, and then tested infants with three displays in which the corners of an illusory square were specified. The test displays consisted of a standard stationary illusory square, a jiggling square in which the four inducing elements were deformed to produce the percept of an illusory square oscillating back and forth (with all four corners of the square specified at all times), and a display in which the illusory square appeared to rotate in place, such that only two corners of the illusory figure were specified at any one time. The relevant comparisons in this study were between habituation conditions. At the older age, infants dishabituated more to all the illusory figures after habituation to the four disconnected right-angle elements than after habituation to the real square. In other words, the 8-month-old infants treated the static illusory square, the jiggling illusory square, and the rotating illusory square as more similar to a real square than to a set of disconnected corner elements. At the younger age, this pattern was observed for the stationary illusory square and for the jiggling illusory square but not for the rotating square. Kaufmann-Hayoz et al. interpret these results to suggest that at 8 months, but not at 5 months, infants were able to integrate the spatiotemporal information required to perceive the rotating illusory figure.

Although 5-month-old infants did not appear to perceive illusory contours from kinetic information alone, the findings of Kauffman et al. suggest that these infants do perceive a stationary and an oscillating illusory square as more similar to a real square than to a set of right angle elements that partially match the local components of the illusory figures. Although this comparison does not necessarily provide evidence that infants see the illusory square as a real figure, it does indicate that they are not simply perceiving the local angles of the inducing elements in the illusion displays. This study is similar to Trieber and Wilcox's (1980) early work with static illusory figures, in which infants judged a real figure as similar to the illusory figure, but it is not entirely clear what basis infants are using for the judgment. The more compelling result from the older infants suggests that they are capable of the spatiotemporal integration required to perceive the rotating illusory figure, and treat that display, which is dissimilar to the real square from any static view, as more similar over time to a real square than to disconnected corners.

Using apparent motion illusory figure displays, Condry, Gentile, and Yonas (1992) examined whether 4- and 7-month-old infants could discriminate a moving illusory square from a nonillusory control pattern in a preferential looking paradigm. In the first study, 7-month-old infants were presented with a video display consisting of two rows of 10 white semicircular inducing elements on a black background. On one side of the display, four of the inducing elements were rotated so that their gaps faced inward, creating an illusory square, and on successive frames the inducing elements rotated in place, such that the illusory square appeared to move from the center to the end of the row and back to the center again. The apparent motion of the illusory figure was mirrored on the other side of the display by the same motion of a set of four inducing elements with their gaps facing outward, following the logic of Bertenthal et al. (1980). All of the inducing elements not involved in creating either the illusory or the nonillusory display on a particular frame were rotated so that their gaps did not align with any other gaps (Fig. 1.7). When adults viewed this video display, they reported clear perception of an illusory square moving on one side of the screen. They also reported that they were unable to track the movement of the nonsquare set of elements, even when instructed to do so.

To investigate infants' perception of this display, their preferential looking and tracking of the side of the display with the illusory square was compared to their looking and tracking of the other side of the display. Results

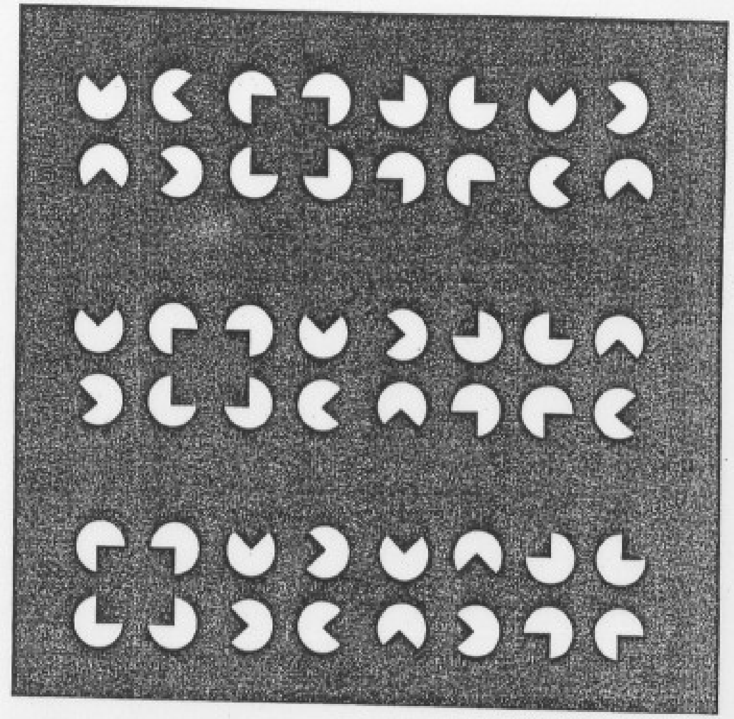

FIG. 1.7. Displays used in a study of infants' perception of illusory contours in a moving display (after Condry et al., 1992).

showed that 7-month-old infants reliably attended to the illusory square side of the display, suggesting they too perceived the illusory figure. Because this display is similar to the ones used in the Bertenthal et al. (1980) and Ghim (1990) studies, however, it is subject to the same interpretive ambiguity as those studies. In all of these experiments, infants were presented with the task of discriminating an illusory square containing low spatial frequency information (because the gaps in inducing elements all faced inward) from a nonsquare group that did not contain low spatial frequency information. In each case the infants responded consistently with the perception of the existence of the low spatial frequency information, and their response cannot clearly be attributed to the perception of illusory figures.

To address this problem, Condry et al. (1992) created a second display in which the inducing elements were alternately colored in reverse contrast (so that a white element appeared next to a black element) on a medium gray background. In this type of display, the low spatial frequency information is no longer present, indeed adults who squinted their eyes to remove high spatial frequency information were unable to discriminate the illusory figure side of the display from the nonillusory side. All other aspects of the display remained the same as in the previous experiment, and 4- and 7-month-old infants' preferential looking to this new kinetic display was measured.

Results again indicated that 7-month-old infants perceived the illusory figure in this apparent motion display, consistently attending preferentially to the illusory side of the display. To our knowledge, this finding presents the first evidence that 7-month-old infants' response to illusory contour displays does not depend on low-level contrast-detecting mechanisms but on a sensitivity to the higher level perceptual organization of the display. This finding strengthens the conclusion that 7-month-old infants perceive illusory contour displays as do adults.

Nevertheless, findings with 4-month-old infants were equivocal: These infants showed a significant side bias that was not influenced by the position of the illusory figure. Although this finding suggested that 4-month-old infants failed to detect the illusory figure, two kinds of interpretations for this failure could be offered. First, young infants specifically may fail to organize inducing elements into groups of layered surfaces so as to perceive illusory contours as do adults. Second, young infants may show lower sensitivity to real as well as illusory figures, or lower abilities to control attention so as to track figures that move. To distinguish these possibilities, a control study was conducted with the 4-month-old infants, in which a similar kinetic display that contained a real, light gray square substituted for the illusory square. Because a real square was present, Condry et al. (1992) reasoned that infants should attend to this display if their failure in the first experiment depended specifically on a failure to perceive the illusory figure. Contrary to this prediction, 4-month-old infants again showed inconsistent preferences between the two sides of the display. These findings are consistent with the possibility that spurious display factors prevented the young infants from responding to both the illusory and the real square. Condry et al. (1992) concluded, therefore, that 7-month-old infants' responses were consistent with perception of the illusory figure but that the results from the 4-month-old infants could not be clearly interpreted.

The question whether infants perceive the central illusory figure in standard illusory contour displays thus receives an affirmative answer at 7 months, but it has yet to be answered satisfactorily at younger ages. And what of the other characteristics of adults' perception of illusory contour displays? Only one study has attempted to determine whether infants perceive the amodal completion of the inducing elements in the same manner as adults. Four- and seven-month-old infants were habituated to either an illusory square with incomplete discs as inducing elements or to a nonillusory display in which all four inducing elements were rotated outward, and then they were tested with a single, semicircular inducing element or a

single complete disc (Condry & Yonas, 1998; Fig. 1.8). If infants perceived the illusory square as occluding four complete discs, then they should have dishabituated to the single inducing element, whereas infants habituated to the nonillusory display should have dishabituated to the complete disc. Seven-month-old infants showed this pattern of response, suggesting they perceived the amodal completion of the inducing elements when they were habituated to the illusory square. The results from the 4-month-old infants again were equivocal, as the infants in both conditions showed no preference between the test displays with complete versus incomplete discs. If the younger infants had shown a clear preference for the complete disc after habituation to the illusory display, this would have suggested that they perceived the individual elements of the illusion display but not the illusory occlusion. The finding of no preference leaves open the possibility that infants noted some aspects of the global configuration and possibly even the occlusion, but did not clearly perceive the amodal completion of the inducing elements. Regardless of how one interprets the results at 4 months, however, the results from infants at 7 months provide strong evidence that they perceived the inducing elements in the illusory display as continuing behind a central, illusory figure.

In summary, there is consistent evidence that infants over the age of 6 months perceive the global organization in illusory figure displays, but more research is required to determine exactly what infants are perceiving. In particular, no research has examined whether infants perceive the brightness or depth effects in illusory figure displays. Moreover, more research is needed to probe the earlier development of perception of illusory contours. Although younger infants show trends in each study similar to the responses of older infants, they are less consistent in their responses.

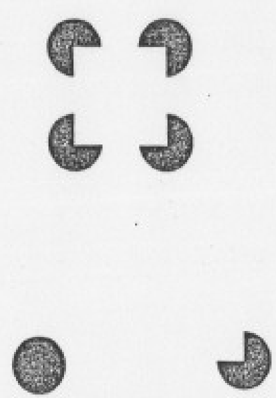

FIG. 1.8. Displays used in a study of infants' amodal completion of inducing elements in an illusory contour display (after Condry & Yonas, 1998).

Investigators also are less consistent in their findings and interpretations of young infants' responses. For example, Ghim (1990) claimed that 4-month-old infants distinguish between illusory and nonillusory figures, but Bertenthal et al. (1980) and Condry et al. (1992) were unable to find clear evidence for early perception of illusory figures using similar displays.

Careful examination of the displays used by these investigators may provide an explanation for their discrepant findings. If the amount of edge that needs to be interpolated in partly occluded figures determines whether young infants perceive completion of the occluded objects, perhaps the same factor influences perception of illusory figures as well. The illusory figure in the Ghim (1990) research subtended a considerably larger visual angle than the illusory displays in the other studies, and it had a smaller gap (unsupported edge) between the elements than did the displays of Bertenthal et al. (1980). Because the ratio of supported to unsupported edge affects whether adults see salient illusory contours, infants too may be less sensitive to edge relationships over larger gaps. Theorists agree that the alignment of the gaps in the inducing elements is critical to perceiving illusory figures. The findings by Johnson and Aslin (1995) that young infants perceive the unity of partly occluded objects and patterns when the occluder is narrowed suggests that illusory figures with smaller gaps (unsupported edges) might be perceptible to younger infants as well.

Although studies of infants' perception of illusory contours have revealed a number of changes in infants' performance between 4 and 7 months, these findings provide no clear evidence for a qualitative, developmental change in infants' perception. Instead, the evidence suggests that the organizational processes that give rise to perception of illusory contours are present in very young infants but fail to operate on standard illusory contour displays because of limits on infants' sensitivity to contour alignment. Note that the illusory contour displays presented to infants have had contour separations of 1.2° or more: far greater than the separations used in the studies of partly occluded objects. As in the case of partly occluded objects (Johnson & Aslin, 1995), therefore, apparent qualitative changes in infants' perception of illusory contours may stem from an increase in the distance over which contour alignment is detectable. If that suggestion is correct, then developmental increases in sensitivity to alignment may account for developmental changes in perception of both partly occluded objects and illusory contours. Except for these changes, the same organizational processes may operate in infants as well as adults.

IMPLICATIONS

In this chapter, we have attempted to reconcile the evidence for developmental change in object perception with the continuity thesis: the claim that perceptual organization is responsive to the same types of perceptual

information, at all ages. All of the developmental changes we have considered are consistent with this thesis, if one assumes that visual sensitivity to this information increases over development. That assumption, in turn, is hardly controversial, for the thesis that visual sensitivity increases over infancy has overwhelming empirical support (see Kellman & Arterberry, 1998; Kellman & Banks, 1998). The twin theses of developmental continuity and developmentally linked increases in sensitivity nevertheless have some interesting, and problematic, consequences.

One consequence of infants' developing perceptual sensitivity is that continuous changes in underlying processes can produce discontinuous changes in perception and perceptually guided action (see Banks & Shannon, 1993). For example, as infants' sensitivity to edge alignment increases, allowing infants to detect alignment over greater and greater visual separations, infants' perception of illusory contour displays may shift from perception of a set of unrelated elements to perception of a set of surfaces, with complete edges, arranged in depth. The continuity thesis therefore is consistent with findings of certain qualitative changes in infants' perception.

A related consequence of children's developing sensitivity is that studies of perceptual development must distinguish *competence* from *performance*. For example, when one studies newborn infants' perception of center-occluded objects, one wants to know whether the mechanisms by which adults interpolate hidden surfaces and perceive unitary, partly hidden objects are present and functional at birth. When one finds, as did Slater et al. (1990), that such infants do not respond to a fully visible connected object as similar to a partly occluded one, however, one cannot conclude that this perceptual competence is absent. It is possible that mechanisms of surface interpolation are present and functional, but that their performance is blocked by limits on infants' sensitivity to the information on which they operate. This possibility, in turn, can be tested by measuring newborn infants' sensitivity to the relevant information and by designing displays that minimize the demands on their sensory systems (see Slater et al., 1996, for an example).

If visual sensitivity is extremely limited at birth, however, there may be no displays for which certain perceptual competencies will be manifest. In that case, investigators will need to change strategy to study developing perceptual competence.

One strategy is to study the competence in other animals: either animals with precocial visual sensitivity or animals whose visual experience can be strictly controlled. For example, studies by Regolin and Vallortigara (1995) and by Lea, Slater, and Ryan (1996) now provide evidence that 1-day-old chicks, who have never been exposed to any occlusion display, perceive the unity of both stationary and moving center-occluded objects. Inexperienced chicks use both contour alignment and common motion to perceive object unity, casting doubt on earlier claims that sensitivity to contour alignment depends on visual experience (Spelke, 1990).

A second strategy is to probe the mechanisms of object perception using the methods of cognitive neuroscience. For example, experiments probing the neural locus for perception of illusory contours in human adults (e.g., Paradiso, Shimojo, & Nakayama, 1989), monkeys (e.g., Peterhans & von der Heydt, 1989; von der Heydt & Peterhans, 1989), and cats (Bravo, Blake, & Morrison, 1988; Redies, Crook, & Creutzfeldt, 1986) provide evidence that illusory contour perception reflects activity in early visual cortical processing areas. As techniques for imaging neural activity in humans become increasingly available for studies of infants and children, these findings should allow investigators to probe whether similar patterns of neural activity occur in infants.

A third strategy for investigating "hidden" competencies in infants is to test for linkages, in human infants, between developmental changes in perceptual sensitivity and developmental changes in perceptual organization. For example, if infants' failure to perceive the unity of a moving, center-occluded object stems from a failure to detect the common motion of its spatially separated surfaces, then their perception should shift at the point in development when sensitivity to the relevant motion emerges. The existence of all three strategies suggests, contrary to frequently heard criticisms (e.g., Thelen & Smith, 1994), that the competence–performance distinction is not a source of untestable claims but rather a call for further research, exploring the development of perceptual capacities from multiple perspectives (see Spelke & Newport, 1998, for discussion).

Where the continuity thesis is found to be correct, and investigators succeed in tracing the perceptual competencies of adults back to the youngest infants, this endeavor has implications both for the study of vision and for the study of cognition. We end by considering each in turn.

Research on the nature and mechanisms of visual organization has focused on four problems. One is the problem of characterizing the nature of perceptual organization in human adults, a problem addressed primarily through studies of visual psychophysics. Second is the problem of characterizing the neural mechanisms that give rise to perceptual organization, a problem addressed primarily through studies of visual anatomy and physiology. Third is the problem of characterizing the computational processes that give rise to perceptual organization, a problem addressed primarily through studies of artificial vision systems. Fourth is the problem of characterizing the development of perceptual organization in relation to growth and experience, a problem addressed through studies of human infants and young children and through studies of other animals.

As already noted, these problems tend to be pursued by scientists in different disciplines, but findings that bear on one problem frequently bear on the others. In particular, we suggest that studies of infants can make a singular contribution to understanding perceptual organization at psychophysical, neural, and computational levels, if the continuity thesis is correct. In adults, basic mechanisms of perceptual organization are complemented and modulated by a wealth of acquired knowledge and learned strategies, and this knowledge may obscure aspects of their functioning. Moreover, the mature brain is highly interactive, and interactions among different subsystems complicate the task of analyzing any single subsystem. By analyzing perceptual functioning in young infants, we may see the operation of basic perceptual mechanisms in purer form.

The implications of the continuity thesis for studies of cognition and cognitive development are no less important. If the continuity thesis is correct, then infants perceive fundamentally the same world as adults. Although infants' perceptions often may be indistinct and indeterminate where those of adults are sharp and clear, infants' clearest perceptions will accord with those of their elders. Insofar as infants learn from their perceptual experiences, the things they learn should not need to be unlearned at older ages. Instead, the development of knowledge in infancy could stand at the foundation of the systems of knowledge that serve humans all our lives.

The continuity thesis has often been presented as an alternative to the thesis that infancy is a time of extensive, rapid, and all-important learning (e.g., Haith, 1998). In fact, we suggest, these are complementary theses. If infants perceive the same world of objects as adults, then infancy is likely to be a time of extensive learning about that world. Learning in infancy can mesh smoothly with later learning, building the belief systems that guide our thoughts and actions as adults. For those who would foster human development, the infancy period could be a time when learning experiences will have lasting consequences. Understanding what infants perceive and learn therefore will be central to understanding the foundations of human knowledge.

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CHAPTER

2

Task Dependency in Infant Behavior: Toward an Understanding of the Processes Underlying Cognitive Development

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Infants can appear precocious or limited in almost any domain depending on the task administered to them. For example, 3.5 month-old infants demonstrate apparent sensitivity to hidden objects in violation-of-expectation experiments (Baillargeon, 1993), yet infants fail to retrieve hidden objects through 8 months (Piaget, 1954). Such simultaneous failures and successes are arguably equally important aspects of development, because the same developing system produces both the flawed and the competent behaviors. Accounting for both thus seems to be critical for understanding the origins of knowledge (see discussion in Braine, 1959; Brown, 1976; Flavell, 1985).

This chapter focuses on understanding why infant behavior is so task dependent. Why do infants simultaneously fail and succeed on different tasks meant to measure the same knowledge? What might this tell us about the nature of cognitive development? How can we understand the changes that underlie these developmental patterns? This chapter explores these questions in the context of the Piagetian notion of object permanence, the understanding that objects exist independent of our percepts of them and maintain their identity through changes in location. I contrast two approaches to these questions—principle based and process based. The more prevalent principle-based approach assumes that knowledge takes the form of generally accessible principles. Early signs of competence indicate that infants have the tested principle, so task dependencies must be attributed to deficits in ancillary systems. In contrast, the process-based approach focuses on the mechanisms underlying particular behaviors. These