Chapter 4

Origins of Visual Knowledge

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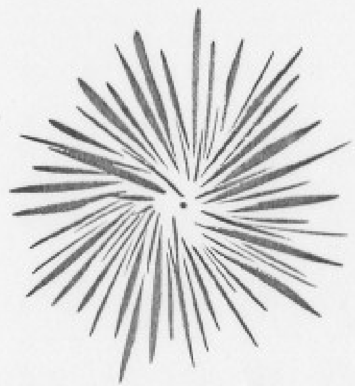

A new enterprise has emerged over the last thirty years: the experimental study of visual perception and visual processes in human infants. This enterprise, made possible by the development of some simple techniques, has been fruitful in a number of ways. First, it has led to a greater appreciation of young infants and their abilities. Infants, we now know, have considerable capacity to make sense of the world. Second, it has given pediatricians, and those engaged in medical research, ways of assessing problems in the development of individual infants and insights into the potentially harmful effects of early sensory abnormalities. Third, it has helped neurobiologists and psychobiologists to chart relationships between visual experience and its physical basis, through studies of how perception changes with the development of the nervous system. Fourth, it has begun to reveal something about human beings as adults: our visual processes, visual experience, and visual knowledge.

The present chapter focuses on this fourth set of insights, for it is here that the study of early visual development joins the enterprise of cognitive science. As philosophers and psychologists have long hoped, studies of the origins of visual knowledge are beginning to suggest which aspects of visual experience are intrinsic to humans, deriving from biologically given capacities, and which aspects depend on the particularities of our encounters with light-reflecting surfaces and objects. In addition, these studies are beginning to suggest how our mature capacities are structured. Since our earliest developing perceptual capacities give rise to the first experiences through which we learn, the things we learn will bear their imprint. Initial visual capacities will therefore tend to remain central to our experience of the visual world. Moreover, those initial capacities will set boundaries on what we are capable of learning, limiting the states of the world that we are able to perceive or understand. Studies of infancy therefore promise to shed light on the nature and the limits of the cognitive functioning of adults.

4.1 Problems for a Developing Visual System

There are two basic problems that the newborn infant's visual system must solve. First, that system must be able to learn, improving its operation in response to the experience it receives. The need for a learning capacity is clear when one considers the perceptual accomplishments of adults. We as adults perceive three-dimensional arrangements of familiar and meaningful objects from highly limited arrays of visual information, such as static two-dimensional images of cluttered environments. Our ability to do this testifies, in part, to the knowledge we have acquired about the characteristic shapes, sizes, and arrangements of familiar objects. Moreover, adults adapt to new visual experiences: we adjust to unfamiliar optical devices (new glasses, a microscope) and acquire new visual skills (distinguishing species of birds, identifying types of baseball pitches). These adjustments also testify to the influence of experience on visual perception.

The need for a learning capacity is equally clear when one considers the physical growth of the visual system in infancy and childhood. Over the course of development each eye increases in size, the two eyes move farther apart, and neurons in the visual system undergo numerous changes of state, position, and connectivity. Perceivers must adjust to these changes, in order to avoid growth-related distortions of perception. For example, changes in the distance between the two eyes affect important sources of information for depth. Depth perception would become systematically distorted, with development, if perceivers could not adapt to these changes.

If perceivers are to learn from visual experience, however, their immature visual systems must deliver experience in usable form: they must detect some of the order that inheres in visual encounters with the surrounding world. This requirement places a different, seemingly contradictory demand upon the visual system. The system must include mechanisms, themselves unlearned, that order visual experience in ways that permit learning. The existence of perceptual learning thus raises two questions: what are the innate mechanisms by which humans first experience the visual world, and how are these mechanisms modified by the experiences they deliver?

In the rest of this chapter we will consider these questions and outline what appear to be some answers to them. We will on two aspects of visual development: first on the development of perception of the surface layout, particularly perception of surface arrangements in depth, and then on the development of object perception, particularly perception of objects as unitary, bounded, and persisting physical bodies.

4.2 Perception of the Surface Layout

4.2.1 The Problem of Surface Perception

For many centuries philosophers, physiologists, and psychologists have pondered the capacity of humans to perceive visible layouts of surfaces. Fundamentally, the puzzle of surface perception derives from the geometry of the surface layout in relation to the geometry of the arrays of light it reflects to the eyes. The layout itself is a three-dimensional array of surfaces. Each surface has a particular size, shape, and curvature, is encountered at a particular orientation, distance, and direction, and undergoes a particular pattern of motion or change. In contrast, visual information about the layout is contained in two two-dimensional arrays of light, one reflected to the retina of each eye, that preserve none of these properties in a straightforward way. Surface distance, orientation, and curvature are obviously lost when a three-dimensional layout is reflected onto a two-dimensional surface (see figure 2.2). Surface size and shape are also lost, because the size and shape of a surface's image are affected by the surface's distance and orientation. Even surface direction and motion are lost, because changes in the position of a surface's image occur constantly as the observer scans the layout by moving her eyes, head, or body.

As adults, we perceive a stable layout of three-dimensional surfaces, not two changing arrangements of two-dimensional forms. Our perception corresponds, at least approximately, to the true spatial properties of surfaces: things that look far away usually are far away. We perceive depth relations in the layout by detecting a variety of relationships within the patterns of light at the eyes. Two of these relationships are particularly important. First, there are systematic optical motions that occur as a perceiver moves through a rigid environment (Gibson 1966; Longuet-Higgins and Prazdny 1980) or as rigid objects move in front of him (Wallach and O'Connell 1953; Ullman 1979). The extent and the direction of the motion of any point in the image depend, in part, on the distance from the observer of its source in the layout. Human adults can perceive the three-dimensional relationships among surfaces by analyzing these two-dimensional patterns of optical motion. Second, there are systematic differences between the two images that a layout projects to the two eyes. For any given point in the layout, the magnitude of the difference in the location of its images depends, in part, on its distance from the observer. This relationship is the basis of *stereopsis*: human adults perceive depth by detecting these binocular differences, or "disparities."

4.2.2 Nativism and Empiricism

How does depth perception develop? This question has been at the heart of theories of visual perception for at least 300 years, since the French philosopher and mathematician René Descartes (1638) and the Anglican philosopher and theologian George Berkeley (1709) propounded sharply contrasting views of the development of visual knowledge. Although kinetic and stereoscopic depth perception were not recognized at that time, Descartes and Berkeley offered accounts of the development of depth perception that continue, in some ways, to animate theories of visual development. Much of their discussion focused on a different source of information for depth: the degree of convergence of the two eyes as they are directed to a single object.

Descartes noted that geometric principles govern the relationship between the convergence of the eyes and the distance of an object. When the two eyes are directed to the same object, the distance of the object and the distance between the eyes determine the eyes' angles of regard (figure 4.1). Thus, Descartes reasoned, a perceiver could compute object distance "by a sort of natural geometry" (1638, VI). Given a certain interocular distance and two angles of convergence, the distance of the object that is converged upon can be inferred. According to Descartes, knowledge of geometry originates in humankind's divinely given reason (Descartes 1637). Principles of geometry, grasped by humans innately and tacitly, allow us to infer the three-dimensional sources of two-dimensional stimulations.

In contrast, Berkeley denied that geometric computations enter into the apprehension of space: "I appeal to anyone's experience whether upon sight of an *object*, he computes its distance by the bigness of the *angle* made by the meeting of the two *optic axes*? ... In vain shall all the mathematicians in the world tell me that I perceive certain lines and angles ... so long as I myself am conscious of no such thing" (1709, XII). Instead, Berkeley proposed, space perception results from learned associations between sensations: in this case associations between the muscular sensations produced by turning the eyes inward to direct them at an object and the muscular

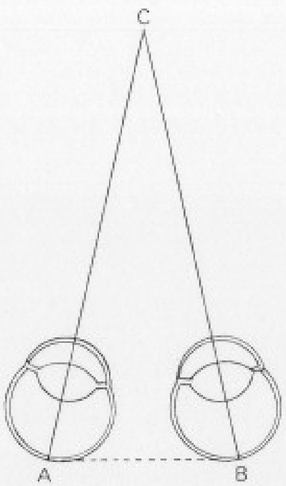

Figure 4.1
Schematic drawing (after Descartes, 1638, VI) illustrates the distance information provided by convergence. Given the distance between the centers of the two retinas (AB) and the eyes' angles of regard (∠CAB and ∠CBA), the distance of the fixated object C can be computed.

sensations that accompany other behaviors directed at the object such as reaching or locomoting toward it. In general, humans learn to see a three-dimensional world by associating the sensations evoked by looking at objects with the sensations that accompany object-directed actions. Because these sensations tend to occur together, perceivers can learn to relate them directly, without recourse to reasoning.

The debate between *nativists* such as Descartes, who root perceptual abilities in inborn capacities, and *empiricists* such as Berkeley, who root perceptual capacities in a history of learning, has undergone many changes since the seventeenth century. At the heart of the nativist-empiricist debate, however, are enduring questions: What is the initial basis of visual depth perception, and how does depth perception change with experience? Would the layout of the world look different if perceivers had to cope with different surface-to-image relationships? What aspects of the capacity to perceive depth are most central to us as humans and most protected from the vagaries of experience?

4.2.3 The Modifiability of Surface Perception in Adults

Experiments addressed to these questions began in the nineteenth century with the work of the great physicist, physiologist, and psychologist Hermann von Helmholtz (1866). Helmholtz did not attempt to study surface perception in human infants. Rather, he sought to uncover the origins of space perception by studying its modifiability in adults. If space perception can be modified by altering the visual information that an adult receives, Helmholtz suggested, it is simplest and most reasonable to assume that space perception depends initially on learning. Any process of learning that can be observed with adults might be presumed to be present and functional at earlier ages, when it would be most useful for shaping children's perception in response to their experience.

Helmholtz noted that perception of the positions of objects could be modified by wearing spectacles of various kinds. If one looks at objects through prism spectacles that displace the objects' images to the left, for example, one initially makes errors in reaching for the objects, reaching too far to the left. These errors decrease with time, however, and they eventually disappear. Helmholtz concluded that visual perception of space can be modified in adults. Like Berkeley, he proposed that vision is modified as perceivers act on the world by reaching or moving around, observing the systematic effects of their actions on visible objects.

Helmholtz's observation is familiar to anyone who has had to adjust to new glasses or other optical devices, and it has been reproduced in hundreds of laboratory experiments. These experiments have not always supported the Berkeley/Helmholtz view of perceptual adaptability, however. They challenge that view in three principal ways.

First, experiments show that when perceivers adapt to a conflict between vision and action by learning to reach for an optically displaced target or learning to walk in an optically distorted world, the changes that occur most often are not changes in visual perception. Instead, changes occur in the perceivers' tactile sense of the positions of their limbs and body (Harris 1980) or in the systems that coordinate visual perception with active movement (Held 1965).

Consider, for example, this experiment by Harris (1963).[1] An observer wears prism spectacles that displace everything she sees to the right. She is allowed to adapt to the distortion by pointing to and reaching for visible objects, but only with her right hand. After a short period of practice, her pointing has greatly improved: she has adapted to the discrepancy between vision and reaching, as in the experiment described by Helmholtz. But which perceptual system has undergone the adaptation: vision or touch? Harris addressed this question by asking the adapted subject to point to the objects with her untrained *left* hand. If the period of practice had produced a visual change, pointing should have been as accurate with the left as with the right hand. In fact, however, the accuracy of pointing with the two hands differed greatly. Subjects made the same errors with the untrained

1. The description of this experiment (and later ones) has been simplified in certain respects.

hand that they had made at the start of the session. Clearly, this adaptation experience did not bring about a change in vision. Harris suggested instead that the experience of reaching with the right hand led to a change in perception of the hand's felt position. Visual perception appears to be more resistant to change than tactile perception in this situation, contrary to Helmholtz's view.

A second challenge to the Berkeley/Helmholtz theory comes from studies of adaptation to purely visual conflicts. True changes in visual perception appear to occur most readily when two sources of visual information are brought into conflict with each other. Wallach (1976) has extensively investigated the effects of such visual conflicts. In one set of experiments (see Wallach 1976, chap. 10) he introduced a conflict between the two sources of visual depth information mentioned earlier: kinetic information and stereoscopic information. A stationary observer was allowed to watch an object that rotated in front of him so as to provide kinetic information for its three-dimensional shape. The observer looked at the object through an optical device that increased the differences between the two eyes' views of the objects: these increased disparities made the object appear thicker than it actually was. Wallach thus produced a conflict between two sources of information for the three-dimensional shape of the object.

As in Harris's experiment, adaptation occurred in this situation, reducing the perceptual conflict. Subsequent testing revealed that the adaptation experience had produced a change in stereoscopic depth perception but no change in kinetic depth perception. Based on this and other experiments, Wallach has suggested that kinetic depth perception is not modifiable. Instead, it serves as a basis for modifying other sources of depth information. The existence of an unmodifiable capacity to perceive depth would seem to support aspects of a nativist view of space perception.

Wallach's study also provides evidence that vision can be modified in the absence of any conflict with touch. Wallach's observers experienced a change in stereoscopic depth perception, even though they watched a rotating object without moving their heads, arms, or bodies, and thus without encountering any discrepancy between vision and action. Actions such as reaching and locomotion play no essential role in processes of visual adaptation.

Research on perceptual adaptation challenges the Berkeley/Helmholtz view in a third way. It appears that perceivers cannot adjust to all perceptual modifications with equal ease. Instead, there are limits, or *constraints*, on the kinds of conflicts between two sources of spatial information that humans easily learn to resolve. An experiment by Bedford (1989) makes this point most clearly. Like Helmholtz and Harris, Bedford introduced a discrepancy between the seen and the felt positions of objects. She went

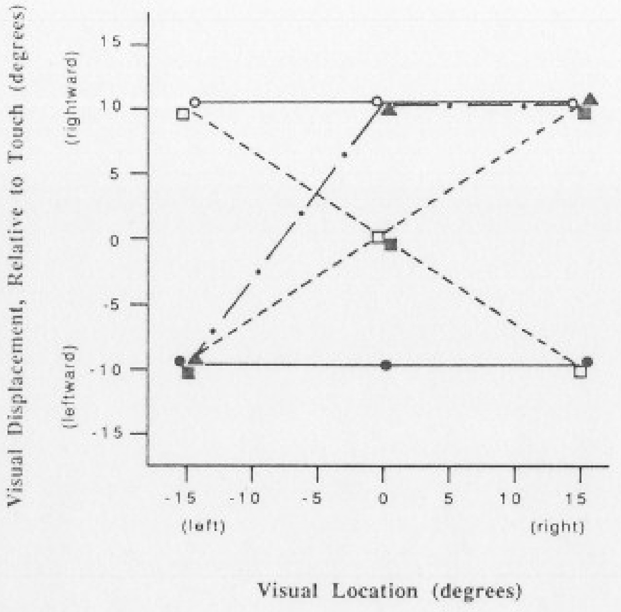

Figure 4.2
Some visual rearrangements studied by Bedford (1989): a uniform leftward displacement (filled circles), a uniform rightward displacement (open circles), a uniform expansion (filled squares), a uniform contraction (open squares), and a nonlinear change (triangles). Subjects experienced shifts of 10 degrees left or right at 2 or 3 locations: 15 degrees left, center, and 15 degrees right. (Figure adapted from Bedford 1989.)

beyond her predecessors, however, in investigating discrepancies of three kinds: (1) a uniform leftward or rightward displacement of the visual field, relative to touch, (2) a uniform expansion or contraction of the visual field, relative to touch, and (3) a change in which different parts of the visual field were displaced in different directions, relative to touch (figure 4.2). Subjects adapted to the first two changes but not to the third. Instead, they coped with the third change by rescaling and shifting the visual-tactile relation to minimize (but not eliminate) the conflict. Bedford suggested that human adults adapt most readily to *linear* changes in the relation between vision and touch: lateral shifts and/or changes of scale.

Bedford's experiment seems to point to a deficiency in our capacity to adjust to changes in the perceptual world. Bedford showed, however, that this limitation has a positive side. In principle, any linear change in the relation between two systems for perceiving spatial direction can be specified uniquely by information about the discrepancy at just two spatial locations: two points define a line. Bedford showed that people can take advantage of this constraint. After exposure to a visual-tactile discrepancy

at two spatial positions, her subjects showed a change in pointing to all directions between those positions. Indeed, the change was as large for positions that were never experienced during the adaptation period as for the positions on which the subjects were trained. Intrinsic constraints appear to limit our adaptability as perceivers, but they also enable us to adapt quickly, on the basis of a small number of encounters with the seen and felt world.

In summary, visual perception is difficult to modify. Some visual systems, such as the system for computing depth from motion, may never be modified when they are brought into conflict with other systems. Some visual systems may be modifiable, but only when they are placed in conflict with another visual system, not when they are placed in conflict with touch. Finally, visual and tactile systems may only be modifiable in a restricted set of ways. Taken together, these findings reveal considerable limits on the adaptability of mature visual capacities to perceive space. With logic similar to that of Helmholtz, we might speculate that these limits derive from innate properties of the human visual system. This speculation can only be tested, however, through studies of human infants.

4.2.4 Depth Perception in Infancy

Experimental studies of the origins of surface perception began some thirty years ago, with investigations that focused on infants' visually guided, spatially appropriate behavior. In studies by Gibson and Walk (1960) young animals of various species were tested on the "visual cliff." The infant stood on a narrow central board facing two horizontal surfaces, one a short distance below it and the other much farther away. (The surfaces were actually covered with Plexiglas just below the centerboard, both to protect the infant and to ensure that only visual information specified the drop-off on the more distant side.) Gibson and Walk observed whether the infant animal avoided the visually specified drop-off. Such avoidance would suggest that it perceived the surfaces' relative distances, at least approximately.

Gibson and Walk found evidence of cliff avoidance in nearly every terrestrial animal they tested. Avoidance was observed as early as an animal could be tested—that is, as soon as it became capable of independent locomotion. In species that can see and walk at birth, such as goats, cliff avoidance was observed at 1 day of age. In species that begin to see and to locomote by sight at later ages, such as rats, cliff avoidance could not be tested at birth. When rats were tested at 4 weeks of age, however, cliff avoidance was observed. Moreover, cliff avoidance in rats was shown to be independent of experience: dark-reared rats, tested on first exposure to light at 3 months, consistently avoided the visual cliff. Depth perception appears to develop without visual experience in many species.

Gibson and Walk's studies of human infants were limited by the fact that humans do not begin to locomote independently until about 7 months of age. Although human infants avoided the cliff at that time, the earlier development of this ability remains a subject of dispute (for discussion, see Gibson and Spelke 1983). Accordingly, some investigators have turned to observations of other spatially appropriate behaviors for insights into the earlier development of space perception in humans.

Between 4 and 5 months human infants begin to reach effectively for visible objects. At that time reaching is adapted to an object's direction, distance, and pattern of motion: infants reach farther for a more distant object, and they reach ahead of a moving object so as to intercept it. These observations indicate that infants perceive an object's position and motion appropriately by 5 months of age (von Hofsten 1986). Three-month-old infants engage in a different spatially appropriate behavior: they react defensively to an approaching object by blinking or withdrawing their heads (Yonas and Granrud 1984). These reactions suggest that the changing distance of an approaching object is perceived by 3 months of age. Unfortunately, neither object-directed arm movements nor defensive reactions provide clear evidence concerning surface perception at younger ages (von Hofsten 1982; Yonas and Granrud 1984).

Although these studies leave the newborn human infant's capacities in some doubt, they provide evidence that infants' actions are spatially appropriate as soon as they emerge. A capacity to perceive depth appears to arise early and spontaneously in humans, as in other animals. This capacity evidently does not depend on learning about surfaces by reaching for them or locomoting around them, as Berkeley and Helmholtz proposed. Depth perception precedes the development of these actions and it may help to guide their development.

Studies of reaching, of behavior on the visual cliff, and of defensive reactions to approaching objects have been used to investigate the emergence of sensitivity to different kinds of visual depth information. In these studies infants are presented with selected kinds of depth information and their locomotion, reaching, or defensive reactions are observed in order to discover the stimulus conditions under which they can act in a spatially appropriate way. The studies suggest that motion provides the first effective information for depth. The kinetic patterns that accompany the motions of the infant or the motions of an object specify depth relations to human infants by 3 months of age, and perhaps earlier (Yonas and Granrud 1984). For a variety of other species, motion appears to specify depth innately. For example, motion serves as effective information for depth in dark-reared rats and for newborn animals with functioning visual and locomotor systems (Gibson and Walk 1960). These converging findings of human and animal studies suggest that kinetic depth perception becomes functional on the basis of little or no visual experience.[2]

In contrast, human infants do not begin to perceive depth from stereoscopic information until about 4 months of age (for a review, see Banks and Salapatek 1983). The development of stereopsis has been shown to depend on cortical maturation in monkeys, and it is probably maturationally dependent in humans as well (Held 1985). It is also affected by visual experience: human and monkey infants with abnormal binocular experience (caused, for example, by muscular abnormalities preventing the infant from directing the two eyes to the same object) fail to develop normal binocularity (for discussion, see Mitchell 1988). Visual experience would seem to be necessary for the development of binocular depth perception because the distance between the two eyes increases with age, changing the relationship between binocular disparity and object distance.

What are the mechanisms by which binocular experience leads to the development of stereopsis in humans? Although this question has not been answered fully, the findings of some recent experiments support two suggestions. First, as noted, stereopsis develops in the 4th month of life. Since infants of 4 months can neither reach for objects nor locomote around them, the development of stereopsis does not appear to depend on active movement or object manipulation. Rather, infants may learn to perceive depth from binocular disparity by correlating disparity information with the already functional kinetic information for depth. That is, infants may use kinetic information to perceive a three-dimensional surface layout, and then they may assign to disparity values in the binocular representation of that layout the depth values specified by motion. Second, stereopsis has been found to develop quite rapidly in individual infants (Held 1985). The speed of this development suggests that the learning mechanism exploits constraints on the possible mappings between binocular disparity and object distance. Infants may learn to perceive stereoscopic depth by detecting relationships between binocular disparity and kinetic depth at a restricted set of locations, mapping the entire field on the basis of a limited set of inputs.

4.2.5 Overview

In summary, research on infants of a variety of species, including humans, suggests that the visual capacity to perceive depth forms part of our innate

2. Kinetic depth perception does require some modification during development, because of the growth of the infant's eyes and because of growth-related movements of individual neurons in the retina (see Aslin 1988; Banks 1988). Banks has shown, however, that kinetic depth perception can be recalibrated internally, through the detection and elimination of inconsistencies in the kinetic patterns produced by a functioning, but poorly calibrated, system (Banks 1988). Other depth information need not enter the calibration process.

endowment. Kinetic depth perception appears to develop in the absence of any specific visual experience. Although stereoscopic depth perception is affected by experience, the effects of experience appear to be limited by the infant's maturational state and perhaps by constraints on the binocular arrangements to which infants can accommodate. These findings are contrary to the empiricist theories of Berkeley and Helmholtz; they lend some support to nativist theories such as that of Descartes.

The findings of developmental experiments with infants converge in interesting ways with the findings of adaptation experiments with adults. Kinetic information, the least modifiable depth information for adults, is also the first effective depth information for infants. Binocular disparity, which undergoes adaptation in adults when it is placed in conflict with kinetic information for depth, may develop in infants through a process that builds on the already effective kinetic information. Visual learning occurs rapidly both for adults and for infants, suggesting that constraints on the modifiability of systems for perceiving depth operate both in adulthood and in infancy. These findings suggest that the mechanisms of adaptation observed with adults are also the mechanisms of perceptual learning, just as Helmholtz proposed. These mechanisms may operate throughout life, allowing humans to develop and adjust their visual capacities on the basis of visual experience.

4.3 Object Perception

4.3.1 Problems of Perceiving Objects

The capacity to perceive objects is as intriguing as the capacity to perceive surfaces, and it raises new issues and problems. As adults, we perceive the surrounding world as a layout of persisting physical bodies. Perception of objects is usually immediate, effortless, and accurate. Object perception is a puzzling achievement, however, because visual information for objects is both incomplete and potentially misleading. Objects come to us in a continuous surface array in which they sit upon and beside each other. Objects also are partly hidden: the back of every opaque object is hidden by its front, and the front surfaces of most objects are partly hidden behind other objects (figure 4.3). Finally, the images of objects continually enter and leave the visual field as we shift fixation and as objects move in relation to one another. Despite these complexities, we perceive objects as bounded bodies that are distinct from one another, as complete bodies that continue where they are hidden, and as persisting bodies that exist whether they are in or out of view.

Figure 4.3
A typical visual environment (child's birthday party). Cups, plates, napkins, and chairs are recognizable, although each is partly occluded. Cups and plates are also seen as distinct, even when their images are adjacent.

4.3.2 Theories of Object Perception and Its Development

Like those who study surface perception, students of object perception have attempted to shed light on these abilities, in part, by turning to development. Two theories have dominated discussion. According to one thesis, again from the empiricist tradition, newborn perceivers experience just the momentarily visible surfaces in a scene. As children move around surfaces and manipulate them, they learn how different views of an object are related (Helmholtz 1866) and how object unity and boundaries can be predicted from certain properties of visible surfaces such as their proximity, their similarity in texture and color, and the alignment of their edges (Brunswik and Kamiya 1953). This learning eventually allows children to infer complete and bounded objects from partial visual information.

The principal rival to empiricist theory has come from Gestalt psychology, an early twentieth-century movement that attempted to explain perception in terms of the intrinsic organizational properties of complex physical systems (see Koffka 1935; Köhler 1947). Because of its nature as a physical system, the brain was thought to tend toward a state of equilibrium. This physical tendency was thought to have a psycholgical counterpart: perceivers tend to confer the simplest, most regular, and most balanced organization on their experience. Thus, perceivers group together surfaces so as to form units that are maximally homogeneous in color and texture and maximally smooth and regular in shape (Wertheimer 1923; Koffka 1935). The tendency toward simplicity allows perceivers to apprehend the boundaries, the unity, and the persistence of most objects, because physical objects tend to be relatively homogeneous in substance and regular in form. Since the tendency toward simplicity follows from innate properties of the nervous system, learning was thought to play no essential role in the development of object perception.

Like theories of surface perception, these theories changed over the years as more was learned about perception, its physical basis, and its computational structure. The core of the debate between empiricist and Gestalt theories has remained alive, however, and it has stimulated research both on the modifiability of object perception in adults and on the development of object perception in infancy.

4.3.3 The Modifiability of Object Perception in Adults

Like Helmholtz, the Gestalt psychologists attempted to test their theory by studying the effects of experience on a mature perceiver's apprehension of objects. Their experiments appeared to show, however, that experience has little or no effect on object perception. In the most famous learning experiments (Gottschaldt 1926) subjects were repeatedly shown a complex figure, and then they were shown a simple figure that had been embedded within it (figure 4.4a). They were asked if the simple figure looked familiar. Even after viewing the complex figure on hundreds of occasions, the subjects failed to recognize the simpler figure within it. What they learned from their encounters with the complex visual display appeared to depend on their organization of that display.

In a later demonstration (Michotte, Thinès, and Crabbé 1964) Michotte showed subjects a triangle with an irregular center, and then he covered its irregular regions by a finger (see figure 4.4b). Asked what they saw when the figure was covered, Michotte's subjects reported a complete, regular triangle, despite what they had apparently learned about the display. Michotte concluded that intrinsic organizing tendencies are impervious to explicit knowledge or instruction. Demonstrations by Wertheimer (1923; figure 4.4c) and by Kanizsa (1979) support the same conclusion.

These experiments have been thoroughly criticized. Just because learning cannot be demonstrated in one laboratory session with adults, it is argued, one cannot conclude that learning does not occur in infancy. Adults might learn to perceive objects differently if they were given more time in which to learn. Moreover, even if learning never occurred for adults, such

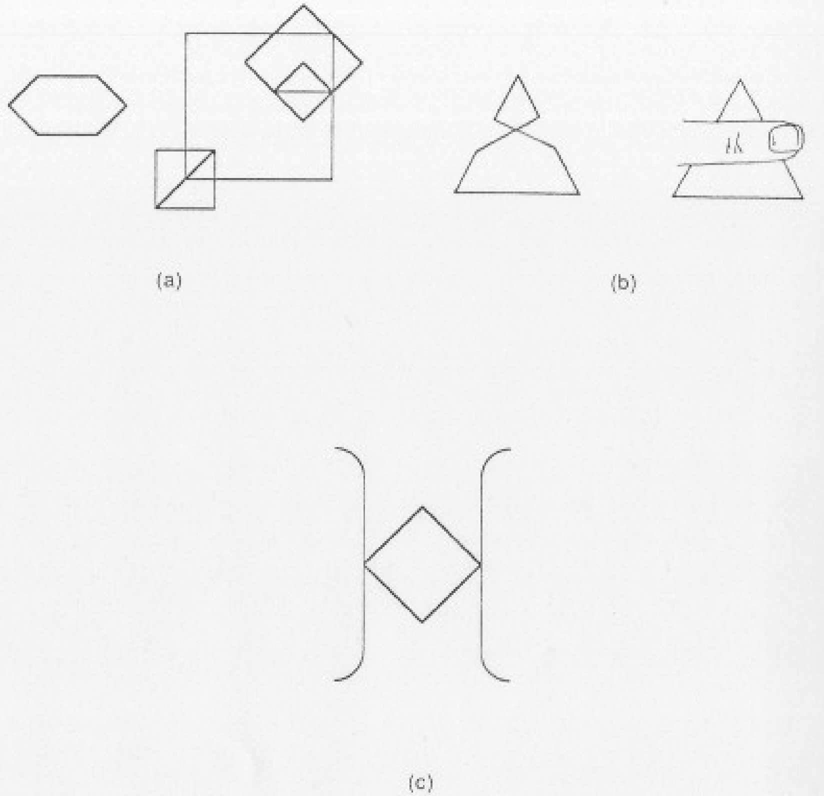

Figure 4.4
Some noneffects of knowledge or experience on perceptual organization: (a) after hundreds of exposures to a complex figure (right), subjects fail to recognize a simpler figure embedded with it (left) (after Gottschaldt 1926); (b) after viewing an irregular triangle, subjects still perceive a simple, complete figure when the irregular region is occluded, contrary to what they know is there (after Michotte, Thinès, and Crabbé 1964); (c) a single abstract figure is perceived, despite the presence of the familiar embedded letters "M" and "W" (after Wertheimer 1923).

learning might occur earlier in life. For example, most adults never learn to speak a second language without a detectable foreign accent. Accents are not innate, however; they are acquired by speakers as children. Demonstrations of a lack of plasticity in adults do not imply a lack of plasticity during development.

Nevertheless, a different lesson may be drawn from the Gestalt experiments: what one learns from a given experience depends on how one organizes that experience. This lesson comes originally from the work of the philosopher Immanuel Kant (1781). It was expounded forcefully by Köhler (1947) in a classic critique of the empiricist theory of object perception. Suppose, Köhler reasoned, that object perception is learned. How does this learning take place? An empiricist would reply that children learn to perceive objects by encountering them repeatedly, observing each object under various circumstances. For example, a child might learn to perceive a violin by encountering the violin on a table, in its case, in the hands of a violinist, and so forth. At different times the violin would appear at different distances and orientations and under different conditions of illumination. Eventually, each of these encounters would become associated with the others and with experiences such as hearing a violin sonata, touching the violin's strings, and hearing the word *violin*. Perception of the violin would emerge from this network of associations.

To proponents of such a theory, Köhler posed this question: How does the child determine which of his sensory experiences should be associated together to form the perceptual experience of a violin? What tells the child, for example, that the sight of a violin on a table should be linked to the sight of a violin in the hands of a violinst and not to the sight of a lamp on a table? In order to associate the violin's appearances with one another, one needs to perceive, somehow, that all those appearances are appearances of the same object—the violin. But that perceptual ability is just what the empiricists were attempting to explain by learning. The empiricist explanation seems to turn in a circle, presupposing the very ability that it seeks to explain: how one perceives a bounded, unitary, and constant violin from changing and varying arrays of light.

Köhler's argument suggests that what one learns from experience will depend on how one organizes that experience, and the demonstrations by Gottschaldt, Michotte, and Wertheimer appear to underline the point. Can this point be reconciled with the possibility that perceptual organization itself is subject to learning? I think it can, if the organization of surfaces into objects, like the perception of surfaces in depth, normally depends on multiple and redundant sources of information. If perceivers begin with a small set of mechanisms for detecting this organization, sufficient for recognizing objects under certain conditions, then they could learn to perceive objects by other means. But how do infants perceive objects initially, and

how do they extend their initial abilities by learning? Developmental research can best address this question.

4.3.4 Object Perception in Infancy

Research on object perception in infancy began with studies of perception of partly occluded objects (Kellman and Spelke 1983). These studies used an experimental method, developed by Fantz (1961), that assesses infants' preferential looking at familiar and novel displays. When young infants are presented repeatedly with the same visual display, they tend to look at it less and less. If the infants are then presented with the original display and with a new display, they tend to look longer at the new display. This preference indicates that infants discriminate the two displays and detect the novelty of the second display. Fantz's method—often called the *habituation/dishabituation method*—has since been used to study a variety of perceptual capacities in infancy, including the capacity to perceive the complete shape of an object that is partly hidden.

Four-month-old infants were presented with an object whose top and bottom were visible but whose center was occluded by a nearer object (figure 4.5). They saw this display repeatedly until their visual interest declined, and then they were shown a complete object, which corresponded to the display adults report seeing behind the occluder, and two object fragments, which corresponded to the visible surfaces of the partly hidden object. Infants were expected to look longer at whichever display appeared more novel to them. If they experienced the display as a mosaic of visible surface fragments, they should have looked longer at the complete object; if they organized the occlusion display into a single continuous unit, they should have looked longer at the fragmented object.

Like adults, infants were found to perceive a center-occluded object as a complete and continuous unit if the visible areas of the object moved in unison. Motion in depth was as effective as vertical or lateral motion—further evidence for depth perception in infancy. Unlike adults, however, infants did not perceive the completeness of a center-occluded, stationary object of a simple shape. Familiarization with such an object was followed by increased looking both at the complete and at the fragmented displays, with no preference between those displays. It appeared that the infants' perception of the stationary displays was indeterminate, as is an adult's perception of a stationary, center-occluded object with irregular coloring and form.

These studies provided evidence that motion specifies object unity to infants but that static configurational properties do not. Similar conclusions were suggested by investigations of young infants' perception of object boundaries. Three- to five-month-old infants were presented with displays

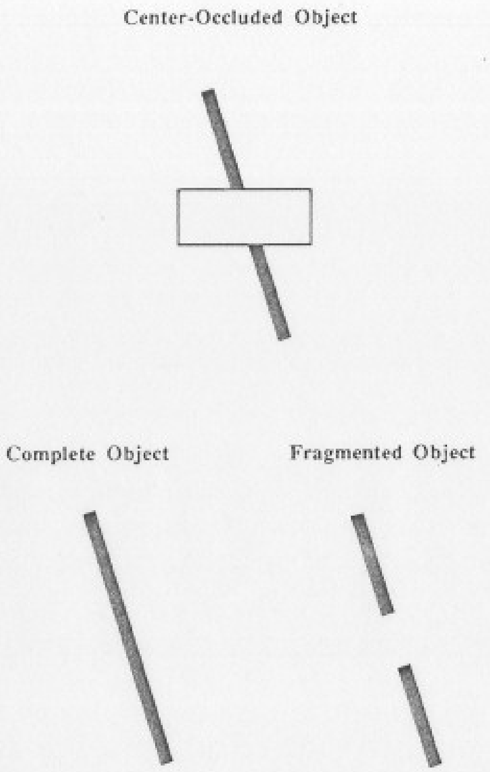

Figure 4.5
Habituation display (top) and test displays (bottom) for an experiment on infants' perception of partly occluded objects (after Kellman and Spelke 1983).

of two objects, arranged so that their images overlapped at the infants' eyes. Perception of the objects' boundaries was tested in various ways, including preferential looking methods (for details, see Spelke 1985). All the studies provided evidence that infants perceived object boundaries by detecting the spatial arrangements of surfaces: two objects were perceived as distinct units if they were separated in depth. Infants also perceived object boundaries by detecting the relative motions of surfaces: two objects were perceived as distinct if they moved independently, even if they touched throughout their motion. Infants did *not* perceive object boundaries, however, by analyzing the static, configurational properties of surfaces: two adjacent, motionless objects were not perceived as distinct, even if they differed in color, texture, and shape. Unlike adults, young infants perceived neither the unity nor the boundaries of objects by analyzing the static, configurational properties of visual arrays.

Experiments by Schmidt (1985) have focused on the development of sensitivity to static configurational information for object unity. Children are sensitive to the properties of figural simplicity and color/texture similarity by 2 years of age. Sensitivity to these properties appears to emerge gradually; the development of gestalt perception is a slow process. For example, 7-month-old infants perceive a stationary, center-occluded object as a single, continuous unit if the object is three-dimensional and its visible surfaces are coplanar, with collinear edges and homogeneous coloring. If these same relationships indicate that two partly occluded surfaces lie on distinct objects, however, 7-month-old infants' perception of the occlusion display is indeterminate, in contrast to the perceptions of adults. These findings suggest that gestalt organization by the principles of good continuation and similarity (see figures 2.14 and 3.1) is not a unitary phenomenon.

We have considered infants' perception of objects as unitary and bounded. What about their perception of objects as persisting over a succession of sporadic encounters? Experimenters have recently begun to investigate this ability, by means of the same preferential looking method. In one study 4-month-old infants were habituated to events in which one or two objects moved in and out of view behind one or two occluders (for details, see Spelke 1988). For different groups of subjects, the identity or distinctness of the object(s) was specified by the apparent continuity of the path of object motion, the apparent discontinuity of the path of object motion, the apparently constant speed of object motion, or the apparently irregular speed of object motion. Figure 4.6 depicts the displays for the first and second conditions. Perception of object identity or distinctness was assessed by presenting the infants, after habituation, with fully visible events involving one or two objects (figure 4.6). Patterns of looking at these test events provided evidence that the infants perceived object identity by analyzing the spatiotemporal continuity of motion, as do adults: when object motion was discontinuous, infants perceived two objects, each moving continuously through part of the scene. In contrast to adults, infants did not perceive object identity or distinctness by analyzing the apparent constancy or change of an object's speed of motion. The development of this last ability has not been investigated.

In summary, humans have some early-developing abilities to perceive the unity, the boundaries, and the identity of objects in visual scenes. These abilities are present before the onset of visually directed reaching or independent locomotion. Capacities to apprehend objects appear to emerge without benefit of trial-and-error motor learning.

Unlike adults, young infants fail to apprehend objects by analyzing the static configurational properties or the velocity relations of surfaces so as to form units that are maximally simple and homogeneous or that move in

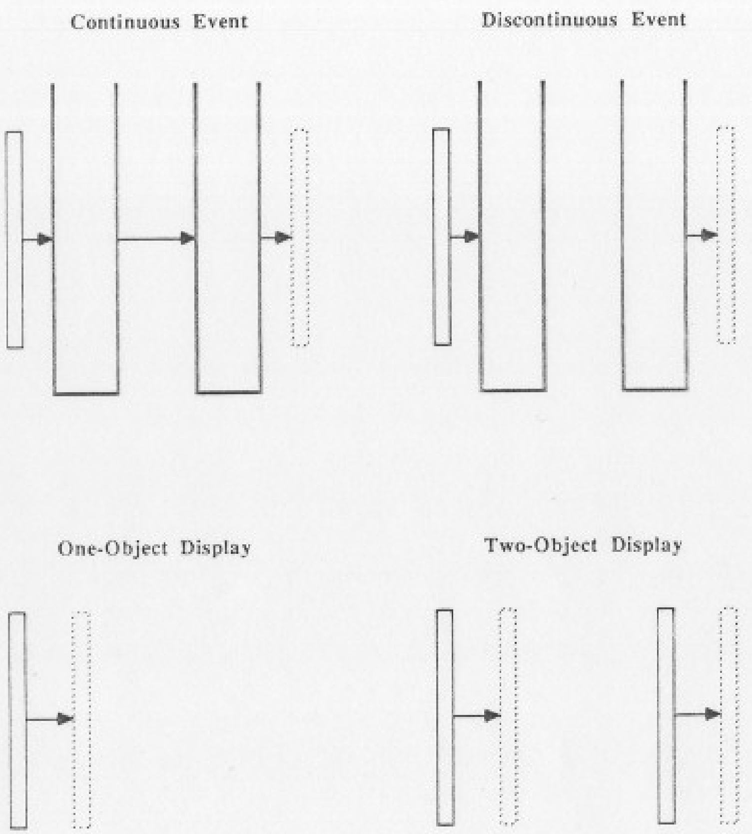

Figure 4.6
Habituation displays (top) and test displays (bottom) for an experiment on infants' apprehension of the identity of objects that leave and return to the field of view. An object's initial and final positions are indicated, respectively, by solid and dotted lines (after Spelke 1988).

maximally regular ways. Some of the latter abilities have been shown to emerge quite early in development, however, before infants can locomote around objects or communicate with others about them. Capacities to perceive objects thus appear to be extended spontaneously over the course of early development.

Experiments on infants' perception of objects cast doubt on the two theories with which we began. Contrary to empiricist theory, infants can perceive the unity and boundaries of certain objects before they can reach for objects or locomote around them. Contrary to Gestalt theory, however, infants fail to perceive objects by organizing arrays of surfaces into units with the most regular shapes, colors, and textures. This failure is especially striking, because experiments provide evidence that infants do detect these configurational properties (for discussion, see Spelke 1988). Infants detect the static configurational properties of a visual scene, but they do not appear to use these properties when they divide the scene into objects. Young infants divide surfaces into objects only by analyzing the three-dimensional arrangements and motions of surfaces.

On the positive side, young infants appear to apprehend objects by analyzing the arrangements and the motions of surfaces so as to form units that are *cohesive* (the units are spatially connected and move as wholes), *bounded* (the units are spatially distinct from one another and move independently), and *spatiotemporally continuous* (the units exist continuously and move on connected paths). What kind of mechanism could accomplish this?

Two sets of experiments provide evidence that the mechanism of object perception is quite central. The first studies, by Kellman (see especially Kellman, Gleitman, and Spelke 1987), investigated the conditions under which infants perceive object unity from surface motion. In particular, the experiments investigated whether infants perceive the unity of an object by analyzing the two-dimensional displacements of its images in a relatively low-level representation (such as Marr's primal sketch) or by analyzing the three-dimensional displacements of its surfaces in a higher-level representation (such as Marr's $2\frac{1}{2}$-D sketch).

Infants were presented with a center-occluded object under four conditions of motion (figure 4.7). In the first condition both the infant and the object were stationary. In the second condition the infant was stationary and the object moved laterally, producing both image and surface displacements. In the third condition the infant was moved in an arc around the stationary object; the motion of the infant produced nearly the same two-dimensional displacement of the object's images as the object motion in the second condition, without any true displacement of the object's surfaces. In the fourth condition the infant again was moved in an arc but the object moved so as to cancel any two-dimensional displacement of the object's images. Infants were found to perceive the unity of the object in

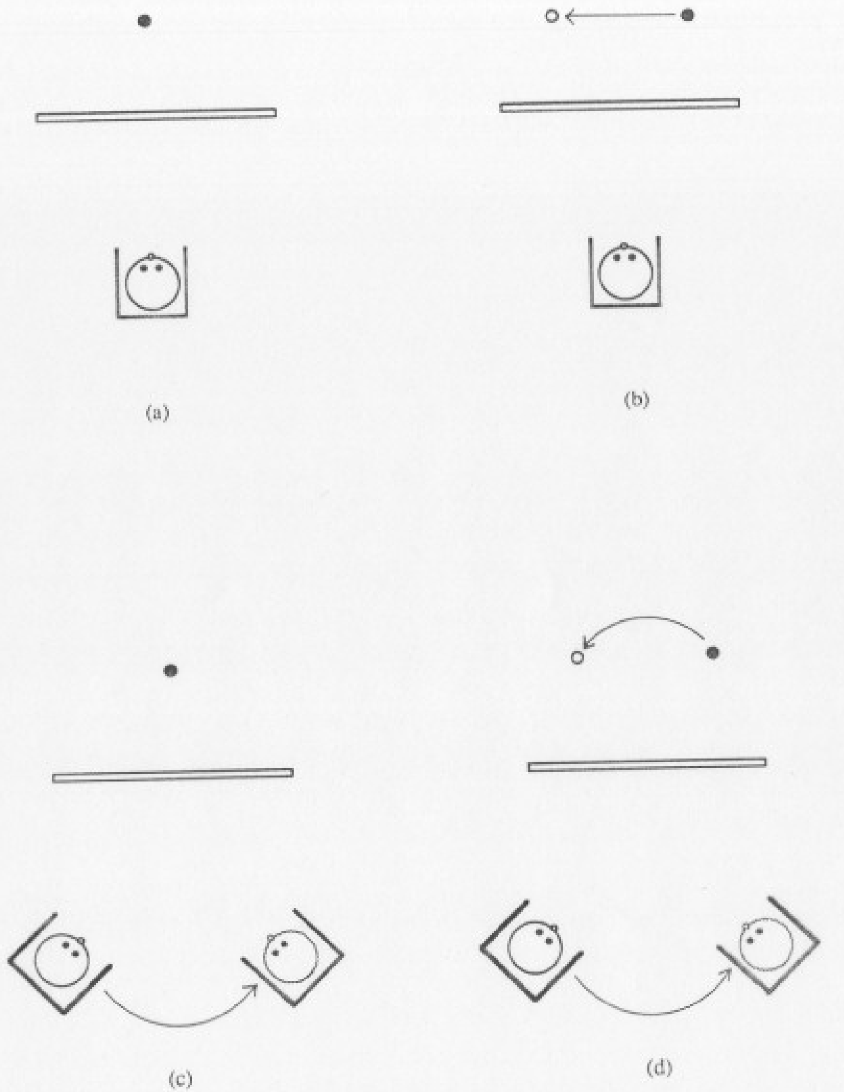

Figure 4.7
Habituation displays for experiments on the effects of motion on object perception, seen from above (after Kellman and Spelke 1983 and Kellman, Gleitman, and Spelke 1987). The displays present (a) neither image motion nor object motion, (b) both image motion and object motion, (c) image motion but no object motion, and (d) object motion but no image motion.

the second and fourth conditions, in which the object moved, but not in the first or third condition, in which it did not. Two-dimensional image displacements were neither necessary (fourth condition) nor sufficient (third condition) for perception of object unity. It appears, therefore, that mechanisms for perceiving objects take as input representations of the three-dimensional layout as it is perceived, rather than operating on more primitive, two-dimensional image representations. Representations of objects are constructed after, and on the basis of, representations of three-dimensional surface arrangements and motions.

The second series of studies, by Streri and Spelke (1988, in press), investigated object perception in the tactile mode. In particular, the experiments investigated whether infants perceive the unity and boundaries of objects under the same conditions when they feel objects as when they see them. Four-month-old infants held two spatially separated rings, one in each hand, under a cloth that blocked their view of the rings and of the space between them (figure 4.8). In different conditions the rings either could be moved rigidly together or could be moved independently, and they either shared a common substance, texture, and shape or differed on these dimensions. Perception of the connectedness or separateness of the rings was tested by means of a habituation-of-holding-time method similar to that used with visual displays (for details, see Streri and Spelke 1988).

The infants were found to perceive the two rings as a single unit that extended between their hands if the rings could only be moved rigidly together; they perceived the rings as two distinct objects separated by a gap if the rings could be moved independently. Perception was unaffected by the static configurational properties of the ring displays. These findings indicate that 4-month-old infants perceive object unity and boundaries under the same conditions in the visual and tactile modes. That finding, in turn, suggests that the mechanisms of object perception are amodal. Humans may not be endowed with visual and tactile mechanisms for perceiving objects; we may perceive objects by means of a single set of mechanisms, located more centrally in the brain, that operate on representations of surfaces derived from either sensory modality.

All these findings suggest that perceiving objects may be more akin to *thinking* about the physical world than to *sensing* the immediate environment (Spelke 1988). That suggestion, in turn, echoes suggestions from philosophers and historians of science that theories of the world determine the objects one takes to inhabit the world (Quine 1960; Kuhn 1962; Jacob 1970). Just as scientists may be led by their conceptions of biological activities and processes to divide living beings into organs, cells, and molecules, so infants may divide perceived surfaces into objects in accord with implicit conceptions that physical bodies move as wholes, separately from one another, on connected paths.

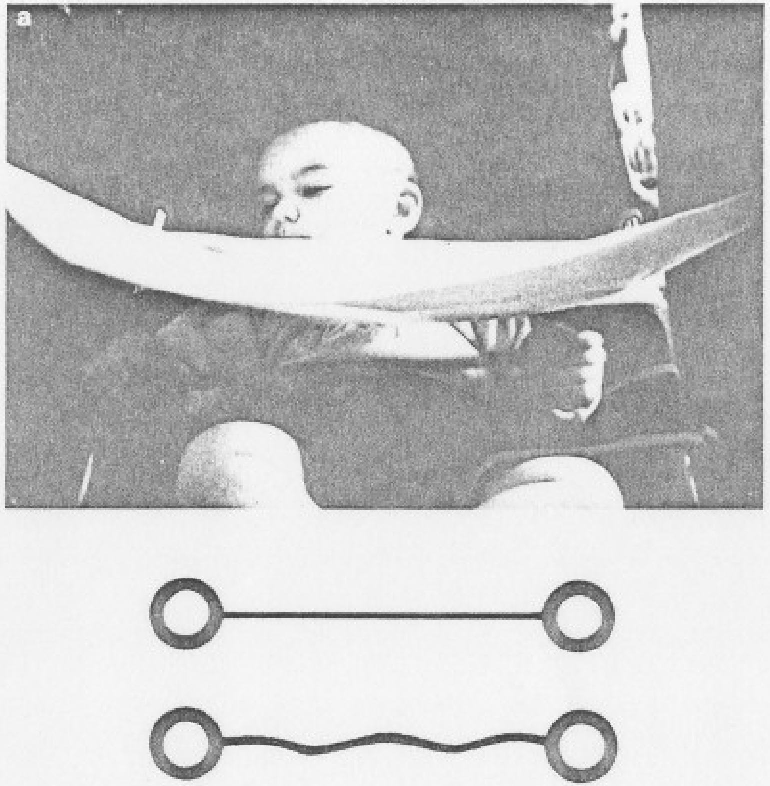

Figure 4.8
Habituation displays for an experiment on infants' perception of object boundaries through active touch (Streri and Spelke 1988).

4.3.5 Overview

Before human infants can reach for objects to manipulate them, they can already perceive objects as bounded, as complete, and as persisting over occlusion, under certain conditions. As Köhler proposed, mechanisms for organizing the world into objects may be present and functional before infants learn about particular objects and their properties, and they may serve as a foundation for such learning.

Nevertheless, young infants do not appear to experience the same arrangements of objects that adults do. When they face a stationary array such as that in figure 4.3, they do not segment that array into objects by analyzing relationships such as edge and surface continuity, or color and texture similarity, in accord with a tendency to maximize figural goodness. The development of this tendency is not understood, but it appears to be a long and gradual process. Gestalt organizational phenomena may not depend, at any age, on general rules or wholistic processes but rather on a wealth of slowly accumulated knowledge about objects and their properties. If that is the case, then there are aspects of object perception in infancy that lend some support to empiricist conceptions of percepual learning.

Research on the mechanisms of object perception in infancy suggests that those mechanisms are relatively central in two respects: they take as input a representation of the surface layout as it is perceived, rather than operating directly on more primitive sensory representations, and they are amodal, operating on representations derived from different perceptual systems. Object perception may depend on the same mechanisms for adults, despite the rapidity and the apparent "impenetrability" of the processes by which we as adults apprehend the things around us. Here is a case in which studies of infancy may shed light on mature cognitive processes: they may reveal processes that operate throughout life but that are hard to discern in adulthood beneath the layers of skills and knowledge that adults have acquired.

There is a second way in which studies of infants may shed light on the perceptual knowledge of adults. The properties that infants appear to find in the things around them—cohesion, bounds, and spatiotemporal continuity—are among the properties that are most central to our mature intuitive conceptions of physical bodies. Adults conceive quite easily of physical bodies with poor Gestalt properties: bodies that are irregular in shape (rocks), heterogeneous in substance (vacuum cleaners), and subject to complex patterns of motion (flags). We do not readily consider something as a physical body, however, if it lacks cohesion (a pile of leaves), bounds (a drop of water in a pool), or continuity (a row of flashing lights). The latter entities may be collections of objects or parts of objects, but they are not unitary and independent objects for us.

These observations suggest that the infant's first mechanisms for apprehending objects remain central to human perception and thought. As in the case of depth perception, early-developing capacities to apprehend objects may remain powerful capacities for adults. These capacities may be enriched but not fundamentally changed by the wealth of further abilities whose acquisition they support. Studies of infancy may help to reveal what these core capacities are.

Suggestions for Further Reading

The best place to start on the nativist-empiricist debate is to plunge into the writings of some of its original protagonists, especially Descartes (1637, 1638), Berkeley (1709), J. S. Mill (1865), Hering (1864), and Helmholtz (1866, especially chapter 26). Herrnstein and Boring (1965) collect key excerpts from these sources, and Hochberg (1959) offers a summary and discussion of the work of these writers and others. Kitcher (forthcoming) provides an excellent discussion of Kant's (1781) philosophy as it pertains to issues in cognitive science. On Gestalt psychology, Koffka (1935) provides an introduction, and Hochberg (1974) provides a retrospective overview and critique. The Gestalt experiments of Gottschaldt and others have been translated, in abridged form, by Ellis (1939).

Those who wish to explore the voluminous literature on adaptation to rearrangements of visual space may choose from a number of guides. Rock (1966) provides a review and discussion that is still illuminating, especially if complemented by the updating of Welch (1974). To delve more deeply into this literature, and into the controversies it has engendered, readers may turn to papers by Held (1965), Harris (1980), Wallach (1976, chapter 10), and Bedford (1989).

Banks and Salapatek (1983) give a good general introduction to the sensory capacities of infants and a brief discussion of perception of space and form. Gibson and Spelke (1983) provide an introductory discussion of infants' perception of surfaces, objects, and events. For more detailed discussions of surface perception in infancy, see the papers by Held (1985), Yonas and Granrud (1984), and Banks (1988). Spelke provides methodological (1985) and theoretical (1988) reviews of research on object perception in infancy.

There are few studies of the origins and development of surface and object perception in nonhuman animals. This lack is especially regrettable, since animal research is indispensable to the study of the neural basis of perception, and it provides a variety of means to address the nativist-empiricist controversy (through studies of newborn, precocial animals, for example, and through controlled-rearing experiments). Binocular functions relevant to stereopsis have been studied quite extensively in animals (for a review, see Mitchell 1988). Capacities for motion-based depth perception and for object perception, in contrast, have received less attention. If this chapter stimulates any beginning investigator to study when and how infant rats, cats, or monkeys begin to perceive depth from motion or to segment the continuous visible layout into units, it will have served its prupose.

Questions

4.1 In the case of adaptation to visual rearrangements of space, there seems to be a relation between the size of the set of rearrangements perceivers can adjust to and the amount of experience that is needed to make each adjustment: the more limited the changes are that a perceiver can adapt to, the less experience the adaptation requires. Why might this be true? Should it be true for all cases of visual learning? All cases of learning?

4.2 Design an experiment to test whether human infants can adapt to prism spectacles that change the visible directions of objects. Would you expect infants to adapt to this change?

4.3 Human infants have been found to begin using the Gestalt relation of good continuation as information for object continuity over occlusion between 5 and 7 months of age. How might one study the relative contributions of maturation and of learning to this developmental change?

4.4 Do inexperienced animals perceive the continuous existence of an object that moves fully out of view? Design an experiment to address this question, with the species and method of your choice.

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