CHAPTER 11

Nature, Nurture, and Development

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I. INTRODUCTION

How can human knowledge both be adapted to human experience and go beyond the evidence that experience provides? How can knowledge show both diversity, and universal properties, across different societies and cultures? How different would human systems of knowledge be if humans were to grow up in a radically different environment? Why do humans develop some domains of knowledge rapidly and with ease, and yet persist in reasoning erroneously, and with great effort, in other domains? Finally, how do humans develop systems of knowledge that are unique in the living world, from mechanisms and processes that appear to be closely similar to those of other animals?

After a century of intense study, the answers to these questions are still elusive. Nevertheless, psychologists have made considerable progress in characterizing the development of basic systems of human knowledge, and their characterizations hint at answers to deeper questions. In this chapter, I sketch some of the empirical progress made in the study of cognitive development, focusing on research on one topic in perceptual development (space perception), one topic on the border between perception and cognition (object perception and representation), and one topic in cognitive development (number). Although the sketches will emphasize what has been learned in these domains, each sketch will end with a set of persisting questions. In closing, I will suggest tentative answers to some of these questions and a path for future research.

Perception and Cognition at Century's End

II. DEVELOPMENT OF PERCEPTION OF DEPTH AND DISTANCE

The ability to apprehend a stable, three-dimensional layout from changing, two-dimensional patterns of optical stimulation has long occupied a central place in the dialogue between nativist and empiricist theories of perception. On the former views, the human visual system is intrinsically built to interpret particular patterns of stimulation as specifying particular arrangements of objects; on the latter views, humans learn such interpretations by looking around the world and acting upon it. These contrasting possibilities continue to guide research on perceptual development.

At the start of this century, debates about the origins and development of visual depth perception focused primarily on the findings of studies of the modifiability of depth perception in adults, coupled with arguments of logic, parsimony, and plausibility about the probable origins of modifiable systems. Studies of adaptation to inverting or displacing prisms suggested that depth perception showed considerable flexibility in the face of changing optical conditions: On first looking through new lenses, the world appeared distorted and actions were perturbed; with prolonged viewing, the world began to look more predictable, and skilled actions resumed (e.g., Helmholtz, 1867/1962; Stratton, 1897). In addition, studies of the information specifying depth and layout revealed that depth perception depends on a number of parameters that change with postnatal growth, including the size of the eyes and the distance between them, suggesting that the processes for recalibrating space perception found in adults are needed in children as well (again, Helmholtz, 1867/1962). If children have mechanisms for learning new relations between optical stimulation and perceived depth, however, then parsimony considerations suggest that they are not endowed with innate systems for perceiving depth as well. A nativist theory of space perception would appear to be "an unnecessary hypothesis" (Helmholtz, 1867/1962, vol. 3, p. 17).

More recent studies of perceptual adaptation have undercut aspects of this argument. The extent of the adaptability of the mature visual system to changes in the relation between optical stimulation and perceived depth has been called into question (e.g., Harris, 1965), as has the relation between learning in infants and relearning in adults (Bedford, 1989; cf. Ghahramani, Wolpert, & Jordan, 1996). If adaptation in adults depended on local remappings between visual and haptic information, for example, then such remappings also might account for the initial development of depth perception. If adaptation in adults, and adaptation to growth-induced changes in childhood, instead depend on a global recalibration of visual information, then the adaptation process itself might require an initially structured system for perceiving depth.

These developments suggest that logical arguments, coupled with studies of the learning capabilities of mature perceivers, are no substitute for direct investigations of perceptual development in children. Fortunately, the present century has seen a flowering of developmental studies. I focus here on three lines of research from the disciplines of developmental neurobiology, psychophysics, and behavioral ecology.

A. Developmental Neurobiology of Spatial Vision

Mature perception of the spatial layout depends on elaborate and precise patterns of connectivity in the visual pathways. Major insights into the nature of these patterns have been achieved in the second half of this century, beginning with Hubel and Wiesel's studies of the response properties of individual neurons in the visual cortex (see also Nakayama, chap. 10, this volume, for discussion). The discovery of cortical neurons in the adult cat and monkey that respond to edges at particular orientations and in particular regions of the visual field, organized in an exquisite topographic arrangement, has begun to unravel the code by which the mammalian visual system represents the positions of surface features in the visual field. The discovery that neurons relaying signals from the retina of each eye (the retinal ganglion cells) project to cells in different layers of a subcortical nucleus (the lateral geniculate nucleus or LGN), which in turn project to alternating bands of cells in the input layer of the primary visual cortex (the "ocular dominance columns"), begins to clarify the neural basis of stereoscopic depth perception, a process for computing depth from the relative positions of the projections of surface features to the two eyes. Importantly, psychophysical studies and functional brain imaging studies of normal humans and of patients with brain damage suggest that the basic organization found in the visual system of cats, monkeys, and other mammals exists in humans (see Goodale, 1995; Sereno & Allman, 1991). To a first approximation, therefore, studies of the development of neural connectivity in the visual systems of other mammals should shed light on this development in humans as well.

From Hubel and Wiesel's earliest investigations, studies of developing animals and of animals reared in darkness or with altered vision have probed the development of this neural organization. Studies of the development of layers of monocularly driven cells in the LGN and of the ocular dominance columns reveal that cells in both structures initially receive input from both eyes, and that the layered and striped patterns form later in development. Because the layered pattern in the LGN emerges prior to birth both in cats and in monkeys, visual experience evidently is not necessary for its development (see Shatz, 1992). In monkeys, the pattern of ocular dominance columns also is discernible at birth (Rakic, 1977). In both cats and monkeys, however, the pattern of ocular dominance columns undergoes considerable postnatal development, and so experiments have investigated the influence of visual experience on this development.

The most direct studies have compared the development of the ocular dominance columns in cats or monkeys reared in darkness to those of animals reared with normal vision. Ocular dominance columns were found to develop normally in dark-reared animals of both species (LeVay, Wiesel, & Hubel, 1980; Sherk & Stryker, 1976), providing evidence that visual experience is not necessary for shaping or sharpening this pattern. In further studies, animals were raised with a single eye occluded, and then visual function was assessed and patterns of connectivity from each eye to the primary visual cortex were mapped. Such monocular deprivation was found to have a marked effect both on an animal's ability to see with the occluded eye and on the relative widths of the alternating bands of ocular dominance, with wider bands of cells receiving inputs from the nonoccluded eye (LeVay et al., 1980). Nevertheless, the banded pattern of organization was discernible even in animals who had only viewed the world through one eye. These findings suggest that the basic pattern of binocular connectivity to the cortex is innate but can be influenced by visual experience that is systematically biased (LeVay et al., 1980).

A concerted goal of developmental neurobiology, since the time of these discoveries, has been to investigate the mechanisms by which visual experience comes to influence the connectivity and the functioning of the brain. Although these mechanisms have not been conclusively isolated, a growing consensus suggests that they operate in accord with principles articulated fifty years ago by Hebb (1949), following centuries of empiricist proposals (see Hochberg, chapter 9, section III.A.3, this volume; Proffitt & Kaiser, chap. 7, this volume). Hebb suggested that the connection between a neuron and its target is strengthened when the firing of the former is immediately followed by the firing of the latter. Because the firing of a target is more likely when many of the neurons that impinge upon it fire in concert, Hebb's principle implies the selective strengthening of connections from synchronously firing neurons to their common targets. When only one eye receives visual stimulation, synchronous activity in the visual pathway from that eye to the cortex may outweigh any such activity in the pathway from the occluded eye, increasing the active eye's cortical territory.

In addition to these studies of experience effects, neurobiologists have probed the developmental mechanisms that give rise to organized patterns of connectivity in the absence of visual experience. Highly interesting studies have focused on frogs, whose retinal ganglion cells normally project to nonoverlapping regions in the optic tectum and therefore produce no alternating bands of cells like those found in the mammalian cortex. When frog embryos were implanted with a third eye, close to one of the two normal eyes, and then were allowed to develop, the tectum of the frog was found to have alternating bands like those of cats and monkeys in the regions where the projection fields of the two eyes overlapped (see Constantine-Paton, Cline, & Debski, 1990, for discussion). These findings suggest that the ocular dominance columns do not develop in accord with a genetically specified program, for such a program could hardly exist either to guide the development of an eye that frogs normally do not have or to form ocular dominance columns that never appear under natural conditions. Some mechanism other than genetic specification evidently leads to the development of the alternating band pattern.

How can the organization of the visual cortex develop in advance of visual experience if that organization is not genetically specified? Recent research by Shatz and her colleagues (see Shatz, 1992) suggests that the same Hebbian mechanisms thought to produce plasticity in response to postnatal visual experience play a role in structuring the visual system before birth. In the prenatal eye of the cat or ferret, retinal ganglion cells are spontaneously active even before the visual receptors develop, and their activity follows a particular spatiotemporal pattern. Activity travels across the retinal ganglion cells of a single eye in waves, such that activity in one retinal ganglion cell is followed by activity in neighboring cells (see Feller, Wellis, Stellwagen, Werblin, & Shatz, 1996). If connections between these ganglion cells, their targets in the LGN, and the targets of those cells in the visual cortex are strengthened and stabilized by Hebbian associative processes, then these waves of activity will tend to produce a retinotopic organization both in the LGN and in the visual cortex. Moreover, if the activity waves of ganglion cells in the two eyes are uncorrelated but the targets of these cells are topographically overlapping, computational modeling reveals that Hebbian learning processes will give rise to segregated bands of cells in the cortex that are sensitive to inputs from each eye (Miller, Keller, & Stryker, 1989).

Evidence that spontaneous activity in the fetal eye in fact contributes to the prenatal development of topographic maps and monocularly driven layers of cells in the LGN comes from experiments in which the activity waves are chemically blocked in fetal animals. Such animals failed to develop the normal layered organization of the LGN (Shatz & Stryker, 1988), and infant kittens whose postnatal visual activity was blocked failed to develop normal ocular dominance columns (Stryker & Harris, 1986). Nevertheless, such animals do develop topographic maps, providing evidence that spontaneous activity is not the only mechanism producing organization in the developing visual system.

This brief excursion through the neurobiology of visual development suggests a recasting of the traditional debate between nativists and empiricists over the origins and development of space perception. As empiricists have always emphasized, the plasticity found in mature visual systems exists as well in developing systems, and it provides a means by which early visual experience can shape the brain. In accord with nativist theories, however, the very processes of activity-dependent change that alter the brain in response to visual experience also shape the connectivity of the visual system prior to an animal's first contacts with the external visual environment. This initial structuring constrains and guides subsequent visual learning, and it allows the newborn visual system to respond adaptively and systematically to visual stimulation. Activity-dependent processes therefore may account, in part, both for the adaptability of visual perception in response to visual experience and for the existence of perceptual capacities in advance of experience. Innate perceptual capacities may not be an "unnecessary hypothesis" but a product of the same mechanisms of plasticity that attune an animal's perception to the environment it perceives.

B. Psychophysical Studies of Space Perception in Infants

The first systematic studies of the perceptual capacities of human infants date from the same, fertile period in the 1950s that initiated the modern study of the neurobiology of vision. Fantz (see Fantz, 1961, for review) developed the preferential looking method, in which an infant human or other animal is presented with two visual displays side by side, and the infant's relative looking times to the two displays is assessed. Systematically looking longer at one of the displays, over pairs of trials in which the lateral positions of the displays are reversed, indicates that the infant discriminates the displays on some basis. By varying the properties of the two displays, investigators can probe both the extent and the basis of these discriminations.

Fantz found that human infants of all ages look longer at a display of thick, black-and-white stripes than at a display that is homogeneously gray, a finding that led both him and later investigators to develop tests of the development of visual acuity and contrast sensitivity over the first year (see Banks & Salapatek, 1983). Fantz also demonstrated that infants prefer solid objects to flat surfaces, a finding that laid the foundation for later, highly productive studies of depth sensitivity (see Held, 1985). In further studies, Fantz showed that 2-month-old infants prefer faces to other displays of comparable complexity, a finding that has given rise to vigorous and productive studies of face perception and recognition (see Johnson & Morton, 1991). Finally, Fantz found that infants look preferentially at novel over familiar (i.e., repeatedly presented) displays, a tendency that underpins much subsequent research on infant perception (see Bornstein, 1985; Spelke, 1985, and below). Other investigators showed other reliable preferences, including a preference for moving displays over stationary ones, making possible a variety of studies of motion and depth perception (see Kellman, 1993).

When do human infants first become sensitive to information for depth and distance? The answer appears to depend on the nature of the information presented. When depth is specified pictorially, by relations such as interposition and linear perspective, sensitivity to this information appears to develop rather late in human infancy, between 5 and 7 months (Yonas & Granrud, 1984). Sensitivity to binocular disparity, the basis of stereopsis, emerges in the fourth or fifth month, and stereoacuity improves rapidly thereafter (Fox, Aslin, Shea, & Dumais, 1980; Held, Birch, & Gwiazda, 1980). Before these developments, however, infants evidently perceive depth on some basis, for they have been shown to use information for an object's distance in perceiving its size and motion.

Kellman, Condry, Van de Walle, O'Halloran, and Hofsten (discussed in Kellman, 1993) investigated whether 2- and 4-month-old infants could perceive the absolute distance of an object by probing their capacity for position constancy. Infants who moved back and forth in a lateral translation were presented with objects that either were stationary or moved conjointly with them. When an observer moves, the patterns of retinal displacements produced by other objects depend both on the objects' motion and on their distance: Moving babies therefore would perceive the displacement of a conjointly moving object only if they perceived the object's distance. The investigators found that at 4 months, and under some conditions at 2 months as well, infants looked longer at the conjointly moving object. This preference provides evidence both for position constancy and for distance perception at these ages.

Two further experiments have investigated perception of object distance in newborn infants by focusing on the infants' capacity for size constancy (Granrud, 1987; Slater, Mattock, & Brown, 1990a; see also Bower, 1966). Slater et al. (1990a) familiarized infants ranging in age from 13 hours to 5 days with either a large or a small cube, presented at different distances on different trials. Then the infants were tested with the small and large cubes side by side, presented at two new distances chosen so as to equate their projected sizes in the visual field. The infants showed a highly reliable preference for the cube with the novel real size. Because the cubes' retinal sizes were equated, this preference provides evidence for size constancy, and distance perception, in the first days of life.

To date, the information used by newborn infants to perceive the relative distances of objects has not been clarified, although the ocularmotor cue of convergence is a plausible candidate (see Kellman & Arterberry, in press). This suggestion brings the modern study of depth perception back to Descartes (1637/1971), who first suggested that humans perceive depth from convergence "as it were by natural geometry" (p. 250).

These last experiments provide evidence that newborn human infants have some initial capacity to perceive object distance. Nevertheless, this capacity expands greatly over postnatal development. Older infants perceive depth and distance from more sources of information, and they exhibit this perceptual ability under a wider range of circumstances. Infants' capacities for perceiving space must be modifiable, moreover, in order to account for the considerable changes that occur over postnatal development due to the migration of visual receptors, the growth of the eyes, and the increase in interocular distance (see Aslin, 1988; Banks, 1988). Both initial structure and later growth and experience contribute to perception of depth and distance in humans.

C. The Comparative Psychology and Ecology of Perceptual Development: The Visual Cliff

Although psychophysical studies can reveal whether infants are sensitive to depth information, they do not reveal whether infants use such information to guide their spatial actions. This limitation is serious, because some of the most basic functions of spatial vision are to guide actions such as reaching and walking by bringing information about the existence and location of objects, supporting surfaces, and barriers.

At about the same time as the earliest investigations of Fantz and of Hubel and Wiesel, landmark studies of the emergence and the nature of these visual capacities were performed by Gibson and Walk (1960; Walk & Gibson, 1961), who tested depth perception and visually guided locomotion on the "visual cliff." Infants of a variety of species were placed on a centerboard between two tangible but nonvisible Plexiglas surfaces, through which a near surface was visible on one side and a distant surface—the cliff—was visible on the other side. Young animals of all the terrestrial species tested were found to locomote onto the optically near side and to avoid the optically specified cliff.

Visual cliff avoidance typically was observed at the earliest age at which an animal could be tested, when independent locomotion began. In precocial walkers such as goats, avoidance of the cliff was observed at birth, providing evidence for innate visual perception of depth and innate use of this information to guide locomotion. In animals who begin walking at later ages, such as rats, cats, and human infants, avoidance of the cliff was first tested, and exhibited, at those ages. In general, findings indicated that mechanisms for perceiving visually specified depth and guiding locomotion onto visibly supporting surfaces were present and functional at the time they were first needed, when an animal began to locomote independently. This developmental pattern makes sense, Gibson and Walk suggested, because later development of these mechanisms could lead newly locomoting animals to make costly, even fatal, errors.

Further studies of rats and cats investigated the effects of visual experience on the development of cliff avoidance, revealing interesting variations on a common theme. Rats who were reared in darkness were found to avoid the cliff on their first exposure to the light (Walk, Gibson, & Tighe, 1957). Just as visual experience is not necessary for the development of the basic patterns of connectivity in the visual system, it is not necessary for the development of this functional, visually guided behavior. In contrast, cats reared in darkness or in a visual environment in which they were displaced only passively showed no consistent visually guided locomotion when first exposed to the light (Gibson, 1991; Held & Hein, 1963). As in the case of rats and goats, however, trial-and-error learning appears to play no role in cats' developing cliff avoidance. In experiments described in Gibson (1991), dark-reared cats were given visual experience locomoting on the visual cliff apparatus itself. Because both sides of the cliff were covered with Plexiglas that prevented an animal from falling, one might predict these subjects would learn that the deep side of the cliff was a safe place to locomote. Nevertheless, the cats began to avoid the cliff just as much as their normally reared counterparts after 6 days of visual and locomotor experience. Similar conclusions come from Held & Hein's (1963) studies, in which cats who moved actively developed normal cliff avoidance, even though all their movements occurred within a harness that permitted no falls and obscured their view of their own bodies. These findings suggest that cats require experience with active motion in a visible environment in order to attune their visual system but do not require experience locomoting and falling in order to learn to avoid visible drop-offs.

Human infants begin to crawl at about 7 months of age. Given the ample evidence from psychophysical experiments that much younger infants perceive depth and distance, and given the finding that the development of cliff avoidance does not depend on trial-and-error learning in any nonhuman species yet tested, one might expect human infants to avoid the visual cliff as soon as they began to crawl, irrespective of experiences such as falling. Consonant with this expectation, the original studies of Gibson and Walk (1960) and some later investigations (e.g., Adolph, Eppler, & Gibson, 1993; Rader, Bausano, & Richards, 1980) revealed that visual information for a supporting surface guides locomotion in crawling infants. Nevertheless, further studies of human infants suggest truly surprising developmental changes in cliff avoidance.

First, cliff avoidance has been found to be affected by locomotor experience in human infants. More consistent avoidance of visible drop-offs is shown by infants who have been crawling for a longer time and by infants who have been given locomotor experience in a "walker": a device that supports prelocomotor infants in an upright posture and allows them to propel themselves forward by striking the floor (Campos, Bertenthal, & Kermoian, 1992). Second, even infants who avoid the cliff when they crawl are apt to cross it if placed in a walker: a finding that may account in part for the numerous accidents that have been reported when walkers are used in the home (Rader et al., 1980). Third, precrawling infants who are lowered over the shallow and deep sides of a cliff apparatus show, by raising their arms in anticipation of contact on the near side, that they perceive the relative distances of the two sides (Walters, 1981). When placed directly on the Plexiglas over the cliff, however, these infants show interest but no fear. Older infants show progressively more fear on the cliff, and fear reactions have been connected, at least anecdotally, to experience with falls. Finally, infants who have begun to show wariness on the cliff typically will look to a parent before beginning to cross it, suggesting that locomotion over uncertain visible surfaces engages social and communicative processes in our species (Campos et al., 1992).

Over the past two decades, research on visually guided locomotion has extended beyond the visual cliff to studies of crawling and walking infants' perception of the affordances for locomotion of a variety of visible surfaces (e.g., Adolph et al., 1993; Gibson & Schmuckler, 1989). With development, infants' perception of inclined surfaces and nonrigid surfaces becomes progressively differentiated. Interestingly, perception appears to be tied to the mode of locomotion; infants who have come to master an inclined slope by crawling must learn to do so again once they begin walking. In humans, visual-haptic exploration and locomotor experience evidently modify and extend the basic perceptuomotor coordination found in so many young animals.

D. A Puzzle

Three elegant lines of research, each starting in the 1950s and culminating today in a rich array of findings, appear to support the same general conclusion: Visual perception of space shows both initial structure and adaptability to experience. Perception and its neural mechanisms develop in accord with a set of epigenetic processes that begin to operate long before birth. In consequence, many nonhuman animals can use visual information for supporting surfaces to guide their actions in space on their first exposure to light, and newborn humans can use information for object distance to arrive at veridical, though imprecise, perceptions of object size and motion. After birth, perceptual systems continue to grow, both in accord with intrinsic processes and in accord with the structured visual environment.

A puzzle nevertheless remains. The human visual system evidently follows the same basic plan as that of other vertebrates. Moreover, the evolution of human perceptuomotor systems likely was subject to very similar ecological constraints to those of other terrestrial mammals: For humans as for mountain goats, mistaken steps off a cliff can be fatal. Finally, human infants, like the young of other species, show initial sensitivity to depth information. Despite all these findings, every parent knows that a newly crawling infant must be protected from drop-offs. Humans are the only species whose avoidance of the visual cliff has been shown to depend in part on locomotor experience, perhaps even experience with falls.

Another possible difference between humans and other animals emerges once infants begin consistently to avoid visual drop-offs. Whereas other animals may respond to the cliff by freezing or withdrawing, humans come to respond by manifesting fear or checking with a parent to confirm that all is well. Both fear of drop-offs and "social referencing" to a parent suggest a developing understanding of the consequences of locomoting without support. Although other animals avoid drop-offs, it is far from clear that they do so because of any understanding that walking off a cliff would lead to injury.

Research on perceptual development has done little to elucidate these possibly unique characteristics of human depth perception, but it invites some speculations. First, given the many homologies in the neural structures subserving space perception in humans and other animals, and given the common ecological constraints on all mammalian perceptuomotor systems, it is likely that humans and other animals have similar systems for perceiving depth and for using depth information to guide spatial actions, and that these systems develop in common ways, without shaping by trial-and-error learning. Second, humans may modulate these systems in distinctive ways, connecting their basic systems for perceiving depth and guiding locomotion to other systems for negotiating and making sense of the world. A human infant who plays near a parent on a bed may perceive a drop-off at the bed's edge, relate this perceptual information specifying the drop-off to other perceptual information specifying the parent's location and emotional state, and decide she is safe at the parent's side. Conversely, a child who sits at the edge of a visually continuous but structurally unsound surface may use the alarmed expression of her caretaker, as much as the signals form her own perceptual systems, as information for how to proceed. If these suggestions are correct, then a full understanding of human perception and perceptually guided action will require that investigators go beyond the basic perceptual and perceptuomotor systems revealed by the last half-century of research. Study of the uniquely human processes that coordinate and modulate distinct perceptual systems will become an important task for the decades ahead.

III. DEVELOPMENT OF PERCEPTION AND CATEGORIZATION OF OBJECTS

The world humans perceive, act upon, and reason about is not just an extended surface layout but an arrangement of stable, solid bodies with enduring properties: chairs, trees, cats, and houses. Although most objects in any layout are at least partly occluded, adults perceive objects seemingly at a glance, detecting their boundaries and complete shapes and categorizing each object as a member of a familiar and meaningful kind. How do we accomplish this feat? To what extent, and in what respects, are human representations of objects shaped by contacts with those objects, on the one hand, and by the inherent structure of human perceptual and cognitive systems, on the other? (See also Medin & Coley, chap. 13, this volume.)

Early in this century, a comprehensive set of answers to these questions was attempted by the Gestalt psychologists (see Koffka, 1935; Köhler, 1947) (see also Hochberg, this volume). Object perception, they suggested, results from inherent propensities to confer the simplest organization on perceptual experience. In the absence of any sensorimotor learning, perceivers will group arrays into figure and ground, perceiving solid objects with definite boundaries standing in front of surfaces that extend indefinitely behind them. The borders between two such objects also will be perceived, in part, through processes that produce the simplest, most regular figures that are consistent with the scene, grouping together surfaces of a common color and texture, with aligned edges and a symmetrical shape, that undergo common motion. Because natural objects tend to exhibit all these Gestalt relations, perceivers' inherent organizational tendencies typically will give rise to accurate perceptions of object boundaries in the absence of any specific learning about visual scenes.

Like Helmholtz, the Gestalt psychologists supported their claims primarily through studies of experience effects in adult perception and arguments from parsimony and plausibility. They showed, for example, that repeated presentation of an array sometimes has little influence on adults' perceptual organization (Gottschaldt, 1967), that even very commonly viewed figures, such as alphabetic characters, will fail to be perceived if Gestalt organizational principles do not favor them (Wertheimer, 1923/1958), and that Gestalt relations within a scene can overpower specific knowledge about the kinds of objects that the scene contains (Kanizsa, 1979; Michotte, Thines, & Crabbe, 1964). Because knowledge and experience do not influence adults' organization of scenes in these cases, they reasoned, it is unlikely that knowledge and experience give rise to humans' original abilities to perceive objects.

As in the case of the empiricists' opposite but symmetrical arguments, this reasoning can be questioned (see Brunswik & Kamiya, 1953; Hochberg, 1974) and is no substitute for direct study of the development of object perception in humans and other animals. Such research has advanced considerably in this century, although some basic questions remain outstanding. Here I consider two lines of study of the development of object perception: studies of the development of perception and categorization of objects using preferential looking methods, and studies of the development of actions on objects, such as reaching and visual following.

A. Object Perception and Categorization in Infancy

The early development of object perception has been investigated most extensively through experiments that rely on infants' tendency to look longer at displays that are more novel. These experiments provide evidence that 4- to 6-month-old infants perceive figure–ground relations in natural, 3-D displays as the Gestalt psychologists predicted: presented repeatedly with an object in front of a background surface, infants' looking times to other displays, including parts of the object or background, provide evidence that they perceive the object as bounded and the background to extend behind it (Arteberry, Craton, & Yonas, 1993; Termine, Hrynick, Kestenbaum, Gleitman, & Spelke, 1987). Infants also perceive objects to continue behind occluders under conditions similar to those studied with adults by Michotte et al. (1964). After repeated presentation of a moving object whose ends were visible and whose center was hidden by a nearer object, 4-month-old infants subsequently showed little interest in a nonoccluded, complete object and greater interest in a nonoccluded display with a gap where the occluder had been (Johnson & Nanez, 1995; Kellman & Spelke, 1983). This preference provided evidence that they had perceived the original display as a complete object that was connected behind the occluder (see Kellman, 1993, for more evidence and discussion).

Further preferential looking experiments have investigated infants' perception of an object that progressively becomes fully occluded. Michotte et al. (1964) proposed that Gestalt principles of organization lead adults automatically to perceive such an object as persisting over occlusion. To investigate whether infants perceive a persisting object in this situation, Craton and Yonas familiarized 6-month-old infants with a disk moving in and out of view behind an occluder and presented, in alternation, a nonoccluded complete disk, which had been visible only briefly in the original display, and a nonoccluded half-disk, which had been visible for a longer time. Infants looked longer at the half-disk, suggesting that they had perceived a complete disk, not just its visible surfaces, during the occlusion event (Craton & Yonas, 1990; see also Van de Walle & Spelke, 1996). Other preferential looking experiments provide evidence that infants represent objects that are fully hidden at ages as young as 2–3 months (e.g., Baillargeon & DeVos, 1991; Rochat & Hespos, 1996; Simon, Hespos & Rochat, 1995; Spelke, Kestenbaum, Simons, & Wein, 1995; Wilcox, Rosser, & Nadel, 1994; Wynn, 1992a).

Finally, Michotte (1963) proposed that perceivers automatically apprehend causal relations between the motions of two objects, under appropriate spatiotemporal conditions: If a stationary object is contacted by a moving object and immediately begins to move, the moving object is perceived as the cause of its motion. Preferential looking experiments provide evidence that infants as young as 3 months perceive the same causal relation in such events (Kotovsky & Baillargeon, 1994; Leslie, 1988), even when the launching of one object by another is partly occluded (Ball, 1973; Van de Walle, Woodward, & Phillips, 1994).

This brief review suggests that abilities to perceive the boundaries, complete shapes, and causes of motion of visible objects, and abilities to represent the existence, motion, and causal interactions of occluded objects, begin to emerge quite early in human infancy, consistent with Gestalt theory. Nevertheless, further studies exploring both the limits and the origins of these abilities have appeared to cast doubt on aspects of that theory. First, a series of experiments suggested that 3–5-month-old infants perceive objects primarily by analyzing spatiotemporal properties of the surface layout, grouping together surfaces that are connected and that move together (see Spelke & Van de Walle, 1993, for review). For example, 4-month-old infants perceive a center-occluded object as connected behind its occluder by analyzing the motion of its visible surfaces. In contrast, infants are less apt to perceive the connectedness of a center-occluded object by analyzing the similarity and alignment of its surfaces (Kellman & Spelke, 1983; Needham, 1994; Smith, Johnson, Spelke, & Aslin, 1996), even though they use similarity and alignment relations to organize surface patterns (Quinn, Brown, & Streppa, 1997; Johnson & Aslin, 1996). These findings initially led some investigators to propose, following Brunswik & Kamiya (1953), that Gestalt relations such as good continuation and similarity are learned (Kellman & Spelke, 1983; Spelke, 1988).

Further suggestions that learning gives rise to object perception were prompted by studies of object perception in younger infants. Two-month-old infants, presented with a center-occluded rod similar to that used by Kellman and Spelke (1983), were found to have no determinate perception of a connected object behind the occluder (Johnson & Nañez, 1995), although infants of this age did perceive a connected object when the size of the occluded region was reduced (Johnson & Aslin, 1995). More striking, newborn infants presented with the same display appeared to perceive two separated objects rather than one connected object (Slater et al., 1990b). This last finding suggested that the initial visual world of the infant might be a mosaic of visible surfaces after all, and that abilities to perceive complete objects over partial occlusion might depend on visual experience, such as the experience of viewing repeated object coverings and uncoverings (Slater et al., 1990b; see also Munakata, McClelland, Johnson, & Siegler, 1997).

Studies of object perception in chicks cast some doubt on both of these suggestions (Regolin & Vallortigara, 1995). These studies used an interesting variant of the familiarization and novelty preference method, based on the phenomenon of experimentally induced imprinting. A chick who is reared in isolation from any other animal, but in the presence of an inanimate object, comes to show filial behavior toward that object. Placed in an elongated test cage with the object of imprinting and a discriminably different object at opposite ends, the chick spends most of its time in proximity to the imprinted object (Horn, 1985). This "familiarity" preference allows for the design of experiments exactly analogous to the novelty preference test method of Fantz, except that it is the preferred test object, not the nonpreferred object, that is inferred to be perceptually more similar to the object of familiarization.

Using this method, Regolin and Vallortigara (1995) familiarized newborn chicks with a fully visible triangle that dangled from the end of a string at the center of an empty cage. Because the cage was devoid of other objects, a chick never saw the object occluded or disoccluded. After two days' exposure, chicks were tested with a center-occluded triangle and with a broken triangle containing a gap where the other triangle was occluded (see Regolin & Vallortigara, 1995, for further conditions of the experiment). The chicks spent most of their time near the occluded triangle. Together with their appropriate control conditions, this finding suggests that chicks who view a partly occluded object for the first time perceive the object to continue behind its occluder, contrary to Slater's findings with newborn human infants.

In a further experiment, newborn chicks were imprinted to a center-occluded, stationary triangle and then were tested with stationary complete and broken triangles. In an experiment with human infants using essentially the same displays, 4-month-olds had shown no differential looking at the two test displays (Kellman & Spelke, 1983). In contrast, the inexperienced chicks showed a consistent preference for the complete test triangle, providing evidence that they had perceived the original, stationary triangle as connected behind its occluder. This finding suggests that inexperienced chicks are predisposed to perceive objects by organizing the visual layout into bodies with aligned edges, homogeneous surfaces, and simple shapes.

Both these experiments support the original Gestalt analysis over the empiricist suggestions of Brunswik and Kamiya (1953), Slater et al. (1990b), and Kellman and Spelke (1983). Because the visual system of chicks is similar to that of humans but is more mature at birth, the authors suggest that maturational changes account for much of the development of object perception in humans (Regolin & Vallortigara, 1995). Nevertheless, this suggestion remains to be tested directly in our species.

Thus far, we have considered the development of abilities to perceive objects as unitary, bounded, and enduring. Adults also categorize objects rapidly, perceiving each body as a member of a particular kind, and recognize specific individuals such as a neighbor, dog, or favorite chair. When and how do children develop these abilities?

When object categorization and face recognition are tested by preferential looking methods, both are found to emerge early in infancy. For example, 4-month-old infants have been familiarized with a series of photographs of different species of cats and then have been shown novel photographs portraying a cat of a new species paired with a bird, dog, or horse. Infants looked longer at the photograph of the animal that did not belong to the familiar category, suggesting that they had formed a category including cats and excluding these other animals (e.g., Quinn, Eimas, & Rosenkrantz, 1993). Studies using this method provide evidence that young infants can make quite subtle categorizations, such as discriminations within the feline family (cat vs. female lion) and discriminations among more global and heterogeneous categories of objects (animals vs. vehicles) (see Eimas, 1994, for review and discussion). Mature animals of a variety of species, including pigeons, show similarly subtle categorization abilities (see Herrnstein, 1990).

Preferential looking studies also provide evidence that infants come to recognize visually the face of a parent within the first few days of life (Bushnell, Sai, & Mellon, 1989). Like chicks in an imprinting test, human infants exhibit this recognition by looking at the face of the mother in preference to the face of another woman of similar age and coloring. Although infants fail to discriminate the face of their mother if only the internal features of the face are available to distinguish her face from that of another person of similar appearance (Pascalis, de Schonen, Morton, Deruelle, & Fabre-Grenet, 1995; see also Diamond & Carey, 1977), attention to internal features increases over the first few weeks of life (Haith, Bergman, & Moore, 1977).

All these findings suggest that infants rapidly become sensitive to the patterns of perceptual similarity and difference that mark both distinct natural categories and distinct individuals. Abilities to recognize and categorize objects begin to develop early in the first year of life, hand in hand with abilities to perceive object unity, boundaries, and persistence over occlusion.

Nevertheless, infants' representations of objects have a curious limitation: Abilities to perceive object boundaries and to categorize objects do not appear to be well coordinated. For adults and older children, objects have enduring properties and belong to enduring kinds: a cat does not radically change its texture, internal structure, or boundaries over time, and it does not cease to be a cat as it moves about. Adults therefore can use information about kind membership to perceive where one object ends and another begins (perceiving a sleeping cat or a sofa as a distinct object and not as part of the sofa) and to trace the paths of objects over occlusion (perceiving the mouse that scurries out of a closet as a distinct object from the cat that previously entered the closet).

Research suggests that these abilities develop surprisingly late in infancy, between 10 and 12 months of age (Xu & Carey, 1994, 1996; see also Simon et al., 1995). At 10 months, infants who view a toy animal sitting on a toy vehicle, or an animal and vehicle that appear in succession from behind a single occluder, appear to have no determinate perception that the two toys are distinct objects. At 12 months, these perceptions change and converge with those of adults. This developmental change suggests that initial abilities to perceive objects as unitary and bounded are quite separate from initial abilities to perceive similarity relations among a set of distinct members of a single category. I will return to this suggestion.

B. The Development of Object-Directed Actions

Although the Gestalt psychologists provided the most thorough analysis of object perception, the central 20th-century figure in the study of the development of object representation is Piaget (1952, 1954), whose studies of infants' changing abilities to act on objects continue to dominate contemporary research and debates. Piaget discovered dramatic changes in children's actions on objects, from simple, early-developing actions, such as grasping and sucking, to complex, coordinated actions, such as making an object approach by pulling on something to which it is attached, or obtaining a hidden object by removing its occluder. His most well-known findings—that infants do not search for occluded objects until about 8 months, and that they do not confine their search to physically possible locations until almost a year later—prompted the well-known thesis that object representations are constructed slowly over the first 18 months of life as children come progressively to coordinate their object-directed actions. Before this coordination, Piaget suggested, infants have no ability to represent objects as enduring bodies.

More recent studies of object-directed action serve to qualify Piaget's conclusions in some respects and extend them in others. First, babies who are presented with an object that then is obscured by darkness have been found to reach for and obtain the object well before infants who are presented with an object that is hidden by an occluder (Hood & Willats, 1986; see also Clifton, Rochat, Litovsky, & Perris, 1991). Second, babies who are presented with an object hiding game, but with no hidden object, have been found to make the same search errors as those given Piaget's search tasks (Smith & Thelen, 1995; cf. Munakata & McClelland, 1996). Both these findings suggest that search failures stem, at least in part, from factors other than immature representations of unseen objects. Nevertheless, research by Munakata et al. (1997) has extended Piaget's essential findings by showing that young infants fail to search for hidden objects even when a search task is made extremely easy and the infants are trained to perform it. This finding and others (Munakata, 1997; Spelke, Vishton, & Hofsten, 1994) suggest that the occlusion of an object genuinely poses problems for an infant who would act upon it.

Comparative studies of object-directed actions cast an interesting perspective on the search errors of human infants. Nonhuman primates such as rhesus and capuchin monkeys solve Piaget's object search tasks in the same developmental order as human infants, but on an accelerated timetable. For example, rhesus monkeys begin to search successfully for an occluded object by removing its occluder at about 3 to 4 months (Antinucci, 1989; see also Diamond, 1990). Most interestingly, a version of Piaget's object search task has been presented to domestic chicks in the second day of life, using a variant of the imprinting paradigm described above (Regolin, Vallortigara, & Zanforlin, 1995a). On their first day, chicks were presented with a fully visible, moving inanimate object (a ball), to which they became imprinted. On the next day, chicks watched as the ball was placed behind one of two identical occluders. With high reliability, the chicks searched for the ball by moving around the appropriate occluder. Over successive trials, moreover, the chicks searched only physically possible locations (i.e., they did not return to the place where the object was hidden on a previous trial). Similar findings were obtained when the occluded object was a desirable food (Regolin et al., 1995a) and when a different procedure was used (Regolin et al., 1995b), suggesting that the ability to search for hidden objects is robust in this species (although Etienne, 1973, and Regolin et al., 1994, 1995a, describe conditions in which chicks fail to exhibit this behavior). Thus, 2-day-old chicks and 4-month-old monkeys succeed at "object permanence" tasks that are strikingly like the tasks that 7-month-old human infants fail.

The findings of these comparative studies suggest that object permanence is attained by many animal species, but at quite different times in postnatal development. Because 2-day-old chicks, 3-month-old monkeys, and 8-month-old human infants differ greatly in the nature and extent of their experience with objects, such experience appears to play only a limited role in the development of object permanence. In particular, the chicks in Regolin et al.'s, studies had had just one day of visual experience, they had never seen one object occluded and disoccluded by another, and they had never had the opportunity to follow an object behind a barrier. (The chicks did, however, view the object and move around it throughout the day.) Chick's success at retrieving the hidden object casts doubt on the thesis that perceivers learn to represent hidden objects by repeatedly witnessing their occlusion and disocclusion (Munakata et al., 1997). More positively, comparisons across species suggest that the common predictor of the time of emergence of object search is the state of maturation of the young animal: Animals that are relatively mature at birth, such as chicks, develop abilities to search for hidden objects long before those that mature more slowly. Maturational changes may play a large role in the development of actions on hidden objects (Regolin et al., 1995a, 1995b; Diamond, 1990).

Although the preferential looking studies described in the last section focused primarily on object perception, and the Piagetian studies described in this section focused primarily on object representation and action, psychologists have become intrigued by an apparent conflict between the findings from these two lines of research. When tested by preferential looking methods, infants appear to represent occluded objects and to use knowledge of constraints on object motion to infer how such objects move (see Baillargeon, 1993, for review). When tested by search methods, infants under about 8 months act as if occluded objects do not exist, and those under about 18 months act as if the movements of such objects are not constrained by physical laws.

A study that directly compared infants' behavior toward occluded objects in search tasks and in preferential looking tasks reveals this discrepancy clearly (Ahmed & Ruffman, 1996). Eight-month-old infants first were given a search task in which they repeatedly found an object that was hidden at one of two hiding places, then observed the object hidden at the other hiding place, and after a delay were allowed to reach for the object. As in Piaget's original studies, the infants reached to the incorrect location where the object had been found before. Then the same infants were given a preferential looking task, in which they viewed the same object hidden and revealed in the same locations, on the same succession of trials with the same delay. As in previous preferential looking studies, the infants looked longer when the object was revealed at the original, incorrect location than when it was revealed at the more novel, correct location. The infants' preferential looking therefore appeared to be guided by a veridical representation of the hidden object's location, whereas their search appeared to be guided by a misrepresentation of that location (see also Spelke et al., 1994).

In summary, young infants can act an objects both when they are visible and when they are occluded by darkness. In preferential looking experiments, young infants also appear to represent objects that are occluded and to keep track of an occluded object's location. Young infants fail, however, to put these two abilities together so as to reach for an occluded object. To date, there is much speculation but no consensus concerning the meaning of this dissociation or the developmental processes that overcome it (see Baillargeon, 1993; Bertenthal, 1996; Diamond, 1990; Mandler, 1992; Munakata, in press; Munakata et al., 1997; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Thelen & Smith, 1994). I sketch one possible account below.

C. Overview

Research on the development of object perception and representation suggests that central features of mature human abilities to perceive and represent objects trace back to the early months of life. Under certain conditions, young human infants can perceive the unity and boundaries of objects and the complete shapes of objects that are partly hidden. Young infants also can perceive the existence and location of fully hidden objects, and they can recognize specific individuals and categorize objects as members of specific kinds. Studies of other animals suggest that these abilities are widespread among vertebrates, at least, and that some of the abilities arise with minimal shaping by visual experience. Nevertheless, the role of experience in the development of object representation has been far less well studied than the role of experience in the development of perception of depth.

Despite all the abilities outlined above, young human infants' perception of objects shows some striking limitations. One limitation is revealed by tasks that require infants to conjoin information about the properties and category membership of an object with information about the object's boundaries (e.g., Xu & Carey, 1996): Such tasks are surprisingly difficult for infants under 12 months of age. Another limitation is revealed by tasks that require infants to act upon objects that are occluded (e.g., Piaget, 1954): Such abilities undergo lengthy and extensive developmental change over the first 18 months of life.

Both the strengths and the limitations of infants' object representations prompt a suggestion and further questions. I suggest that humans have multiple, early-developing systems for perceiving and representing objects, and that these systems are poorly coordinated early in the development (see also Bertenthal, 1996; Xu &

Carey, 1996). Although 5-month-old infants represent visible objects as targets for reaching and represent the unity and persistence of objects that are occluded, they may not be able to conjoin these representations so as to reach for an occluded object. And although infants perceive spatiotemporally specified object boundaries in visual scenes and detect perceptible differences between objects in different categories, they may not be able to conjoin these representations so as to use perceptible differences between objects in different categories as information for object boundaries.

Evidence for separate systems of object representation abounds in other areas of visual science and neuroscience. In particular, there is evidence for separate cortical visual pathways for perceiving and categorizing objects, on one hand, and for grasping and manipulating objects on the other (Goodale, 1995; Jeannerod, 1994; cf. Ungerleider & Mishkin, 1982). There also is evidence that the neural processes subserving figure–ground organization and perception of object unity are quite different from those subserving detection of object features or spatial properties guiding actions (e.g., Singer & Gray, 1995). The present suggestion accords with these findings.

If humans form multiple, independent representations of objects early in development, then how does the relationship between these representations change over development? Studies of developmental changes in human object representations are consistent with the possibility that the initially separate systems of representation become intercoordinated over the course of the first 2 years. Developmental changes in search for objects may depend in part on emerging abilities to relate the system for representing hidden objects to the system of representation that is linked to action. And developmental change in object categorization may result from mappings of the categorization system to the action and perception systems. Nevertheless, this possibility remains to be tested, for existing research has hardly begun to investigate the existence of such coordinations, the processes by which they arise, or the changing representations of objects that they make possible.

IV. DEVELOPMENT OF KNOWLEDGE OF NUMBER

Knowledge of number contrasts with perceptual knowledge of space and objects in several respects. At its higher reaches, it is indisputably a distinctly human ability that may have emerged late in human evolution, coincident with a host of other developments, such as symbolism, rapidly changing technology, art, ritual, and language (Mithen, 1996). Knowledge of number continues to grow into adulthood. Extending this knowledge requires effort, whether it is the efforts of preschool children learning to count and perform intuitive addition, elementary school children learning arithmetic facts, or of high school students learning algebra or calculus. Finally, knowledge of number appears to vary to some degree across individuals and cultures: Although every normal person probably represents space and objects in much the same ways, not everyone achieves the same mathematical knowledge and skills.

Despite the striking differences between this topic and the preceding ones, insights into the development of knowledge of number have come from some of the same approaches that have shed light on the development of perception of space and object. Studies of human infants using preferential looking methods (e.g., Wynn, 1995), studies of young children's counting and spontaneous numerical reasoning (e.g., Gelman & Gallistel, 1978), studies in comparative psychology and behavioral ecology (e.g., Gallistel, 1990), and studies in cognitive neuroscience (e.g., Dehaene & Cohen, 1991) all have shed light on the origins and nature of humans' unique "number sense" (Dehaene, 1997). My brief summary of research focuses on studies of perception and representation of number in human infants and studies of developmental changes in number knowledge as children learn to count.

A. Number Representations in Infants

Experiments using preferential looking methods provide evidence that young human infants represent the number of objects or events in a scene, provided that number is small (up to three or four). For example, infants who are familiarized with a succession of arrays containing three objects show a novelty preference for a new array containing two objects over a new array containing three objects; infants habituated to a succession of arrays containing two objects show the reverse preference. This finding has been obtained with arrays of simple geometrical figures in varying positions (Antell & Keating, 1983; Starkey & Cooper, 1980), drawings of common objects varying in size and position (Strauss & Curtis, 1981), photographs of arrays of heterogeneous objects in varying arrangements (Starkey, Spelke, & Gelman, 1990), and animated displays of moving objects that progressively occlude and disocclude one another (van Loosbroek & Smitsman, 1990). Infants also dishabituate to changes in the number of events in a sequence, such as the number of jumps performed by a puppet (Wynn, 1995) or the number of syllables in a word (Bertoncini & Mehler, 1981). Small number discrimination has been shown at a variety of ages throughout the first year, including newborn infants (Antell & Keating, 1983).

Infants' sensitivity to number also has been tested with a different visual preference method: an intermodal matching test. Infants view two visual arrays containing two versus three objects, arranged side by side, while listening to a sequence of two or three sounds. In other research, infants sometimes have been found to look longer at a visual display that matches an accompanying sound: on hearing speech, for example, infants tend to look longer at a face that appears to be its source (e.g., Kuhl & Meltzoff, 1982; see Spelke, 1989). Accordingly, experiments have investigated whether infants would show this preference when number provided the matching variable. In one series of experiments, 6-month-old infants indeed looked longer at the visual array with the matching number of objects (Starkey, Spelke, & Gelman, 1990). In other research, however, infants showed the opposite preference or no preference (Moore, Benenson, Reznick, Peterson, & Kagan, 1987; Mix, Levine, & Huttenlocher, 1994). These inconsistent findings may stem from a competing tendency for infants to look preferentially at nonmatching or unfamiliar visual arrays. Alternatively, abilities to represent an intermodal numerical correspondence may be fragile or absent in infants.

Finally, the most dramatic studies of number representation in infants have focused on infants' capacities for small number addition and subtraction, using arrays in which objects become fully occluded. Wynn (1992a) presented 5-month-old infants with an array containing one object, covered the object by a screen, and then introduced a second object and placed it behind the same screen. When the screen was lowered to reveal either the correct number of objects (two) or the number of objects presented at the outset (one), infants looked longer at the latter outcome. Similarly, infants presented with an event in which two objects were screened and one was removed looked longer at the superficially familiar but incorrect outcome array of two objects. These findings provide evidence that infants represented the number of occluded objects in the original array, represented the occluded addition or subtraction of an object, and inferred the number of objects in the outcome array.

Numerous experiments have replicated and extended these findings. First, infants were found to succeed at the 1 + 1 addition task when the two outcome displays contained two (correct) versus three (incorrect) objects, suggesting that infants computed the exactly correct outcome in this condition (Wynn, 1992a). Infants also succeeded at the addition task when the screened objects stood on a moving turntable, such that the number of objects could serve as a basis for recognition, but the objects' spatial positions could not (Koechlin, Dehaene, & Mehler, in press). Finally, infants succeeded at the addition and subtraction tasks when the objects used to produce the events changed behind the screen, such that specific object features could not be tracked over time (Simon et al., 1995). All these studies suggest that object number is a salient property of visual displays for infants, even when objects are occluded.

Studies of infants also have revealed some striking failures in number-discrimination tasks. First, infants often fail to discriminate arrays containing more than three or four objects. For example, 6-month-old infants showed no preference to four objects after habituation to six objects or the reverse (Starkey & Cooper, 1980) and no preference for eight objects after habituation to twelve objects or the reverse (Xu & Spelke, 1998). These failures are noteworthy, because the numerosity ratios used in these studies are as large as those used in the successful, small-number studies. Nevertheless, infants do show a novelty preference for eight objects after habituation to 16 objects or the reverse (Xu & Spelke, 1998), providing evidence for some sensitivity to large numerosities.

Second, infants fail to exhibit number discrimination when they are presented with nonsolid substances or collections instead of solid objects. For example, Huntley-Fenner (1995) presented 8-month-old infants with a Wynn addition task involving either sand piles or solid objects with the shapes and textures of sand piles. Infants were familiarized with sand or with a solid object before the study, and they watched the sand piles (or solid objects) undergo nonrigid (or rigid) transformations whenever they were introduced into the display. Infants succeeded at the task when the stimuli were solid objects, as in Wynn's original studies, but they failed when the stimuli were sand piles. This finding suggests that infants do not treat nonsolid substances as enumerable entities. In a further study (Chiang & Wynn, 1996), infants were presented with the Wynn addition task using two sets of five construction blocks arranged so as to form pyramids. In principle, this task could be performed either by adding pyramids (1 + 1 = 2) or by adding blocks (5 + 5 = 10 rather than 5). Contrary to either possibility, infants failed Wynn's addition task with the pyramids but succeeded in a parallel experiment involving two pyramidal-shaped, solid objects. This finding supports two conclusions. First, although solid objects and certain events appear to be countable entities for infants, aggregates and collections are not. Second, although infants can discriminate large numerosities in a 2:1 ratio, they do not add such numerosities.

Studies of other primates suggest that the representations of number found early in human development are not unique to humans. Both cottontop tamarins and rhesus monkeys succeed at Wynn's addition and subtraction tasks (Hauser, MacNeilage, & Ware, 1996; Uller, Carey, & Hauser, 1996): an especially significant finding, because the tasks involve no training. A variety of animals including parrots, raccoons, rats, and primates also have been trained to discriminate small numerosities (see Davis & Perusse, 1988; see Boysen & Capaldi, 1993, for review). Laboratory and field experiments suggest, moreover, that a wide range of species represent the approximate numbers of objects and events in scenes or situations containing large numerosities (see Gallistel, 1990, for review). For example, rats and pigeons who are trained that food will arrive after they make, for instance, 50 bar presses or key pecks come to make approximately that number of responses before anticipating food delivery (e.g., Mechner, 1958). As the number of responses increases in these tasks, so does the variability in the animal's responding, suggesting that the accuracy of number representations decreases with increasing set size. In addition, ducks and fish distribute their time between two food sources in rough proportion to the rate of food provisioning at those sources (e.g., Harper, 1982; see also Herrnstein & Loveland, 1975), suggesting that they form some approximate representation of the amount of food presented in a given interval of time (Gallistel, 1990). Finally, rats can be trained to discriminate four from eight sound bursts, responding to relative number over variations in other qualitative properties of the items, such as the duration of each burst (Church & Meck, 1984). These findings provide no evidence that the sources of uniquely human number abilities lie in the abilities exhibited by young infants in preferential looking experiments.

B. Developmental Changes in Number Representations in Young Children

The most striking changes in number abilities occur after children begin school, where they learn to perform new arithmetic calculations and develop new number concepts such as zero, fractions, and negative numbers (Gelman, 1991). Nevertheless, important changes in number representations also occur before formal schooling, coincident with the development of verbal counting. I focus on these earlier changes.

At about 2 years of age, children begin to count, and their counting shows interesting systematicity. As documented in the landmark studies of Gelman and Gallistel (1978), early counting tends to conform to the principles of one–one correspondence (children apply each number term to exactly one object), stable ordering (children tend to use a sequence of count terms in a constant order, although the orders of early count sequences, and even the terms themselves, sometimes are idiosyncratic), and cardinality (the last term in the count sequence has special significance for the child, possibly indicating the numerical value of the set). Although the extent and the meaning of this systematicity has been debated (e.g., Fuson & Hall, 1983, Gallistel & Gelman, 1992; Wynn, 1990), the existence of early developing, systematic counting is beyond dispute. Children appear to learn some form of counting spontaneously, in nearly all the cultures of the world (see Gordon, 1994, for a possible exception). Early counting is performed only on the entities that infants enumerate in preferential looking studies: solid objects or discrete events (Shipley & Shepperson, 1990). When children are asked to count the forks in an array containing three solid forks and one fork that has been broken into two pieces, for example, they typically count five bodies rather than four forks. All these findings suggest that young children are predisposed to develop procedures for counting the entities that their early developing perceptual systems pick out, and that these procedures yield representations of number (Gallistel & Gelman, 1992).

Despite these findings, young children may have marked gaps in their understanding of counting procedures and number words. First, 2- to 3-year-old children who are presented with a pile of objects and asked to give an experimenter, for example, "four" of the objects typically will give a handful of objects, without counting. Although such children reliably give just one object when asked for one and give more than one object when asked for a different number, the number that children give in the latter case is essentially random with respect to the number requested (Wynn, 1990). Only at about $3\frac{1}{2}$ years of age, more than a year after children begin counting objects, do children count when asked for a specific number of objects and then give the number requested.

Similar findings emerge when children are given a number word comprehension task. Children at the same ages were shown two pictures of multiple objects (e.g., a picture of three fish and a picture of four fish) and were asked to point to "the three fish." Children pointed successfully when one of the two alternatives depicted a single object, providing further evidence that they knew the meaning of "one" and knew that other number words refer to numerosities above one. In contrast, children pointed at random when each of the two alternatives depicted more than one object (Wynn, 1992b).

Further studies of children's changing performance on these tasks suggested an interesting developmental progression (Wynn 1992b). About 9 months after the onset of counting and after mastery of the meaning of "one," most children came to understand the meaning of "two," pointing to or giving exactly two objects on verbal requests. Months later, most children came to understand the meaning of "three." Still later, children came to understand the meanings of the rest of the number words in their vocabulary, and they began to use counting when asked to produce a given number of objects. Because no children could be found who understood "four" but not "five," Wynn suggested that understanding of counting and number words developed in a regular progression, with children first coming to understand the words "one," "two," and "three," in that order, and then coming all at once to understand the counting routine and the rest of the number words within it.

A variety of animal species other than humans also have shown changes, with training, in their abilities to represent exact numerosities and to use symbols to stand for these representations. In a typical training study (e.g., Matsuzawa, 1985; see also Boysen, 1993; Pepperberg, 1987), an animal first is introduced to symbols for a few small set sizes and is reinforced for correctly pairing each set size with its corresponding symbol. After the animal reliably chooses the appropriate symbol when shown a given set size (a test of number word production) and creates the appropriate set size in response to a given symbol (a test of number word comprehension), a new set size is introduced and further training is given. With such procedures, a chimpanzee has been taught symbols (plastic Arabic numerals) for the numbers one through six (Matsuzawa, 1985) and a parrot has been taught symbols (aural "words") for even higher numerosities (Pepperberg, 1987; see Davis & Perusse, 1988, for discussion of these and other studies).

Although these experiments reveal impressive number discrimination abilities, their findings suggest that the process by which animals learn to match tokens with specific numerosities is quite different from the process by which human children learn the meanings of number words. First and most obviously, the animals in these studies required extensive training, whereas young children appear to learn to count spontaneously, with little or no correction. Second, animals appear to be less constrained than human children with respect to the kinds of entities they enumerate. Monkeys, for example, have been trained to enumerate the sides of a polygon (Terrell & Thomas, 1990), which would be unlikely to qualify as countable entities for young children (Shipley & Shepperson, 1990).

Third, the developmental progression in learning number symbols is strikingly different in nonhuman primates from the progression observed with human children. For animals, the task of learning a symbol for a given numerosity becomes harder and harder as symbols for progressively higher numerosities are introduced. In Terrell and Thomas's (1990) study, for example, three of four monkeys met criterion on discriminating between six and seven elements within the 1000 trials allowed for each pairwise number discrimination, but only two of the three monkeys met criterion on discriminating between seven and eight elements, and no monkey met criterion on discriminating eight from nine elements. Human children, in contrast, appear to have great trouble learning words for sets of two or three entities. Once they have mastered this task, however, they come very rapidly to learn the meanings of words for higher numerosities.

Finally, animals appear to relate number symbols to exact numerosities only as a last resort, when task demands require this. For example, after Matsuzawa's chimpanzee had learned to apply different symbols to sets of one, two, three, and four items, sets of five items were introduced, with a new symbol. At this point, the chimpanzee applied the symbol "4" randomly to the sets of four vs. five items, suggesting that she had learned to apply "4" to any set size other than one, two, or three. Once she mastered the symbols "4" and "5," the symbol "6" was introduced with corresponding set of six items. Once again, the chimpanzee treated "5" as applying indiscriminately to sets of five and six. This pattern suggests that the chimpanzee never came to appreciate that each symbol would apply to exactly one numerosity (see also Davis & Perusse, 1988). In contrast, children who have learned the symbols for the first three set sizes come to infer, all at once, that each remaining symbol refers to exactly one set size.

C. Overview

Human infants can represent the exact numerosity of small sets of objects, and infants can represent the approximate numerosity of larger sets of objects. Both these abilities are found in a variety of other vertebrates, suggesting that they alone do not account for the uniquely human capacity for formal mathematical reasoning.

In early childhood, children begin quite spontaneously to learn the counting procedure of their culture, and their counting subsequently shows striking systematicity and universality. Studies of the development of understanding of the words in the counting routine show a systematic but surprisingly slow developmental progression: children first learn the meaning of "one," then "two," then "three," and then they come all at once to use counting to represent higher numbers and to produce and comprehend the remaining terms in their count sequence. This developmental progression contrasts with that found in other animals, who require extensive training to learn any number terms and never show the burst of understanding found in children.

The sources of this uniquely human development are not clear. Gallistel and Gelman (1992) have suggested that children come to understand counting by reflecting on the isomorphic relation between the principles underlying verbal counting (the domain to be learned) and the principles underlying nonverbal representations of approximate numerosity. Bloom (1994), following Chomsky (1988), has proposed that an understanding of counting rests on an implicit understanding of the iterativity of language. Tsivkin and I have recently suggested that children achieve this understanding by using language (particularly the counting routine and the number words) as a medium for combining two nonverbal systems of number representation that initially are quite separate: a system of exact representation of small numbers (revealed most clearly in Wynn's addition and subtraction studies) and a system of approximate representation of large numbers (revealed in the large-number discrimination studies). By mapping words such as "two" and "three" to representations constructed by both of these nonverbal systems, children may come to conjoin the systems together to arrive at a new system of representation, unique to humans, that allows the representation of the exact numerosity of sets that are indefinitely large (Spelke & Tsivkin, in press).

If any of these suggestions is correct, then the number estimation abilities found in other animals might well serve as the foundation of human knowledge of number. Understanding our uniquely human capacity for representing and reasoning about number then would require study of the distinctive processes by which humans alone come to elaborate these foundational systems, possibly with the aid of language.

V. LOOKING AHEAD

The primary task of this chapter has been to depict where the field of perceptual and cognitive development has arrived. In closing, I consider some of the new directions in which it may move. I begin by discussing some of the changing disciplines that promise to contribute to this field. Then I consider a particularly difficult and persistent question that may become amenable to study.

A. A Synthesis

Although major insights into perceptual and cognitive development have come from the fields of experimental psychology, perceptual and behavioral ecology, and developmental neurobiology, each of these disciplines has developed rather independently of the others. With some notable exceptions (e.g., Held, 1985), studies of the emergence of topographic maps and ocular dominance columns in the developing visual system have connected only indirectly with studies of the development of depth perception or spatially guided behavior in humans. Fortunately, these fields now are beginning to converge. In particular, studies probing the visual pathways subserving spatial representation (e.g., Andersen, 1994), object representation (e.g., Goodale, 1995), and memory (e.g., Desimone, Miller, Chelazzi, &

Lueschow, 1994) suggest new insights into the development of depth perception, object representation, and even representations of number (e.g., Bertenthal, 1996; Dehaene, 1997).

This synthesis has been fostered by the rise of computational studies of perceptual and cognitive development (see Elman et al., 1996, for extended discussion of the potential fruits of such studies, and Johnson, 1997, for discussion of a synthesis of computational studies with studies in developmental neurobiology and psychology). At its best, developmental computational modeling takes as starting points the findings of (a) perceptual ecologists, concerning the information available to young perceivers; (b) developmental neurobiologists, concerning the perceptual and cognitive mechanisms by which this information is detected and transformed; (c) developmental psychologists, concerning the objects and events infants perceive and represent, and (d) behavioral ecologists, concerning the action patterns that perceptual and cognitive processes support. From these ingredients, computational modelers attempt to construct systems whose internal architecture mirrors that of infants and that, when given the information available to infants, solve the perceptual, cognitive, and action problems that infants solve. Because developmental studies in perceptual and behavioral ecology, neurobiology, and experimental psychology are works in progress, insights from computational modeling in turn can suggest which of the provisional conclusions from those fields are most promising. All these disciplines therefore can interact to foster accounts of perceptual and cognitive development.

In a sense, this disciplinary synthesis is not new, for it is foreshadowed in the 19th century in the writings of Helmholtz (1866/1962) and by earlier thinkers as well. What may emerge in the 21st century, however, is the ability to apply this synthesis to specific and concrete problems in perceptual and cognitive development. To date, such applications have not gone far, for they tend to be restricted to artificially limited problems and to engage only distantly the findings of each of the five contributing disciplines. Moreover, such applications have sometimes been hampered by the impulse to use computational models as grist for polemical arguments rather than as tools for empirical study. Nevertheless, recent computational studies of the developing object representations subserving imprinting in chicks (O'Reilly & Johnson, 1994) and of the developing spatial representations subserving aspects of navigation in ants (Muller & Wehner, 1988) begin to suggest how this synthesis could proceed.

B. Comparative Cognition

Central to the study of cognitive development is the problem of understanding how people come to think and reason in distinctly human ways. Solving this problem, psychologists have long known, requires systematic comparisons of the development of cognition in human children and in other animal species. Equally central to the study of cognitive development is the task of teasing apart the perceptual and cognitive abilities that are inevitable for all humans and universal across cultures from those that are variable across people in different circumstances. Accomplishing this task requires systematic comparisons of the development of cognition in children in different physical and cultural environments. The study of perceptual and cognitive development therefore connects to two fields of comparative research.

Until quite recently, progress in these two fields has been somewhat disappointing. The fields of animal cognition and cognitive anthropology have had their full share of brilliant investigators, but the disciplines themselves have been hampered by divisive controversies and conflicting perspectives. I believe this situation has begun to change, and that each of these disciplines will contribute substantially to future understanding of nature, nurture, and development.

Throughout much of this century, the study of animal cognition has suffered from a radical divide. On one hand, ethologists have studied animal behavior in its natural context with sensitive attention to the ecology and the evolutionary history of behaving animals but with less regard for the perceptual and cognitive processes that allow animals to act adaptively within the environment. On the other hand, comparative psychologists have studied animal behavior through laboratory experiments that have aimed for a mechanistic understanding of the processes governing animals' behavior, but often with little regard for ecology and evolution (Gibson & Walk, 1960, are a notable exception). Comparative psychologists also were hampered by the behaviorist movement, which long discouraged many investigators from addressing questions of perception and cognition directly, and by Morgan's canon (1895), which was interpreted to favor the most complicated noncognitive explanations for animal behavior over the most simple, cognitive explanations (see Gallistel, 1990, for extensive examples). Those who escaped these temptations faced a third: the temptation to demonstrate the cognitive heights that animals could scale with sufficient and appropriate training, rather than to study the cognitive processes that underlie adaptive behavior in natural settings.

Fortunately, the empirical study of animal cognition flourished despite its divisions. Rich comparative data have been obtained from field and laboratory experiments, providing the terrain for a newly unified, comparative study of perception, cognition, and action across ontogeny and phylogeny. This unification is now being attempted in a number of quarters (e.g., Cheney & Seyfarth, 1990; Cosmides & Tooby, 1994; Gallistel, 1990; Hauser, 1996; Marler, 1991; Tomasello & Call, 1997; see Kohler, 1925/1959, and Premack, 1976, for earlier examples). The successful unification of this field, and its eventual integration with studies in brain and cognitive science, may be one of the most important achievements to come.

Studies of cultural variation in human perception and cognition also have suffered from conflicting goals and perspectives, in my view. Until the middle of this century, much of this research appeared to consist of poorly designed experiments purporting to show that people in primitive cultures lacked some of the fundamental perceptual abilities and conceptual distinctions that ground the cognitive life of the civilized. In an understandable reaction against this research, more recent contributions to the study of cultural variation often have been founded on a radical critique of the enterprise of comparing individuals across cultures: a critique that leaves little room for systematic inquiry into the universal and variable properties of human cognition.

Today, there are signs that this situation is changing, and that anthropologists and cognitive psychologists are beginning to work together productively on problems of perceptual and cognitive development. Although space limits preclude any substantive discussion, I cite three examples that are relevant to the topics discussed in this chapter. First, investigators are beginning to shed light on the development of natural object categories, through focused study of cultural variability and invariance in mature object categories and in patterns of category development (e.g., Atran, 1990; Lucy, 1992; Medin, Lynch, Coley & Atran, 1997). Second, investigators are beginning to shed light on universal and variable aspects of spatial orientation and spatial representation, through systematic comparisons of the spatial language and cognition of people who live in different physical, cultural, and linguistic environments (e.g., Choi & Bowerman, 1991; Levinson, 1996; see Bloom, Peterson, Nadel, & Garrett, 1996; Bowerman & Levinson, in press). Third, investigators are beginning to probe the universal and variable properties of humans' domain-specific systems of knowledge, such as knowledge of number, physical causality, and intentional action (see the contributions in Hirschfeld & Gelman, 1994, and Sperber, Premack, & Premack, 1995). Importantly, none of the investigators just cited attempts to measure the cognitive performance of children and adults in other cultures against a yardstick of Western industrial societies. Instead, they seek to understand the universal and culturally variable properties of human cognition through a combination of ethnographic, linguistic, and experimental studies of children and adults in particular settings. Testifying to the potential importance of their efforts is the occasional startling insight into our own, familiar cognitive processes and patterns of cognitive development that can come from studying the language, cognition, and development of people whose lives seem most different from ours.

C. Cognitive Change

Do human cognitive capacities grow with development, such that older children perceive entities and entertain thoughts that are beyond the perceptual and conceptual resources of younger children? Can such changes be fostered by learning and experience? These questions have been particularly problematic for students of cognitive development in recent decades. On one hand, studies in the history of science and in science education suggest that the answer to both questions must be yes. When scientists and mathematicians discovered non-Euclidean geometries, or invented classical physics, their thinking underwent radical expansion and change (see Hatfield, 1990; Kuhn, 1957, 1977). When students learn these and other mathematical systems and physical theories, their thinking in turn is changed by the educational process (see Carey, 1985, 1991; Kitcher, 1988; Piaget, 1975). On the other hand, powerful arguments suggest that radical perceptual and conceptual change cannot possibly occur through learning (Fodor, 1975; Köhler, 1947). The important arguments of Köhler and Fodor continue to challenge the field of perceptual and cognitive development and merit a brief exposition.

Köhler considered whether it is possible to learn to organize the perceptual world into objects through one's experience with objects: whether, for example, experience in a world of relatively smooth, symmetrical, homogeneous, and cohesive bodies could lead one to learn the Gestalt organizational principles. Such learning is impossible in principle, Köhler concluded, because a perceiver can only learn about the properties of surrounding bodies if he or she can perceive those bodies: learning about objects requires the very perceptual capacity that is at issue. Fodor considered whether it is possible to learn to organize perceived objects into concepts or categories: whether, for example, experience in a world containing birds could lead a child who lacked the concept *bird* to acquire it. True learning of such concepts is impossible, Fodor concluded, because one can only learn about birds if one already can single out birds as a category: again, the ability at issue.

Most students of cognitive development have responded to these apparent paradoxes either by rejecting the lessons from the history of science and science education and concluding that genuine perceptual and cognitive change is a myth, or by rejecting the arguments of Köhler and Fodor on the grounds that something is wrong with them (although it isn't clear what; see however Hochberg, chap. 9, this volume). Recent developments, nevertheless, suggest a way to preserve the insights of Helmholtz and Köhler, Kuhn, and Fodor alike, granting to humans both innate abilities to perceive and categorize objects and abilities to learn genuinely new perceptual and conceptual organizations. I have hinted at this resolution in the discussion of substantive topics and now sketch it directly.

Empiricist and nativist approaches to perception and cognition have long shared the assumption that the capacity to perceive and conceptualize the world is unitary. On this assumption, infants of a given age either do or do not perceive a given object's boundaries, categorize a given object as a cat, or represent the number of objects in a scene. The nativist arguments of Köhler and Fodor rest on this assumption, for they presuppose that a child either does or does not perceive a given set of objects or possess a given conceptual category.

Research suggests, nevertheless, that this assumption is false: Humans have multiple systems of representation that develop at different times and in accord with different constraints. For example, I have reviewed evidence for three distinct representations of objects: a spatiotemporal system for perceiving object unity and boundaries, a system for perceiving and categorizing objects by their properties, and a system for guiding object-directed actions. Further evidence has suggested that young children have more than one system for representing space and for representing number. Each of these systems differs with respect to the environmental properties it represents, and each system is surprisingly independent of the others.

A young infant therefore both can and cannot perceive and categorize cats, and she both has and fails to have the concept *three.*

If infants possess initial systems of representation, then these systems may allow them to perceive and conceptualize aspects of the environment prior to learning, as Kohler's and Fodor's arguments require. Because these systems initially are separate from one another, however, the youngest children cannot represent complex perceptions or concepts whose elements derive from different systems. Qualitative changes in perceptual and cognitive abilities could come from processes that coordinate children's distinct systems of representation.

Consider, for example, the domain of knowledge of number. I suggested that infants have two early developing, unlearned systems of representation of number: a small-number system for representing the exact number of bounded objects or events in a scene up to about three, and a large-number system for representing the approximate number of entities in sets of indefinitely large size. Each of these systems would allow infants to represent certain set sizes exactly, and all set sizes approximately, prior to learning. If these systems initially are independent, then infants would be unable to perceive or represent sets of, for example, exactly seven elements and would lack the concept *seven.* Perceiving and conceiving of exactly seven entities would be beyond infants' capacities, because *seven* lies outside the range of their small number system and beyond the limits of discriminability of their large number system. By learning to count, children might come to conjoin these two systems of number representation to form new representations that are (a) sensitive to the effects of adding or subtracting exactly one object (a contribution from the small-number system) and (b) applicable to sets of indefinitely high numerosity (a contribution of the large-number system) (see Tsivkin & Spelke, in press, for further exposition).

More generally, processes that conjoin the representations constructed by unlearned perceptual and conceptual systems may yield new representations beyond the expressive power of any of the original systems alone: new representations of exact, large numerosities, new representations of visible drop-offs as dangerous, new representations of objects as spatiotemporal bodies with enduring, category-specific properties, and more. Conceptual changes that occur during science education or in the history of science might depend on the same capacity for conjoining separate systems of knowledge (see Carey & Spelke, 1994; Duhem, 1949). This capacity may account in some measure for the distinctively human features of human intelligence (see Mithen, 1996). It also may begin to explain why human knowledge has developed so much further than that of other species, when the building blocks of this knowledge appear to be so similar to those of other animals.

These possibilities suggest a research agenda for students of perceptual and cognitive development. To understand cognitive development, on this view, one must study the nature of each of humans' initial systems of knowledge and the changes that each system undergoes with growth and experience. In addition, one must study the new systems of knowledge that emerge as initial cognitive systems are combined. Finally, one must study the processes by which distinct representational systems become linked together over human development. The search for these processes will take developmental cognitive scientists into nearly uncharted territory. We may hope, however, that the tools that have helped to elucidate the development of domain-specific perceptual and cognitive systems will begin to shed light on these processes as well.

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