

CHAPTER 6

Nativism, Empiricism, and the Development of Knowledge

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Which of our concepts are inherent in our minds, and which are abstracted from our experience of the world around us? What aspects of human knowledge are present at the beginning of life, and what aspects emerge thereafter? What knowledge is constant over development from its emergence to its highest elaboration, and what changes with growth and experience? What knowledge is common to all mature human beings in all cultures, and what varies among people with different interests, experiences, and backgrounds? Can all conceptions be changed if one works hard enough to change them, or are some conceptions a permanent part of people's mental lives?

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As many writers have pointed out, these are different questions (see Block, 1979; Oyama, 1985): Knowledge that is inherent in the mind might emerge either early or late in development and be either invariant or subject to change, and abilities abstracted from experience might be either universal or variable across cultures. Nevertheless, these questions have certain points in common. First, they have sparked intense interest for at least 2,000 years, because they all bear on our picture of what it is to be a human thinker and knower. Second, the questions are empirical and have been subject to particularly intense and productive study over recent decades. Third, the questions are central to a dialogue that has pervaded the study of human nature since that study began: the dialogue between nativism and empiricism.

THE NATIVIST-EMPIRICIST DIALOGUE

Nativist and empiricist proposals can be traced back at least to classical Greece and the writings of Plato (1961) and Aristotle (1941). The dialogue between those whose proposals emphasize innate structure and those whose proposals emphasize learning can be followed through the writings of Augustine (389/1876) to those of Descartes (1637/1971a), Locke (1690/1975), Leibniz (1705/1981), and Berkeley (1710/1975), among others. Moving forward, the dialogue rings through the writings of Hume (1748) and Kant (1781/1964) and into the 19th-century reformulations and replies of scientists such as Muller (1837/1842) and Helmholtz (1867/1962). In the 20th century, the dialogue has continued to be enriched by such thinkers as Hebb (1949), Tinbergen (1951), Quine (1960), and Chomsky (1975). Indeed, it is hard to find a thinker of depth who has pondered human nature and human knowledge without asking these central questions.

As any study of the above writings makes clear, questions at the heart of the nativist-empiricist dialogue have been raised for a variety of reasons (see Hatfield, 1990, for illuminating discussion). They speak not only to familiar contemporary questions about how psychological processes work, but also to concerns about human nature, the truth of one's ideas, and the state of the world. For most of the thinkers cited above, these questions were largely empirical in principle, but few practical methods existed for addressing them. In part for this reason, traditional answers to these questions have tended to rest on questionable assumptions and indirect evidence.

Today, the study of cognitive development is in a strange state of richness but disarray. On one hand, developmental psychologists and cognitive scientists now have a wealth of means to address the central questions of the nativist-empiricist dialogue. On the other hand, science and the larger intellectual culture are now dominated by the attitude that questions about the nature and sources of human knowledge are misguided or incoherent. The issues raised by our intellectual predecessors therefore are routinely dismissed as outdated, oversimplified, or logically flawed.

The primary goal of this chapter is to argue that the 2,000-year-long dialogue between nativists and empiricists was on the right track: At its heart are meaningful questions that can be addressed by experiments. Where such experiments have been conducted, their findings have shed light on cognitive development, human knowledge,

and human nature, just as thinkers through the centuries have believed. We focus on human development in four domains—action, perception, language, and reasoning—showing in each case how research has succeeded in teasing apart the constant from the changing, the rigid from the flexible, the universal from the variable, and the inborn from the acquired. This research, we suggest, sheds light on larger questions about the nature of human capacities to act, perceive, talk, and think.

When the nativist-empiricist dialogue has not been dismissed as incoherent, it has usually been declared to be settled on the empiricist side. This is especially true today, owing to the rise of connectionist modeling of human cognition, using systems instantiating associationist learning principles (see Churchland, 1995; Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1996; McClelland, 1994). Curiously, those who declare the controversy settled in favor of empiricism rarely appeal to evidence that the emergence of any given cognitive ability depends on learning. Rather, the decision in favor of empiricism usually hinges on considerations of parsimony, burden-of-proof arguments, or analogies to machine learning. We return later to these arguments but note now that they are no substitute for research. Because we want to encourage research addressing the central questions of the nativist-empiricist dialogue, the second goal of this chapter is to illustrate, by example, how experiments undertaken by contributors to both sides of the dialogue have fostered understanding of development. Given the paucity of proponents of nativist theories of cognitive development, we emphasize some of the insights that have come from the nativist side. Our central point, however, is that investigations springing from the dialogue illuminate cognitive development.

We hope this chapter will convince readers that questions about what is innate and what is learned are as meaningful as our ancestors thought they were; that research addressing these questions has already begun to shed light on the origins and development of knowledge; and that future research pursuing these questions holds the highest promise. If it succeeds, we must consider why the field of cognitive development has turned away from the nativist-empiricist dialogue. Why is this dialogue often seen as incoherent? When its questions are not dismissed, moreover, why is any answer short of extreme empiricism viewed as incorrect or even pernicious? Could research returning nativist answers to the traditional questions raised

by this dialogue cause harm to the study of human cognition, to society's treatment of children, or to people's views of one another? Our third and last goal is to examine a spectrum of such possibilities. We will conclude, contrary to much current opinion, that both science and society have nothing to lose and a great deal to gain from research that teases apart the roots of human knowledge in human nature and human experience.

In this chapter, we develop four theses:

1. Questions about the sources of knowledge can be addressed by research. Where experiments have been conducted, both innate structure and experience in a structured environment are found to influence the development of knowledge in intricate ways.
2. Empirical studies of the origins of knowledge mesh fruitfully with investigations in both of the major areas of biology: the evolutionary and ecological study of animal behavior, and the mechanistic study of its underpinnings. In particular, these studies reveal both commonalities and differences between the cognitive capacities of humans and of other animals; and illuminate the physical foundations of those capacities.
3. The findings of this research have shed light not only on cognitive development but on human cognition more generally. In conjunction with research in related disciplines within the cognitive sciences, such studies promise to illuminate the nature of knowledge and the mechanisms by which it arises and is used.
4. Experimental studies of the contributions of innate structure and of learning to psychological development begin to suggest a portrait of human nature that is at variance with many popularly held beliefs. This portrait has profound and positive implications for how people view one another and conduct their affairs.

We have chosen to develop these theses by reviewing research on our example domains (action, perception, language, and reasoning) because each of these examples illustrates both remarkable triumphs of empirical research and a set of important themes and issues. Because the example domains are somewhat different in the issues they raise, we will not attempt to review them with a uniform list of themes for all. Rather, we will use each domain in turn to exemplify the particular issues most pointedly addressed within that domain. In our concluding section, we will attempt to assemble and integrate these various issues

across the four domains in terms of their import for our views of nativism, empiricism, and the development of knowledge.

We begin with the development of action. Recent study has profoundly altered our understanding of how developmental continuity, as opposed to maturation or learning, can underlie what appear to be the most radical changes in action capacities.

KNOWING HOW TO ACT

The study of coordinated action provides fertile ground for students of development. A casual look at any human society reveals that adults are capable of coordinated, purposive actions of exquisite effectiveness and astonishing diversity, from lassoing a reindeer in flight to skiing down a mountain to performing surgery under a microscope. The most searching look at human newborns suggests that nothing approaching these skilled actions is present at the start of life. Beyond suckling and crying and (to our wonderment) occasionally looking around, newborn infants do not appear to do much. How, then, do mature action capacities arise?

In general, the development of action might be explained in three different ways. Developmental changes could depend on (a) learning processes that shape the child's actions in accord with environmental constraints; (b) the maturation of action systems whose structure is determined by intrinsic developmental processes; or (c) action capacities that are constant over development, but whose expression is first masked and then revealed by changing extrinsic factors.

The magnitude of the change from the novice newborn to the expert hunter or surgeon appears to cast doubt on the third view and to suggest that the study of action development is only the study of change. Moreover, the great variety in skilled performance in different domains appears to cast doubt on the second view and to suggest that the processes that bring about these changes are infinitely variable, such that skilled members of different professions or different cultures have little or no common ground. We will see that these appearances are deceptive. Studies of the development of action reveal both constancy and change over childhood, and both uniformity and variation across cultures. We emphasize invariants and universals because their discovery has been so surprising, so at odds

with prevalent views of action development, and such a triumph of recent research. We focus in particular on the development of an activity where change is most pronounced: locomotion.

Locomotion

One of the most dramatic changes in human development occurs between about 9 and 16 months of age, when children become capable of independent, upright locomotion. It is clear to any parent that the transition from crawling to walking reflects a genuine change in ability and not just a change in motivation or preferences. For months before they begin to walk, most children seem to "want" to walk: They struggle into a standing position, inch around furniture while supporting themselves with their arms, and yet cannot manage to walk on their own. The one-year-old child who succeeds at this task undoubtedly has gained the ability to do something new.

The emergence of walking also heralds a development that separates humans from other animals. Whereas the crawling infant engages in locomotor patterns that resemble those of many other terrestrial species, only human children and adults engage in the distinctive pattern of obligatory, upright, bipedal locomotion that frees two limbs for other tasks. What is more, walking emerges far later in development than the locomotion of other mammals: No other animal must wait as long as the human before becoming capable of its own species-specific form of independent movement (Thelen, 1984). When human children begin to walk, therefore, they appear to take a large step away from capacities shared with other animals and into the realm of the distinctively human.

All these features of human locomotion and locomotor development would seem to make this phenomenon a poor place to look for continuity over development. Indeed, earlier treatments of the development of locomotion have linked this change either to the postnatal maturation of higher centers in the human brain (e.g., McGraw, 1940) or to forms of learning, social interaction, or cognitive growth (e.g., Zelazo, 1983). Research over the past two decades nevertheless offers a very different perspective on human locomotor development. Underneath the dramatic changes in the child's locomotor behavior are inborn, foundational action capacities that persist over development and are common across a great range of animal species. These

foundational capacities provide the core of humans' ability to locomote, even though extrinsic factors such as muscle strength and weight distribution limit their expression at early ages. These capacities also serve as fundamental building blocks for the development of the skills that distinguish members of one culture, profession, or avocational group from another.

Both the elegant research and the radical rethinking of locomotor development that we review are the work of Esther Thelen. Although Thelen herself has embraced a very different approach to these phenomena (see Thelen & Smith, 1994, and this Volume), we believe that the nativist and empiricist principles outlined here provide an illuminating perspective on the developmental patterns of invariance and change that her work reveals. Conversely, we believe her research provides an excellent example of how experiments that probe both for continuity and for change, and that tease apart the variable from the invariant, illuminate the nature of human action capacities and their development. The fruits of this research directly counter the view that continuity and change are conceptually inseparable.

The Emergence of Coordination: Kicking

Coordinated actions often are viewed as achievements resulting from practice and exercise (e.g., Piaget, 1952; Thorndike, 1911). The building blocks of this process are reflexes—innate packages of activity that are limited in function and are triggered rigidly by specific external stimulation. Flexibility is achieved, according to such views, as reflexes are exercised in the ways that the child's environment allows: "The child-rearing practices of the particular culture that the infant is born into determine the specific responses from the numerous behaviors in his or her repertoire that are to be encouraged through parental expectation, permission, and practice. With use, those behaviors fostered by the infant's family and culture appear to develop from reflexive to instrumental . . ." (Zelazo, 1983, p. 102).

At first glance, the development of walking appears to accord well with this perspective, and it is the phenomenon on which Zelazo chose to focus. Although newborn infants who are held upright on a surface display a "stepping reflex," moving their legs in an alternating pattern that resembles locomotion, this behavior pattern disappears after a few months unless it is practiced. With practice, however, it is maintained, and its maintenance is associated with an

acceleration in the development of walking (Zelazo, 1983). Walking therefore has been proposed to be an instrumental behavior that is built on initially purposeless and reflexive actions, in accord with the experiences afforded by a particular culture.

Is this view correct? A first step toward evaluating it is provided by naturalistic, observational study of the development of patterns of behavior over the first year of life. One such study focused on behaviors in which infants engage repeatedly and rhythmically, such as kicking the legs, waving the arms, and rocking the torso (Thelen, 1979). If coordinated movement emerges through practice and exercise, one would expect these behaviors to show increasing flexibility and coordination as the infant grows; if only reflexive behavior occurs at the start of development, then one should not observe spontaneously generated, rhythmically repeated actions in the youngest infants.

Thelen described 47 different behavior patterns in which infants from 1 to 12 months engaged repetitively and rhythmically. Even in the youngest infants, the patterns appeared to be internally generated and structured, not triggered by external stimuli. Moreover, the patterns resembled actions observed in other species. These observations suggested that coordination does not result from the shaping of rigid reflexes by external environmental circumstances but rather results from endogenous processes: "Rhythmical stereotypes, from their form-specific appearance and from comparisons with stereotyped behaviors in other primate populations, appear to be behaviors under strong central control" (Thelen, 1979, p. 712).

One prominent rhythmical behavior is kicking. Thelen found that kicking was most prominent from 3 to 7 months of age, when infants lay on their back in a state of arousal. At older ages, kicking was observed less frequently, probably because aroused infants were no longer inclined to remain in a prone position; in infants younger than 3 months, it was less frequent as well. Nevertheless, kicking was observed at every age studied, from 4 weeks onward. In later work, it was observed at even younger ages (Thelen & Fisher, 1983a).

How does kicking change qualitatively over development? Do movements of the hip, knee, and ankle begin as random and independent and become coordinated with practice? Thelen addressed this question through detailed measurements of the displacements of the joints and actions of the muscles. Her studies revealed that changes in

the flexion or extension of the hip, knee, and ankle are tightly coordinated in the first month of life. Because these joints move together, the state of one joint can be reliably predicted from the state of the others (Thelen & Fisher, 1983a). "These detailed observations of spontaneous leg movement in newborn infants challenge the traditional assumptions that movement in the newborn is random and without structure" (p. 373). Instead, these observations suggest that "early movements are a well-orchestrated ensemble of joint changes with defined temporal parameters and recognizable patterns of EMG [i.e., activity in the muscles]" (p. 380).

Kicking evidently reveals an intrinsic coordination that is present in humans at an early age, but what is its function? To begin to address this question, Thelen viewed this behavior from a comparative and ethological perspective. The coordinated rotations of hip, knee, and ankle in the human infant resembled the movements of a wide range of vertebrates during behavior whose function is clear: locomotion. Could infants' kicking also function as a core coordinative capacity underlying human walking? To approach this question, Thelen, Bradshaw, and Ward (1981) looked in more detail at the form and temporal structure of kicking in 1-month-old infants, and they found striking correspondences between early kicking and mature locomotion in humans and other animals. For example, the leg movements of locomoting humans and other animals can be divided into a stance phase (when the foot is on the ground and supporting weight) and a swing phase (when the foot is off the ground and moving forward). Walking speed is increased primarily by shortening the stance phase while leaving the swing duration nearly constant. Similarly, 1-month-old infants increased the rate at which they kicked by decreasing the length of the interval between kicks (analogous to the stance phase), leaving the duration of the kick itself nearly constant. These and other findings led Thelen and her collaborators to suggest that "human locomotion, like that of other species, is controlled by a central program . . . manifest in human infants long before actual walking matures" (p. 45).

Let us pause to consider this suggestion, which can be broken into two parts. First, human upright, bipedal locomotion looks quite different from the locomotion of other animals such as cats and cockroaches, but it depends on a core coordinative capacity that humans share with other species. Such claims of homology often are greeted with

extreme skepticism or are dismissed as errors of "anthropomorphism." Second, 1-month-old infants will display no ability to locomote for another 12 months, on average, but they already possess the core coordinative capacity that will underlie their later success. Again, great skepticism often greets the claim that young infants possess, but do not express, abilities found in adults; this claim often is taken to reflect the false attribution of adult capacities to children.

Is the suggestion of Thelen et al. (1981) prey to these errors? At first glance, it certainly seems to present problems. If human locomotion depends on the same central motor program as locomotion in other species, then why does it take humans a full year to begin walking, whereas goats and cockroaches locomote at birth? If the 1-month-old infant's kicking reveals a coordinated pattern that exists continuously over development and that underlies the older child's walking, why does human locomotion itself undergo radical developmental change? Two developmental changes, in particular, require explanation: (a) the disappearance of the "stepping reflex" at about 2 months and (b) the emergence of independent upright locomotion at about 1 year. Can Thelen's analysis explain these phenomena?

Distinguishing Competence from Performance: Stepping

Thelen's approach to the stepping reflex began with the observation that the 1-month-old infant's stepping and kicking appeared to be very similar actions. Detailed studies of the movements of infants' limbs and the tension in their muscles strongly supported this impression: During stepping and kicking, newborn infants' joints showed the same coordinated displacements, and their muscles showed the same temporal patterns of contraction (Thelen & Fisher, 1982). Thelen and Fisher also discovered that newborn stepping could be converted into kicking, and the reverse, by changing the infant's posture in midstream. These findings suggest that stepping is not a reflex at all; it is a coordinated action pattern expressed under conditions in which babies are appropriately supported, either upright or supine.

Why then does stepping disappear at 2 months? Here, the investigators had a major insight: Perhaps the motor *competence* underlying stepping remains present and functional, but the *performance* of the action is masked by other developmental changes. In particular, stepping competence

may be obscured as the infant gains weight, increasing the mass of the legs to the point where the leg muscles lack the strength to lift them when the infants is in an upright posture.

The distinction between competence and performance is central to this hypothesis. Because this distinction allows developmental psychologists to attribute abilities to children, rather than simply describing changes with age in what children happen to do in particular circumstances, it allows scientists to move from a description of behavior to an account of the underlying neural or mental states that make behavior possible (see Chomsky, 1965; Fodor, 1968). For obvious reasons, the competence-performance distinction was anathema to much of psychology during the reign of behaviorism. Curiously, it is often attacked today as well, even by those who have used it to great advantage: "The distinction between competence and performance does not make sense if cognition is determined by highly interactive systems always in contact with each other and the external world . . ." (Thelen & Smith, 1994, p. 27; see also Oyama, 1985). Rejection of the competence-performance distinction usually is based on the argument that claims of competence are not testable, for how can one ever test whether some competence exists when performance fails to reveal it (e.g., Thelen & Smith, 1994, p. 27)? Should one not be content to describe what infants do, leaving discussion of their mysterious competencies to novelists, philosophers, or mystics?

Contrary to these suggestions, Thelen's research shows that the competence-performance distinction is a source of testable hypotheses providing critical insight into the actions one observes in young infants, the factors that limit those actions, and the factors that bring about developmental change. In a simple and elegant way, Thelen, Fisher, and Ridley-Johnson (1984) tested the hypothesis that infants who no longer step in an upright posture maintained the underlying competence to do so: They plunged the infants' legs under water, reducing the force needed to lift them. Under these circumstances, stepping reemerged! This experiment and others (notably, the complementary experiment in which stepping was abolished in infants who had maintained the pattern, by attaching weights to the legs) showed that the thesis of hidden stepping competence, and the underlying distinction between stepping competence and stepping performance, was not empty talk. Instead,

Thelen's thesis has led to a major insight into the stepping reflex and its developmental vicissitudes. This behavioral pattern disappears not because of disruption of the underlying coordination on which it depends, but because of disproportionate weight gains relative to muscle strength.

The Emergence of New Actions: Walking

The thesis of unchanging competence that fails, at some times in development, to be revealed in performance has shed light on one developmental change: the disappearance of early stepping. Further research by Thelen reveals that this thesis also sheds light on the emergence of a new ability: the appearance of independent walking. Upright locomotion depends not on the molding of new coordinations but on the use of the same preexisting coordinative patterns that underlie stepping and kicking. Her rich and intricate evidence for this claim is a triumph of developmental studies. Here, we consider just one aspect of the developing coordinative capacity underlying walking: the use of alternating movements of the two legs to maintain a stable center of gravity as one moves forward.

To walk without losing one's balance, any terrestrial animal must move its limbs in symmetrical or alternating patterns. Precocial animals who walk at birth engage in the appropriate symmetrical or alternating limb movements as soon as they begin to move, in the absence of any trial-and-error learning. Humans, in contrast, do not walk until 1 year of age, and most engage in crawling and other forms of supported locomotion for months before. Does the experience of crawling or "cruising" allow human infants to learn how to step alternately without falling, by trial and error? Or does the appropriate coordinative structure already exist in infants, as it exists in other animals, prior to the time at which it is first used for locomotion?

Studies of supine kicking do not provide a clear answer to this question, because prelocomotor infants do not consistently kick the two legs in alternation. In one study of infants from 2 to 26 weeks of age (Thelen, Ridley-Johnson, & Fisher, 1983), about 70% of kicks involved leg alternation at the youngest ages, and this percentage tended to decline thereafter. Infants' naturally occurring kicking therefore showed little evidence for a clear coordinative pattern of alternation. From these patterns alone, it is not possible to say whether the capacity for coordinated, alternating stepping exists prior to walking.

Thelen (1986) therefore found a new situation in which to study the leg movements of upright but supported infants: on a treadmill. In one study, 7-month-old infants' leg movements were observed when they were supine and also when they were held under the shoulders in an upright posture on a stationary or moving treadmill. In the prone and upright stationary positions, about half the movements involved alternating legs. When the treadmill moved, in contrast, the rate of alternating stepping rose to 85%. Even though the treadmill pulled both legs backward symmetrically, infants responded to its motion with asymmetric, alternating steps. Crucially, *alternating motions occurred in these infants, even though the infants had never supported their own weight during upright locomotion and were not doing so during the experiment.* Although the pattern of alternating stepping functions to enable an upright locomotor to maintain balance, this pattern is present before it is needed for that purpose. It is a competence that does not normally express itself in behavior, but that can be elicited under appropriate supporting conditions.

Further observations reveal additional richness and structure in this initial competence. We have already noted that adults modulate the speed of forward locomotion primarily by varying the duration of the stance phase of the step cycle, when the foot is on the ground. Seven-month-old infants showed the same pattern on the treadmill: They stepped more rapidly when the treadmill moved faster, and they increased their step rate primarily by shortening their stance phase. When children begin to locomote independently, they evidently do not need to learn to alternate their leg movements so as not to fall, or to decrease their stance phase so as to move forward more quickly.

In the above study, infants' two legs stood on a single treadmill and therefore were pulled backward at the same speed. Further research reveals that the coordinative competence underlying alternating gait is robust enough to maintain itself despite perturbations designed to challenge the symmetry of this pattern (Thelen, Ulrich, & Niles, 1987). Having observed that children stepped at a faster rate at the faster treadmill speed, these investigators tested infants on a split treadmill, where the legs were pulled backward at different speeds. In principle, each leg could have moved at the same rate as in the first study, because alternating motions were not needed to maintain support. Instead, the legs moved at rates intermediate between the

two step rates observed in the first study, and maintained an alternating gait.

Infants' treadmill walking appears remarkable because of its close relation to the independent, upright locomotion of adults and children. Nevertheless, the coordinative competence revealed on the treadmill is observed in a wide variety of animals, even in the absence of a functional higher nervous system (see Thelen et al., 1987, for review and discussion). These findings suggest that our distinctively human form of upright locomotion depends on a basic coordinative competence that we share with other animals. This competence is used at birth in those animals who begin life with the capacity for independent locomotion. Although it is not used at birth by humans, it nevertheless exists long before it is needed, and its existence is revealed by elegant experiments that remove the extrinsic barriers to its expression. This competence appears to be the product of an evolutionary process, for it is adapted to the demands of locomotion but is not shaped by the process of locomoting. Alternating leg movements serve to maintain support while moving forward, but they are observed in human infants not yet capable of autonomous forward motion.

If young infants possess the basic coordinations that are the building blocks of upright locomotion, why do they not walk until the beginning of the second year? Although Thelen cautions against the search for single-factor answers to this question, her research suggests that physical growth and changing muscle strength contribute prominently to this development. To maintain balance in an upright posture, the child's body proportions need to change so as to lower the center of gravity; to move forward on two legs, the muscles of each leg must increase in strength so that a single leg can support all the child's weight. These factors may limit the emergence of locomotion at least as much as developmental changes in coordinative competence (Thelen, 1984).

Effects of Experience on the Development of Locomotion

With an increased sensitivity to what is constant over development comes an increased understanding of what changes with experience and varies over differing circumstances. Developmental research has revealed a number of sources of variability in locomotor development. For example, very young infants who are held in an upright posture over a flat surface on a regular basis, and therefore are given opportunities to exercise their stepping reflex, tend

to maintain the reflex longer and to begin to locomote at a younger age (Zelazo, Zelazo, & Kolb, 1972). Effects of practice may account, to some degree, for cultural variation in the ages at which children begin to walk (Super, 1976). It is likely that these practice effects depend on increases in the strength of the leg musculature that stepping exercise brings (Thelen & Cooke, 1987).

Other effects of locomotor experience have been observed as well. The experience with supported locomotion that young infants receive in a "walker," which supports them in an upright posture while they move around by pressing their feet against the floor, affects their attention to the environment and their memory for the spatial locations of objects (Bai & Bertenthal, 1992; Bertenthal, Campos, & Barrett, 1984). It is likely that locomotor experience also plays a great role in transforming the hesitant and shaky steps of the newly mobile toddler into the confident and graceful strides of the older child, although the contributions of various endogenous and exogenous factors to these changes remain largely to be teased apart. Experience is essential to the transformation from novice to expert in culture-specific forms of locomotion such as skating or mountain climbing. These effects of experience become amenable to more fruitful and focused study as psychologists better appreciate the coordinative competencies that are invariant over locomotor development. To illustrate this point, we turn briefly from locomotor development to the development of much more arbitrary and variable skills.

Learning Arbitrary Actions

Humans are capable of learning all sorts of action patterns, from swimming and climbing trees to hitting golf balls. Moreover, we have a strong penchant for learning from one another—observing how others act in particular circumstances and then perfecting those observed actions ourselves (Tomasello, Kruger, & Ratner, 1993). Even infants engage in such learning (Meltzoff, 1988). Indeed, humans' propensity to learn from the actions of others may explain why tool use has developed so much more in all human cultures than in any societies of nonhuman primates (Tomasello et al., 1993; see also K. Gibson & Ingold, 1993). Does the open-endedness of human motor learning challenge theories that emphasize continuity across species and over development, or can such theories explain how humans learn arbitrary, culture-specific actions?

An important experiment by Thelen and Fisher (1983b) suggests that the basic coordinative structures that underlie universal actions like locomotion also underlie the most prototypic examples of culture-specific learned actions. Their experiment focused on a situation intensively studied by Rovee-Collier (e.g., Rovee-Collier & Gekoski, 1979), in which an infant's leg is tied to a string attached to a mobile. Although we may safely assume that this state of affairs did not prevail during the time period when the basic mechanisms for moving the legs evolved, the infants learned quite readily to move the mobile by moving their own bodies. Thelen and Fisher asked what infants learned to do in this situation: What movements did they learn to make? In principle, infants could have activated the mobile in a variety of ways; a simple rotation of the hip, for example, would have sufficed. In fact, infants moved the mobile by engaging in the same coordinative activity that underlies stepping, kicking, and later walking: They rotated hip, knee, and ankle. Detailed observations of the temporal characteristics of these movements revealed that infants accelerated their kicking, increasing the motion of the mobile, in the same way that adults and other animals accelerate their locomotion: Infants reduced the duration of the interval between kicks while leaving the duration of the kick itself nearly invariant. The learning of this apparently arbitrary skill was not assembled from arbitrary components but from the same core coordinative capacities that underlie universal and species-typical actions.

This study suggests that early-developing core action capacities provide humans not only with the means to accomplish universal, biologically significant tasks like locomotion, but also with building blocks for solving the seemingly arbitrary tasks that humans confront as members of specific cultures. The most open-ended learning may be found, on closer scrutiny, to use these building blocks, providing a universal vocabulary from which culture-specific skills are assembled (see Jensen, Thelen, & Ulrich, 1989, for discussion). Insofar as this thesis is correct, an appreciation of what is given in development will be essential to understanding all the skills that humans achieve, including those attained only by a handful of experts.

The Development of Action: Themes and Prospects

This excursion through the development of locomotion suggests themes that will recur when we turn from the

study of action to the study of perception, language, and higher cognition. In our view, the central ideas emerging from this research are that core capacities exist which (a) emerge in anticipation of their function, (b) are constant over development, (c) reflect evolutionary adaptations providing for phylogenetic continuity, and (d) serve as building blocks for the development of culture-specific actions. Each theme has implications for the future study of action development, which we outline in the following subsections.

Core Structure Anticipating Function

If actions were shaped over ontogenesis by environmental demands, then coordinations should emerge after the need for them arises, as children progressively tailor their acts to fit environmental circumstances. Contrary to this expectation, we have seen that action capacities can arise before they are needed. Before children walk, they engage in the alternate leg movements required for upright locomotion. This example and others suggests that many developing capacities do not emerge by trial-and-error learning but in accord with an intrinsically paced schedule. Experience serves to fine-tune these capacities and to coordinate them with one another in the performance of real, complex actions.

The recognition of coordinative structures that exist in the child before they are used commits one to a thesis central to nativism and to a conceptual and empirical possibility central to the nativist-empiricist dialogue: Competence can emerge prior to its manifestation in overt performance and therefore prior to any shaping by the demands of performance. Although this thesis has been criticized as mystical, research on early locomotor competence shows that the criticism is without force. Claims of hidden competence are testable hypotheses, for what is hidden in natural circumstances can be revealed by astute experiments.

Although we have focused on the development of stepping, studies of other aspects of developing locomotion reveal further competences that emerge in anticipation of their function. We cite two examples. First, forward locomotion depends on vestibular and visual mechanisms for maintaining upright posture and reestablishing balance when it has been perturbed; mechanisms accomplishing this task exist in newborn infants (Jouen, 1990; see Bertenthal, in press, for a review). Human children's developing ability to maintain their balance during locomotion does

not depend on the development of these mechanisms but on changes in body size and proportion that allow the mechanisms to operate effectively (Thelen, 1984). Second, forward locomotion depends on distal (typically, visual) perception of a supporting surface and on a coordination between perception and action fostering locomotion only on surfaces perceived to afford support. In the next section, we will see that such coordinations exist at birth in precocial animals and are functional in humans before walking begins. In these cases and others, an understanding of foundational capacities has depended on the design of experiments that minimize or circumvent limitations on children's performance in order to reveal their competence.

Core Capacities Constant over Development

Few developmental changes are as dramatic as the emergence of independent walking. The locomoting 1-year-old child faces a new world of possibilities and challenges (see Bertenthal & Campos, 1990). Underlying this change, however, is a set of core competences that the youngest infants share with adults. This set provides continuity over human development.

Theories that recognize continuity over development sometimes are criticized as "antidevelopmental," as if they deny change. Research on locomotor development defeats this criticism by showing how the discovery of developmental continuity allows investigators to pose specific and tractable questions about the nature of developmental change. Thelen's studies of hidden locomotor competence suggest new explanations for developmental changes in locomotion. Two-month-old infants stop stepping when held upright because their legs become too heavy for their weak muscles to lift them; 13-month-old toddlers begin walking because their center of gravity descends to the point where they can remain upright in a state of balance. More generally, this research encourages students of development to focus both on invariance and on change, because discoveries of constant and changing competences elucidate one another. This is the heart of the experimental approach to development that animates the dialogue between nativism and empiricism.

Core Capacities Common across Species

Human locomotion is unique. Only people walk while maintaining an obligatory, bipedal, upright stance, and only people require a full postnatal year to develop their

species-typical locomotor pattern. Despite these differences, research on human locomotion reveals strong commonalities with the locomotor capacities of other animals. Vertebrate locomotion appears to depend in large part on a shared set of structures.

This conclusion illustrates a more general point: The human body shows extensive similarities to the bodies of other animals. All animals are composed of the same basic structures at the molecular and cellular levels, and many species share structures at the levels of organs and organ systems. Turning to mind and action, however, it is often assumed that humans are profoundly different from other animals, such that only humans reason, have conscious experience, represent the world, or act intentionally. This assumption follows a peculiar logic: In the absence of evidence concerning whether an animal of a given species can do something that humans can do, it is assumed that the animal differs from humans. This logic has been elevated to a canon (Morgan, 1895) and held as a model of prudent thinking, but it is hardly unassailable. Why not propose the opposite canon and assume, in the absence of evidence for species differences, that an animal with the same molecules, cells, and organs as humans has the same mental and behavioral capacities as well? Contrary both to Morgan's canon and to its opposite, we suggest that questions concerning species commonalities or differences be settled by evidence, not default assumptions. Evidence from the study of locomotion now supports the conclusion that common coordinative structures exist in animals with superficially quite different modes of locomotion, including lamprey, precocial quadrupeds such as goats, and humans. This commonality, in turn, suggests that human action capacities have a strong biological basis (see Thelen, 1984, for eloquent discussion of this point).

Core Capacities as Building Blocks for Later-Developing Skills

Does the discovery of early-developing action capacities that exist in other species and are universal across humans hinder attempts to understand later-developing action capacities that are unique to humans and vary across cultures? The last lesson to be drawn from studies of action development directly counters this concern. As scientists come to understand the core action capacities of humans and the commonalities between humans and other species, this understanding provides special insight into action capacities

that are unique to humans and that arise only in specific physical and cultural environments.

In particular, Thelen and Fisher's (1983) study of children learning to activate a mobile suggests that arbitrary actions on objects may be assembled from universal core capacities. Although these capacities exist in other animals, the propensity to assemble them in novel ways may be distinctively human and may underlie phenomena, such as tool use, that are central to human culture (Tomasello et al., 1993). Research on human development combines fruitfully with research in comparative psychology and ethology to shed light on these distinctive action capacities. The same synthesis has led to insights in the second domain on which we focus: perceptual development. Although the development of perceptual knowledge raises new themes, it, too, reveals distinctively human achievements that arise, over development, from structures that humans share with other animals.

PERCEPTUAL KNOWLEDGE

A glance at any natural scene reveals a world that is stable, organized, and meaningful—a world of familiar objects in sensible configurations. Perception of a scene allows for adaptive actions such as reaching for objects and navigating through the layout. Perception of a scene also brings knowledge. One learns, on looking out the window, that it snowed last night or that the neighbors have returned to town. Because perception is so central to the growth of knowledge, questions about the development of perception have always figured prominently in the nativist–empiricist dialogue. To what extent does perception of the world depend on the nature of the perceptual systems with which humans are endowed? In what ways does perception result from the shaping effects of experiences gained by observing the world and acting on it?

Research addressing these questions has made major strides during the past half-century. Experiments on inexperienced animals and on human infants have answered many questions about the origins and development of perception that were outstanding for thousands of years. These answers, in turn, raise further questions for the next generation of scientists. In this section, we first discuss the development of visual perception of the three-dimensional spatial layout, once the most hotly debated issue in

the nativist–empiricist dialogue. Next, we discuss the development of visual perception of objects, an important ability not only for perceiving and acting on scenes but also for talking and thinking about them. Discussion of these two abilities paints a contrasting picture of the progress of the field. In the case of depth perception, we suggest, the central questions of the nativist–empiricist dialogue have been answered. In the case of object perception, some central questions are still outstanding, but insights have been gained over the course of attempts to answer them.

Visual Perception of the Three-Dimensional Layout

What leads humans to experience the world as three-dimensional? Over the centuries, this question has appeared most pressing in the study of vision, where all perception begins with changing patterns of stimulation on a pair of two-dimensional retinal surfaces. Is this changing stimulation automatically transformed by the visual system into representations of a stable layout of surfaces varying in depth and standing at specific distances?¹ Alternatively, do perceivers learn such transformations by acting on a three-dimensional world? If the former (nativist) alternative were correct, then the three-dimensionality of perceptual experience would arise independently of the nature of the visual environment. If the latter (empiricist) alternative were correct, then the three-dimensionality of perceptual experience would stem instead from an ability to learn to induce the spatial structure that the visual environment presents.

Berkeley (1709/1975b) famously articulated an empiricist account of space perception, focusing his discussion on the perception of depth from the cues of accommodation and convergence. The cue of accommodation is based on the geometrical relation among the shape of the lens, the distance of the lens from the retinal surface on which an image is projected (a constant for the human eye at any given point in development), and the distance of the object on which one focuses. For any given distance between the lens and

¹ Throughout this section, we use *depth perception* to refer to an observer's apprehension of the relative distances of different parts of a scene, and *distance perception* to refer to the observer's apprehension of the absolute distance of a given part of the scene from the point of observation.

the retina, the lens must be thickened in order to maintain focus on an object as the object's distance decreases. The cue of convergence is based on the geometrical relation among the relative angles of regard of the two eyes, the distance between the eyes (again, a constant for human perceivers of any given age), and the distance of the object at which one is looking. With interocular distance constant, the convergence angle of the two eyes increases as the distance of the viewed object decreases. Berkeley proposed that children learn to see depth from convergence and accommodation by associating the depthless sensations arising from the ocular musculature that controls lens shape and binocular convergence with the sensations evoked by reaching and touching an object or by locomoting toward it. Helmholtz (1867/1962) developed these suggestions, proposing that perceivers learn to apprehend a stable, three-dimensional world from all the cues to depth (some of which are discussed briefly below), by moving through the layout and observing the changing visual sensations that movements produce.

In opposition to these suggestions, nativist thinkers including Descartes (1637/1971b), Kant (1781/1964), and Hering (1920/1964) have argued that spatial learning is possible only for a perceiver who already interprets experience within a spatial framework. Thus, depth perception results not from the formation of associations between visual experiences and motor activity but from prestructured mechanisms that derive information for depth from patterns of visual and muscular stimulation "as it were by a natural geometry" (Descartes, 1637/1971b, p. 250; see Hatfield, 1990, for discussion).

In principle, these contrasting proposals are straightforward to test. One investigates whether a person or animal with no visual experience perceives the same depth and distance relations that experienced people do. In practice, such tests have been difficult to devise, because people or animals with no visual experience have few means to indicate what they see. By the middle of the 20th century, nevertheless, experiments were beginning to bear on the contrasting claims offered by proponents of the two sides of the nativist-empiricist dialogue.

Depth Perception and Locomotion

The first major advance came in the 1950s, when Eleanor J. Gibson and Richard Walk devised a brilliant test for depth perception that can be used with many animals at a wide

range of ages. In their studies of the "visual cliff" (Gibson & Walk, 1960; Walk & Gibson, 1961), a young animal or human was placed on a platform between two visible surfaces, one directly below the platform and one considerably farther away. Both surfaces appeared below a sheet of transparent plastic that protected the subject from falling and that removed any nonvisual information that might otherwise distinguish them. If subjects perceived the difference in depth between the two surfaces, Gibson and Walk reasoned that they would avoid crawling onto the deep side of the apparatus and would move preferentially to the shallow side.

Tests performed on a variety of animal species revealed an elegant regularity. As soon as an animal was old enough to locomote independently, the animal avoided the cliff and moved across to the shallow side. In animals that begin to locomote at birth, such as goats, appropriate cliff avoidance was observed when the animals first opened their eyes and began to move. In animals that begin to locomote later, such as rats, cliff avoidance could not be tested at birth. Further experiments with rats revealed, however, that cliff avoidance was independent of visual experience in this species as well. Rats reared in darkness until they were old enough to locomote avoided the cliff on their first exposure to the light, like their normally reared counterparts (Walk, Gibson, & Tighe, 1957).

The most interesting studies of dark-reared animals may be those performed with kittens (see E. Gibson, 1991, for discussion). The visual system of the kitten is very immature at birth, and visual experience serves to fine-tune it. When kittens were reared in darkness until reaching the age at which visually guided locomotion normally appears, they showed no avoidance of the deep side of the cliff on first exposure to the light. This finding suggested that visual experience is necessary for the development of cliff avoidance in this species, but it did not clarify the role that experience plays. Must kittens learn that visually distant surfaces are dangerous? To investigate this possibility, Gibson, Walk, and Tighe (described in Gibson, 1991) allowed a group of dark-reared kittens to locomote with vision for six days, *on the plastic-covered cliff apparatus*. This experience gave the kittens an opportunity to adjust to the light but not to learn that the visible cliff was dangerous. Instead, the kittens' experience was designed to suggest that the cliff was safe. After two days, the kittens, like the young of other species, began to avoid the deep side of

the cliff. Further, concordant findings come from the experiments of Held and Hein (1963), who found that cliff avoidance in cats depends on experience with active locomotion but is observed even by kittens whose locomotion takes place entirely within a harness preventing falls. Visuomotor experience evidently fine-tunes a kitten's visual system, allowing the expression of an innate propensity to avoid visible drop-offs.

These experiments provide evidence that a wide variety of animals are endowed with mechanisms for perceiving the distance of surfaces and for using perceived surface distance as a guide to locomotion. "One is struck . . . with the preparedness to engage in perceptually guided behavior when an action system, such as locomotion, has matured to readiness in a normal environment. . . . Normally maturing vision is essential for the proper outcome, but no learning of specific S-R bonds is involved" (E. Gibson, 1991, p. 142).

Do human infants share these mechanisms? Studies of the behavior of infants on the visual cliff apparatus suggest a complex answer to this question. On one hand, human infants avoid the cliff at about the time when crawling begins: at age 7 to 8 months (Campos, Hiatt, Ramsay, Henderson, & Svejda, 1978; Gibson & Walk, 1960; Rader, Bausano, & Richards, 1980). In addition, younger infants who are lowered toward the cliff apparatus show an appropriate "placing response" (lifting their arms in anticipation of contact with a surface) when they approach the shallow but not the deep side of the display, providing evidence that they perceive the relative distances of the two visible surfaces (Campos, Bertenthal, & Kermoian, 1992; Walters, 1981). Nevertheless, two further sets of findings suggest limits to prelocomotor infants' perception of a drop-off. First, if such infants learn to use a walker, which allows them to locomote independently before they can crawl, they do not show cliff avoidance in the walker (Rader et al., 1980). Even infants who have begun to crawl are apt to cross the cliff when placed in a walker. Infants' propensity to cross the cliff in a walker may explain the high rates of accidents reported when infants use walkers in the home. Second, young infants who are placed directly on the deep side of the cliff react with interest, not fear or wariness (Campos et al., 1978, 1992).

These findings suggest that infants use visual information for distance to guide their visual placing and their locomotion before they understand that locomotion off a cliff is dangerous. Infants may show no fear when placed on a

cliff because they fail to realize that their propensity to avoid crawling off drop-offs functions to protect them from danger. Additionally, infants may fail to understand that a walker will support them only if it stands on a supporting surface. They may falsely assume that support by a walker, like support in a parent's arms, is possible when one is far from the floor. On either of these accounts, human infants' understanding of visual support appears to be limited—a finding corroborated by research using other methods (e.g., Baillargeon & Hanko-Summers, 1990; Kim & Spelke, 1992).

The dissociation between systems for perceiving drop-offs and systems for reasoning about support, falling, and danger can be found in adults as well. Adults who look down through the floor-to-ceiling glass windows at the top of New York's World Trade Center may understand that they are safely supported while perceiving, with trembling, a dangerous precipice. Conversely, adults may perceive safe surface support while locomoting over terrain that they understand to be unsound. Inhabitants of earthquake zones are possibly in this category. The research reviewed above suggests that this dissociation is first observed early in life. Whereas perception of a precipice develops early, and independently of specific experience, understanding of cliffs, danger, and injury appears to develop later. The latter development may depend in part on experience with falls, for locomotor history has been shown to influence reactions of fear or wariness on the deep side of the cliff apparatus. Compared to age-matched noncrawlers, infants who have begun to crawl independently show greater wariness when placed on the deep side of the cliff. Moreover, prelocomotor infants who are given experience moving in a walker show greater wariness than infants with no such experience (Campos et al., 1992).

Depth Perception and Perceptual Constancies

Although the visual cliff is an excellent tool for probing the emergence of depth perception in nonhuman animals, it cannot be used with very young infants because of their locomotor immaturity. Fortunately, other methods exist for studying younger infants, including studies of visually guided reaching, of defensive reactions to approaching objects, and of linkages between perception of depth and perception of other properties of the spatial layout. All these studies provide evidence that infants perceive depth long before they begin to locomote. Because this research

has been reviewed extensively elsewhere (e.g., Kellman & Arterberry, *in press*; Yonas & Granrud, 1985), we focus only on selected research using the last category of methods.

A hallmark of mature perception of a stable, three-dimensional layout is that objects in the layout appear to maintain constant sizes and positions as perceivers move around them, even though motion of the perceiver brings changes in the sizes and positions of the images objects project in the visual field (see J. Gibson, 1950; Marr, 1982). For geometrical reasons, perception of the constant size and position of an object is possible if a moving perceiver detects information for the object's distance, because the image of an object changes in size and direction in strict relation to its changing distance from the point of observation.² One way to investigate whether infants perceive distance, therefore, is to ask whether they perceive objects to maintain constant sizes and positions as the infants' relation to the objects changes.

Kellman, Condry, O'Halloran, Van de Walle, and von Hofsten (described in Kellman, 1993) investigated whether moving infants perceive the constant positions of stationary objects. Infants observed two objects while sitting in a seat that was undergoing lateral translatory motion. One of the objects moved with the infant, producing no subject-relative displacement; the other object was stationary. The experiment was based on prior findings that infants prefer to look at moving objects rather than stationary ones. If infants were capable of position constancy, Kellman and his collaborators reasoned that they would look longer at the moving object. If infants were not capable of position constancy, they would look longer at the stationary object, because only that object projected a moving image as the infant's chair swept past it. Preference for the moving object was observed under all conditions

tested at 4 months of age (see also Kellman, Gleitman, & Spelke, 1987), and it was observed under some conditions at 2 months. Both 2- and 4-month-old infants evidently perceived the constant position and distance of the stationary object.

Evidence for distance perception at 2 months of age rules out a spectrum of empiricist theories of how perceivers come to experience a three-dimensional world. Contrary to Berkeley and Helmholtz, people do not learn to perceive object distances by manipulating objects or crawling toward them, because the young infants in Kellman's experiments (as well as those in studies using other methods; see Yonas & Granrud, 1985) had engaged in neither of those activities. Nevertheless, the youngest infants in Kellman's studies had the benefit of 2 months of visual experience, and active visual experience in itself might serve to calibrate certain perceptual constancies (Banks, 1988; Helmholtz, 1867/1962). Do human infants learn to perceive depth and object constancies over the first 2 months of life?

Two independent experiments addressed this question through studies of newborn infants (Granrud, 1987; Slater, Mattock, & Brown, 1990). In both studies, capacities for perceiving depth were inferred from assessments of size constancy. The experiments were based on a second looking pattern observed throughout infancy: If infants are presented with one object or event repeatedly and then are given a choice between looking at that display and looking at a different display, infants will tend to look preferentially at the novel display. Slater, Mattock, et al. (1990) therefore presented newborn infants with a single object on a succession of trials. On different trials, the object appeared at different distances and therefore subtended images of different sizes in the visual field. The infants then were tested with the same object and with an object of a different real size, presented at new distances that equated the sizes of their images in the visual field. If infants perceived the constant real size of the familiar object over changes in its distance, they were expected to look longer at the new object. The newborn infants indeed showed this preference, providing evidence that they perceived both the objects' distances and their constant sizes. Perception of distance evidently arises independently of visual experience in humans, as it does in other animals.

² It does not follow from the geometrical analysis that a perceiver must first perceive an object's distance and then infer its size and position. Gibson (1966) and Rock (1983) provide very different reasons why size and position constancy might not depend on an explicit inference of this kind. On all theories of the constancies, however, perceptions of the size, position, and distance of an object are inextricably linked. A perceiver who apprehends an object's constant size and position therefore may be presumed to apprehend its distance as well.

Developing Sensitivity to Information for Depth and Distance

The above experiments resolve one question that has long been central to the nativist-empiricist dialogue: Neither humans nor other animals need to learn to perceive a stable, three-dimensional world. These findings do not imply, however, that depth perception is impervious to visual experience. On the contrary, depth perception is known to undergo changes when adults must perceive the spatial layout under altered conditions of viewing, such as when they adjust to new glasses or look through water (see Helmholtz, 1867/1962; Wallach, 1985). It is nearly certain that children's depth perception also changes with experience, because the developing visual system must adapt to considerable changes in the size of the eyes and in interocular distance—factors that alter the geometrical relations underlying most depth cues (Banks, 1988; Helmholtz, 1867/1962). Finally, adults are known to perceive depth from multiple sources of visual information (see Cutting & Vishton, 1995). Research with infants reveals a series of developmental changes in sensitivity to different cues to depth, which we briefly review (see Yonas & Granrud, 1984, for further discussion).

Although newborn infants' sensitivity to different depth cues has not been tested systematically, it is likely that such infants are most sensitive to the cues of convergence and accommodation, which provide information for the absolute distances of nearby objects from variations in the state of the musculature controlling lens thickness and convergence angle (see Kellman & Arterberry, *in press*, for discussion of the reasoning behind this conjecture). Research with newborns therefore appears to bear quite directly on the dialogue between Descartes and Berkeley over the origins of sensitivity to this distance information.

Studies manipulating the availability of different sources of distance and depth information provide evidence for an interesting developmental progression after the newborn period. By 4 months at the latest, infants appear to perceive depth by analyzing patterns of visual motion and change. In particular, such infants perceive certain patterns of relative motion as the rigid displacements of three-dimensional surfaces (e.g., Kellman, 1984; see Kellman, 1993, for review), and they perceive certain patterns of accretion and deletion of visual texture as the occlusion of one opaque surface by

another (e.g., Granrud et al., 1984). At 4 to 5 months, infants begin to perceive depth from stereopsis, interpreting small differences in the retinal projections of the images of edges at the two eyes as information for the relative distances of the edges (Fox, Aslin, Shea, & Dumais, 1980; Held, Birch, & Gwiazda, 1980). Careful longitudinal studies reveal that sensitivity to this source of depth information develops very rapidly in the fifth month (Held et al., 1980). Finally, at about 5 to 6 months, infants become sensitive to a variety of static, monocular cues to depth, such as linear perspective (which European painters since the Renaissance have used to convey impressions of depth) and interposition (in which terminating edges give rise to the perception of partly occluded surfaces ordered in depth) (Yonas & Granrud, 1984).

It is not clear from this developmental timetable whether changes in sensitivity to different depth cues depend on maturation of the visual system, visual experience, or an interplay between these factors. In the case of stereopsis, infants who are unable to direct the two eyes to the same object in the visual field show little or no sensitivity to binocular disparity if they are tested immediately after their convergence is optically corrected (Held, 1985; see also Banks, Aslin, & Letson, 1975). This finding provides evidence that visual experience can modulate the development of binocular functioning in humans, but it does not reveal whether visual experience is necessary for its initial development. Nevertheless, studies of the neural basis of binocular vision in cats, monkeys, and other mammals suggest that binocular development results from an exquisite interplay of endogenous processes of neural maturation and experience. This research, a triumph of developmental neurobiology, deserves a brief discussion.

Development of the Neural Mechanisms of Binocular Vision

As noted, stereopsis depends on the detection of small differences in the locations of the projections of surface features at the perceiver's two eyes. Critical inputs to this process are provided by neurons in V1 (the first visual area in the cerebral cortex), each of which responds to stimulation from a small area within the visual field. Classic studies of cats and monkeys by Hubel and Wiesel (e.g., 1962) have revealed that the input layer of neurons in V1 is organized into bands of cells whose primary inputs derive from

the left eye, alternating with bands whose inputs derive from the right eye: the "ocular dominance columns." These neurons, in turn, derive their inputs from neurons in a region of the thalamus, the lateral geniculate nucleus (LGN), that is organized into distinct layers of cells receiving inputs from retinal ganglion cells in each of the two eyes.

How do these banded and layered patterns develop, and what role does experience play in their development? Studies of fetal development reveal that cells in the LGN and in the input layer of V1 initially receive inputs from both eyes; later, these inputs are pruned to give rise to the layered and striped patterns (see Shatz, 1992). Because both the layered pattern in the LGN of cats and monkeys and the ocular dominance columns of monkeys are discernible at birth, visual experience is not necessary for their initial emergence (Rakic, 1977; Shatz, 1992). Moreover, studies of cats and monkeys reared in the dark after birth reveal mature patterns of ocular dominance that are indistinguishable from those of animals reared with normal vision, providing evidence that visual experience is not necessary for the later development of these connectivity patterns (LeVay, Wiesel, & Hubel, 1980; Sherk & Stryker, 1976). Nevertheless, famous experiments showed that when a cat or monkey is raised with one eye covered, the banded pattern is detectable but the relative width of the two bands is much changed. Bands of cells receiving input from the occluded eye are narrower than in normally reared animals, and bands receiving inputs from the active eye are correspondingly wider (e.g., LeVay et al., 1980). These findings provide evidence that the basic pattern of neural connectivity that gives rise to ocular dominance columns can be altered in response to experience that is strongly biased.

The findings from studies of monocularly deprived animals have generated a wealth of experiments investigating the mechanisms by which visual experience affects neural connectivity. Although the mechanisms are not fully understood, many neurobiologists believe that neural connections are modified in accord with empiricist principles articulated by Hebb (1949). Hebb suggested that synaptic connections are strengthened when the firing of the presynaptic neuron is immediately followed by the firing of the postsynaptic neuron. Because the latter neuron is more likely to fire when many of its input neurons fire in concert, Hebb's principle implies that connections from a group of neurons onto a common target will be strengthened when the neurons fire in synchrony. In a monocularly

deprived animal, synchronous activity in the visual pathway from the deprived eye may diminish, increasing the strength of connections from the active eye.

Further experiments have investigated how neurons establish appropriate connections in the absence of biasing experience. The primary focus producing these connections obviously cannot be visual experience, because dark-reared and normally reared animals develop the same patterns of connections. The patterns also cannot be genetically coded in detail, for two reasons. First, simple calculations show that animals do not have enough genes to specify where each neuron should grow and form synapses. Second, ocular dominance columns can be induced experimentally in animals that do not normally have them. In particular, frogs have widely spaced eyes that show little overlap in their projections to the optic tectum (a brain structure that plays an important role in amphibian vision). When frog embryos are implanted with a third eye in proximity to one of the two normal eyes, the two proximal eyes project to overlapping regions of the tectum, and they come to do so in a banded pattern of ocular dominance columns (see Constantine-Paton, Cline, & Debski, 1990). Because frogs do not plausibly have genes directing the growth of projections from a third eye, ocular dominance columns evidently develop in the absence of genetic specification.

If neither genetic specification nor visual learning produces these patterns of connectivity, what is their source? Experiments suggest that the same activity-dependent processes that shape neural connectivity in response to visual experience also play a central role in the development of connections in the absence of visual experience. In the eyes of a fetal cat or ferret, retinal ganglion cells are active spontaneously before birth, even before the development of the visual receptors. Elegant experiments by Shatz (1992; Feller, Wellis, Stellwagen, Werblin, & Shatz, 1996) reveal that this activity travels over the retinal ganglion neurons in waves, producing correlated firing patterns among neurons with adjacent cell bodies. The waves, in turn, produce correlated firing patterns among neurons in the LGN receiving input from adjacent locations in a single eye. If these waves of activity modify synaptic connections in the ways Hebb described, by strengthening connections among neurons that fire together and weakening connections among neurons whose firing is uncorrelated, they could produce both the layered organization in the LGN and the retinotopic and banded organization in V1, in the absence

of any visual experience. Consonant with this possibility, chemicals that block the spontaneous activity of the ganglion cells were found to prevent the normal development of the connectivity pattern (Shatz & Stryker, 1988).

The research of Shatz and Stryker shows that nativist explanations do not imply genetic determination (also see Block, 1979, 1995). In classical discussions of nativism in visual perception, the concept of innateness did not, of course, refer to genetic specification, but rather to the existence of structured developmental outcomes that arise in the absence of experience of a visible environment. In this sense, the banded pattern of monocularly driven cells in V1 is innate—it arises in the absence of any visual experience—yet it is not encoded in the genes. Rather, it results from a chain of processes that produce spontaneous waves of neural activity. The existence of innate perceptual mechanisms that are not genetically specified undermines recent arguments that perceptual abilities cannot be innate because the human genome does not contain enough information to specify the connections on which those abilities depend (e.g., Edelman, 1987; Thelen & Smith, 1994). Direct genetic specification is not the only process that can produce visual mechanisms that operate prior to one's first encounters with the visual world. Indeed, the central accomplishments of recent research in developmental neurobiology are to reveal a host of epigenetic processes through which neural structures develop in accord with a species-typical, intrinsic plan, without either shaping by the environment external to the organism or detailed genetic instructions. These epigenetic processes may contribute not only to the development of depth perception but also to the development of object perception, our next topic.

Object Perception

Most natural visual scenes are composed of three-dimensional bodies that are stable over time and motion. Nevertheless, these scenes typically are cluttered, such that distinct objects stand side by side and partly occlude one another. When adults view scenes containing multiple adjacent and overlapping objects, they usually perceive each object's unity, boundaries, complete shape, and stability. If an object moves from view, it usually is perceived to persist and to maintain its identity over successive encounters. Because objects have stable and persisting properties, adults also can categorize and recognize objects by

analyzing those properties, perceiving a body in a scene as a chair or as one's favorite pen. To what extent are these perceptions shaped by a history of looking at objects, walking around them, manipulating them, and communicating about them? To what extent, in contrast, does object perception depend on mechanisms that develop independently of visual experience?

In the early part of the 20th century, answers to these questions were dominated by the empiricist theories of Helmholtz and his descendants and by the nativist theories of the Gestalt psychologists (e.g., Koffka, 1935; Kohler, 1947; Wertheimer, 1923/1958; see Hochberg, *in press*, for discussion). As in the case of depth perception, Helmholtz proposed that children learn to perceive objects by handling and moving around them, observing the changing perspectives that active movements reveal. In contrast, investigators in the Gestalt tradition proposed that object perception results primarily from the inherent propensity of the nervous system to assume states of maximal equilibrium, a propensity giving rise to perceptual organizations that are stable and regular.

Discussion of the origins of object perception subsequently was enriched by a number of new ideas. Piaget (1954) proposed that object perception results from the child's progressive coordination among activities such as reaching, grasping, sucking, manipulating, and visual following. Quine (1960) proposed that object perception results from the acquisition of language, particularly from linguistic devices for distinguishing one object from another and for distinguishing bounded objects from unbounded stuff (see Carey, *in press*, for discussion). Wiggins (1980) and others have proposed that object perception results from the acquisition of systematic knowledge of object kinds, such as *chair*, *pot*, *tree*, and *dog*. Although none of these thinkers viewed their contributions within the classic terms of the nativist-empiricist dialogue, all attributed a large role to experience in the development of object perception: sensorimotor experience, experience with language, or experiences giving rise to commonsense understanding of natural kinds and artifacts.

Research addressing these theories has begun to accelerate over the past decade. Experiments with nonhuman animals provide evidence that capacities for perceiving and representing objects emerge after minimal visual experience. Experiments with human infants have shed light on the processes by which infants organize visual scenes, and

their findings have narrowed the space of tenable nativist and empiricist theories of object perception. Nevertheless, no experiment yet reveals whether visual experience is necessary for the development of object perception in humans.

Perception of Objects in Nonhuman Animals

Insights into the development of object perception have come from recent studies of imprinting, a striking capacity for object perception and representation in newborn chicks. In nature, chicks imprint to their mother and siblings based on visual exposure to these objects in the first days of life. In field and laboratory experiments, chicks raised without conspecifics have been found to imprint to a variety of visible objects, including simple geometrical solids if the objects are presented in motion (see M. Johnson & Morton, 1991, for review). Imprinting is revealed in laboratory tests in which the imprinted object and a second object are placed at opposite ends of an unfamiliar cage. Chicks spend most of their time near the imprinted object. This phenomenon has permitted the systematic study of young chicks' representations of visually presented objects.

In one series of experiments (Regolin & Vallortigara, 1995), chicks were raised in a closed, homogeneous box with a single yellow triangle dangling from its center. Because no other objects (animate or inanimate) were present in this environment, the object was never occluded by other objects. After two days' exposure to the moving object, the chicks became imprinted to it. On the third day, the chicks were placed in a test cage with a center-occluded triangle on one side and a fragmented triangle with a gap at the location of the first triangle's occluder on the other side. Although both test stimuli corresponded to the imprinted stimulus equally well with respect to the visible areas of the triangle, human adults who are shown these displays perceive only the center-occluded triangle as continuing behind the occluder (Michotte, 1954). The chicks' perception of the relative similarity of the two test stimuli to the original stimulus was inferred from the relative lengths of time that they spent in proximity to each test stimulus. The subjects spent substantially more time in the vicinity of the partly occluded triangle, providing evidence that they, like human adults, perceived this stimulus as more similar to the complete object (see Regolin & Vallortigara, 1995, for further evidence for this interpretation).

In a second series of experiments, chicks were found to represent an imprinted object, and to search for the object, even when it was fully hidden. After one day of imprinting to an inanimate object in a homogeneous environment, 2-day-old chicks watched as the object was moved fully out of view behind one of two screens. Although the chicks had never before witnessed the occlusion of an object, they reliably searched for the hidden object by moving around its occluder (Regolin, Vallortigara, & Zanforlin, 1995a). Successful search was reported even under conditions that required the chick to turn away from the object in order to reach it (Regolin, Vallortigara, & Zanforlin, 1995b). These findings provide evidence that chicks who view a fully occluded object for the first time represent its continued existence over occlusion (see Regolin et al., 1995a, 1995b, for further findings and discussion).

Human Infants' Perception of Objects

Experiments provide evidence that human infants aged 3 months and beyond also perceive objects under certain conditions. Infants perceive the boundaries, unity, persistence, and identity of objects when these properties are specified by the arrangements and motions of surfaces in the visible layout.

Let us begin with infants' perception of the boundaries that separate objects within a single visible scene. Perception of object boundaries has been studied with preferential looking methods, investigating whether familiarization with a given configuration of two objects leads to longer looking at a new display in which the boundaries of the objects are changed, relative to a new display presenting the same or greater changes in the arrangement of visible surfaces but no change in object boundaries. All these studies reveal that young infants perceive the boundaries between two objects if the objects are separated by a gap in three-dimensional space or if they are adjacent to one another but undergo separate motions, as when one object slides across the top of the other (e.g., Kestenbaum, Termine, & Spelke, 1987; Needham & Baillargeon, in press; Spelke, Hofsten, & Kestenbaum, 1989; Xu & Carey, 1994; see also Hofsten & Spelke, 1985, and Spelke et al., 1989, for converging evidence from studies using a reaching method). In contrast, infants sometimes fail to perceive the boundary between two objects that are adjacent and stationary, even if the objects differ in color, texture, and shape and belong to different, familiar kinds such as commonplace toys (Hofsten

& Spelke, 1985; Kestenbaum et al., 1987; Needham & Baillargeon, in press; Spelke, Breinlinger, Jacobson, & Phillips, 1993; Spelke et al., 1989; Xu & Carey, 1994; cf. Needham, Baillargeon, & Kaufman, in press).

When one object is partly occluded such that its ends are visible but its center is hidden, can infants perceive the object as a connected unit that continues behind the occluder? Perception of the connectedness of such objects has been investigated through preferential looking experiments in which infants are familiarized with a center-occluded object and then are tested for novelty reactions (as reflected in longer looking) to displays consisting either of the complete object or of the two previously visible parts of the object separated by a gap. These experiments provide evidence that 4-month-old infants perceive the connectedness of a center-occluded object if the ends of the object undergo a common, rigid translation in three-dimensional space (S. Johnson & Aslin, 1996; S. Johnson & Nanez, 1995; Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986; Slater, Morison, et al., 1990). In contrast, 4-month-old infants typically fail to perceive the connectedness of a center-occluded object that is stationary (Kellman & Spelke, 1983; although cf., Needham, 1994). Infants who view a center-occluded object while they themselves are in motion perceive the unity of the object if it moves conjointly with them, undergoing no subject-relative displacement, and they fail to perceive the unity of the object if it is stationary, undergoing substantial subject-relative displacement (Kellman et al., 1987). This finding provides evidence that real surface motion, not displacement in the visual field, is informative for infants. It converges with the evidence, reviewed in the previous section, that infants distinguish real object motions from image displacements caused by their own motion (see Kellman, 1993).

Further preferential looking experiments have investigated infants' representations of an object that moves completely out of view. Infants as young as 3 months have been found to represent the continuing existence, position, size, and shape of a fully occluded object (e.g., Baillargeon & Devos, 1991; Craton & Yonas, 1990; Hespos & Rochat, 1996; Wilcox, Rosser, & Nadel, 1994; Wynn, 1992). If part of the object appears behind one side of a central occluder, and then the object completely disappears and a different part of the object emerges from behind the other side under spatiotemporal conditions that specify one continuous motion, 5-month-old infants perceive the two parts to lie on

one connected object (Van de Walle & Spelke, in press). Finally, when a fully visible object moves out of view behind an occluder at one location and then a featurally identical object moves into view at a different location, infants as young as 2.5 months have been found to perceive a single, persisting object over these encounters if they can trace a spatiotemporally connected path of object motion, and they perceive two distinct objects if no such connected path exists (Aguiar & Baillargeon, 1996; see also Spelke, Kestenbaum, Simons, & Wein, 1995; Wynn, 1992; Xu & Carey, 1996). Spelke and Van de Walle (1993) have summarized these findings by proposing that 3- to 5-month-old infants perceive objects in accord with three principles capturing spatiotemporal constraints on object motion: the principles of cohesion, continuity, and contact. These principles dictate that moving objects maintain their connectedness and their boundaries, follow paths that are connected and unobstructed, and influence one another's motion just in case they come into contact.

Spelke (e.g., 1990) further proposed that young infants fail to perceive objects in accord with other visual relationships that specify object unity, boundaries, and identity for adults, such as alignment of surfaces and edges; sameness of surface color, texture, and shape; and goodness of overall object form. Although some more recent findings are consistent with this suggestion (e.g., Needham & Baillargeon, in press; Simon, Hespos, & Rochat, 1995; Xu & Carey, 1996), other findings suggest that this negative conclusion was too strong. In experiments by S. Johnson and Aslin (1996), and by Smith, Johnson, Spelke, & Aslin, (1996), 4-month-old infants' perception of the unity of a center-occluded object was affected by edge alignment. Infants perceived a rigidly moving, center-occluded figure with strongly misaligned edges as two separate objects when the display was two-dimensional, and as indeterminate when the display was three-dimensional. In experiments by Needham (1994), a conjunction of figural goodness and color and texture similarity served to specify the boundary between two stationary adjacent objects for 4.5-month-old infants, although such infants do not use these properties as reliably as do adults and 8-month-old infants (Needham & Baillargeon, in press). Infants therefore show some sensitivity to a variety of sources of information for object unity and boundaries, although they are most sensitive to information provided by motion.

Two further limitations of infants' abilities to perceive and represent objects deserve mention. First, infants under about 8 months of age do not appear to use representations of an occluded object to guide a variety of actions aimed at retrieving the object, including detour reaching (Diamond, 1990), removing the object's occluder (Piaget, 1954), or even pressing a button to bring the object forward (Munakata, McClelland, Johnson, & Siegler, in press). Because monkeys solve object search tasks by 4 months of age (Antinucci, 1989; Hauser & Carey, in press) and chicks solve such tasks at 2 days of age (Regolin et al., 1995a, 1995b), the development of these abilities may depend more on maturation than on experience (see Diamond, 1990, for discussion).

Second, infants under about 11 months of age do not appear to be able to use information about the category membership of an object in perceiving its boundaries or continuing existence over occlusion. This failure has been shown most clearly in a series of studies by Xu and Carey (1994, 1996). By 9 months of age, and possibly much younger, infants have been shown to be sensitive to the categorical differences between toy animals and toy vehicles, both when these objects are presented for active manipulation and when they are presented for visual inspection (Eimas, 1994; Mandler & McDonough, 1993; Van de Walle & Hoerger, 1996). Accordingly, Xu and Carey (1994) investigated 10- and 12-month-old infants' perception of a stationary toy animal that stood on top of a stationary toy vehicle. Surprisingly, 10-month-old infants gave no evidence of perceiving two separate, bounded objects in this situation. In further experiments, 10- and 12-month-old infants viewed a toy vehicle and a toy animal that disappeared and reappeared in succession from behind a single occluder. Although adults perceive two distinct objects in this situation, the 10-month-old infants' perception was indeterminate between events involving one versus two objects (Xu & Carey, 1996). At 12 months, in contrast, infants used the categorical difference between the animal and the vehicle to perceive both the boundary between the two adjacent objects and the distinctness of the two successively visible objects (Xu & Carey, 1994, 1996).

In all of Xu and Carey's experiments, the 10-month-old infants who failed to perceive object boundaries and object identity in accord with information about object categories successfully perceived object boundaries and identity by using the spatiotemporal information discussed

in the previous section. They perceived two adjacent objects as distinct if one moved relative to the other, and they perceived two successively visible objects as distinct if no connected path united them. These findings and others (e.g., Simon et al., 1995) provide evidence that a basic process for perceiving objects as spatiotemporally connected and continuous bodies exists prior to the development of abilities to perceive objects by categorizing them as particular kinds, at the level of "vehicle" or "animal," "car" or "duck."

The Role of Experience in the Early Development of Object Perception

All the above studies provide evidence that abilities to organize visual arrays in accord with the basic spatiotemporal properties of objects are present and functional by 3 to 4 months of age in human infants. How do these abilities develop, and what roles do maturation and experience play in their development? Research on infants' perception of objects indicates that certain kinds of experience are *not* necessary for the development of object perception. In particular, this research provides evidence against both the empiricist proposal of Helmholtz and the constructivist proposal of Piaget, according to which object perception results from the child's actions of manipulating objects and moving around them. Because 3-month-old infants have not yet begun to reach for, manipulate, and locomote around objects, early-developing abilities to perceive objects evidently do not depend on these experiences. This research also provides evidence against Quine's proposal that object perception results from the mastery of natural language syntax, because infants divide the perceptual world into objects long before they learn the relevant aspects of language. Indeed, processes for perceiving object boundaries and object identity appear to guide language learning, rather than the reverse (e.g., Bloom, 1995; Markman, 1990; Markman & Wachtel, 1988; Soja, Carey, & Spelke, 1990; although see Imai & Gertner, in press). Finally, this research provides evidence against the thesis that perception of object unity and identity depends on processes for categorizing objects as members of particular kinds such as "chair" and "dog" (Wiggins, 1980), because abilities to represent objects as members of kinds develop considerably later than abilities to perceive and represent objects in accord with spatiotemporal constraints (Xu & Carey, 1996).

Although existing research limits the class of tenable theories of the development of object perception in humans, studies of human infants below 3 months of age present a tantalizingly inconclusive picture of the origins of this ability. Slater, Morison, et al. (1990) conducted a modified version of Kellman and Spelke's (1983) experiment with newborn infants, and found that infants who were familiarized with a moving, center-occluded object looked longer at a complete than at a broken object. This pattern, which is opposite to that observed with older infants and newborn chicks, suggests that the newborn infants did not perceive the center-occluded object as connected behind the occluder. Research by S. Johnson and Nanez (1995) used a similar method to investigate perception of a moving, center-occluded object by 2-month-old infants. After familiarization with the occlusion display, these infants looked equally at a complete and at a broken object, suggesting that 2-month-old infants still fail to perceive a moving object as connected behind a central occluder.

The studies of Slater, Morison, et al. (1990) and of S. Johnson and Nanez (1995) provide evidence for a developmental change over the first 4 months, but what is the nature of this change? On one hand, it is possible that newborn human infants, in contrast to newborn chicks, lack the ability to perceive unitary, partly occluded objects. Abilities to perceive objects may develop between birth and 4 months through maturation, effects of experience, or a combination of these factors. Alternatively, newborn infants may have the competence to perceive object unity from motion information and yet fail to exercise this competence with the displays used successfully in research with 4-month-olds, because their limited sensory capacities preclude their detection of the relevant spatial and kinetic information. In particular, newborn infants may fail to detect that the central occluder stands in front of the moving object and therefore partly hides it, or they may fail to perceive that the visible ends of the center-occluded object undergo a common, rigid motion.

As in studies of motor development, the distinction between perceptual competence and perceptual performance yields testable predictions, and experiments have begun to test them. Slater, Johnson, Kellman, and Spelke (1995) presented newborn infants with an occlusion display in which the distance relations among the infant, the occluder, and the moving object were enhanced. Infants in this experiment showed the same preference for the complete object

as did those in Slater's original experiments, suggesting that limits on depth sensitivity do not account for newborn infants' failure to perceive object unity over occlusion. S. Johnson and Aslin (1995) next presented 2-month-old infants with a variety of occlusion displays that reduced the spatial distance between the motions of the visible parts of a center-occluded object. In their experiments, infants looked longer at the test display in which the visible object surfaces were separated by a gap, providing evidence that they perceived the unity of the center-occluded object. These findings suggest that limitations on young infants' sensitivity to common motion across distant regions of the visual field account for some of young infants' failures to perceive object unity over occlusion.

To date, there is no evidence indicating whether the competence revealed by Johnson and Aslin (1995) at 2 months exists at birth as well. It is possible that this competence is absent, in which case experiments presenting occlusion displays with motion relations that are detectable by newborn infants should continue to provide evidence that the infants respond only to the visible surfaces in a display. As a second alternative, it is possible that this competence is present and functional in limited contexts, in which case experiments with center-occluded objects undergoing detectable common motion should yield the same findings with newborn infants as with older subjects. Finally, it is possible that the experimental approach pursued by Slater, Johnson, and Aslin will break down with newborn infants, for there may be no situations in which the common motions of the separated parts of a center-occluded object are detectable. As Banks and Shannon (1993) have suggested in a different context, limits on a newborn infant's visual sensitivity may be so great that no ordinary visual environment will reveal some of the perceptual competences that are present and waiting to be exercised. If that is the case, then the study of the origins of object perception must await the emergence of an investigator with Thelen's genius—someone who can devise situations that circumvent the sensory limitations preventing newborn infants' inherent perceptual capacities from functioning in natural contexts.

Computational Approaches to the Development of Object Perception

In the absence of direct evidence concerning the roles of visual experience and endogenously developing visual mechanisms in the emergence of object perception in humans,

theorizing may be sharpened by attempts to model the developmental process with connectionist learning systems (see McClelland, 1994, and Elman et al., 1996, for a discussion of these tools and their potential applications for studies of cognitive development). Although a detailed review of these efforts is beyond the bounds of this chapter, we will try to give a taste of this enterprise by discussing two recent attempts to model the early development of object perception.

Munakata, McClelland, Johnson, and Siegler (in press) focused on the development of the ability to represent the continued existence of an object that moves from view. They designed a network consisting of "input units" that were directly activated by visual scenes and responded only to objects that were visible, "hidden units" that were activated by the input units, and "output units" whose activity constituted the network's prediction of the state of the visible layout at the next moment in time. Critically, the activity of the hidden units persisted briefly after the signal they received from the input units was removed: a property of network architecture called *hysteresis*. At the start of learning, input, hidden, and output units were randomly connected, and so the hidden units activated by a visible object quickly returned to quiescence when the object moved from view. The system therefore did not represent hidden objects over any but the shortest time spans, and it could not track objects over occlusion.

In their simulations, Munakata et al. (in press) presented this system with a simplified visual world in which a single stationary object was occluded and then revealed by a screen that moved at constant velocity. At each time interval, the system predicted the state of the visual scene at the next time interval, representing this prediction as a pattern of activations on the output units. When the next interval arrived, the system detected discrepancies between the scene it predicted and the scene it encountered (i.e., discrepancies between the pattern of activations on the input and the output units), and it modified its connections to reduce those discrepancies. After many time intervals, this system learned to predict successfully when the occluded object would reappear. Most important, the hidden units began to show patterns of activation that were specific to the existence and location of the object while it was occluded.

The simulation by Munakata et al. (in press) is potentially of great interest because their network learned to represent hidden objects purely by visual observation, without

any input from systems for acting on objects or communicating about them. In its current form, however, the system learns to represent hidden objects only when it is trained on a single, exactly repeating event and then is tested with the same event (Marcus, 1996). For example, the system shows no generalization from displays with a stationary object and moving occluder to displays with a moving object and stationary occluder. In addition, this simulation obviously cannot account for the development of object representations in chicks, who represent the existence and location of fully occluded objects without any prior exposure to occlusion events (Regolin et al., 1995a).

A second connectionist project, by O'Reilly and Johnson (1994), approaches the problem of object perception in a somewhat different way. The authors' immediate task was to model imprinting in the chick. They sought to devise a system for learning to recognize a specific object from visual exposure to that object in motion. Their system was a connectionist network whose input units responded to features of objects at particular visible locations, connected to hidden units whose activation again showed hysteresis, connected in turn to a third set of units that may be considered as the system's output. Initially, the connections between the units in these three layers were random. With this architecture, neural connections were modified in accord with the Hebbian principles discussed earlier, by strengthening connections between units which fired in immediate succession. After exposure to a simplified visual environment in which an object with a given set of continuously visible features appeared in continuous motion, some of the hidden units in the system came to be activated reliably by that object. Most important, the three layers of the network developed a regular pattern of connections. Input units that responded to features at nearby locations activated many of the same hidden units, whereas input units that responded to features at distant locations activated different hidden units. Let us call this connectivity pattern "spatiotopic fanning."

Although this system was devised as a model of the learning process that might underlie imprinting in chicks, it is interesting to consider its architecture in light of research on object perception in human infants. Because of spatiotopic fanning, the trained system was more sensitive to simultaneous activation at adjacent regions of the visual field than to simultaneous activation at distant regions of the field. Fanning therefore increased the system's sensitivity to internally connected objects (like a ball) over

spatially scattered ones (like a mobile without detectable wires). Because of the combined effects of spatiotopic fanning and hysteresis, the system also was more sensitive to continuous than to discontinuous object motion. Only when an object moved continuously would the persisting activation of units at one location along the object's path combine with the activation of units at its next location. Finally, the combination of spatiotopic fanning and hysteresis increased the system's sensitivity to objects that moved cohesively and to interactions between objects that occurred on contact, because input units activated by cohesive objects or interactions on contact sent their activation along to hidden units within the same fan of connections. O'Reilly and Johnson's connectionist system therefore was structured, partly by its innate architecture and partly by learning about fully visible objects, in accord with the principles of cohesion, continuity, and contact. It represented objects that obeyed these constraints, as do young human infants (see also Mareschal, Plunkett, & Harris, 1995, for a description of a connectionist model of object representation that embodies these principles in a different way).

The systems created by Munakata et al. (in press) and by O'Reilly and Johnson (1994) are simplified models of object perception. In their present forms, neither could cope with the three-dimensional, cluttered, and changing environments that infants routinely encounter. Nevertheless, the efforts of these investigators provide food for thought. First, the simulations of Munakata and her collaborators suggest that the purely visual experience available to young human infants could, in principle, produce important changes in object representation, allowing infants who begin with weak object representations to develop stronger ones. Second, the simulations of O'Reilly and Johnson suggest that visual experience with objects could produce patterns of connectivity that predispose infants to perceive objects in accord with the spatiotemporal principles derived from research with infants: cohesion, continuity, and contact. These modeling efforts therefore lend plausibility to empiricist accounts of the development of object perception. The assertion that empiricist theories cannot be devised to account for the findings of studies of infants (Spelke, Breinlinger, Macomber, & Jacobson, 1992) now seems too pessimistic.

As Munakata et al. (in press) and O'Reilly and Johnson (1994) acknowledge, however, the fact that certain capacities for object perception and object representation *could be learned* from visual experience does not imply that these

capacities *are learned* from such experience. On the contrary, research in developmental neurobiology suggests that much of the structure that is learned in O'Reilly and Johnson's (1994) simulation is innate in mammals and develops prior to their first encounters with the visible environment. In particular, spatiotopic fanning develops in advance of visual experience, even in mammals whose spontaneous visual activity has been blocked (Constantine-Paton et al., 1990). Moreover, spatiotopic projections are a natural consequence of the activity-dependent changes in synaptic connections that occur as a result of the prenatal waves of retinal activity discussed earlier in this section (Shatz, 1992). As waves of activity move across the retinal ganglion neurons (the analog of Johnson and O'Reilly's input units) of fetal animals, connections of adjacent cells to their targets (analogous to Johnson and O'Reilly's hidden units) will tend to be strengthened, whereas connections of distant retinal receptors onto common targets will tend to be weakened. Thus, processes operating in the absence of visual experience may lead to the development of connections that predispose newborn infants to perceive objects in accord with the principles of cohesion, contact, and continuity. The assertion that objects could not be perceived in accord with innate principles because there is no biologically plausible mechanisms for embodying such principles (e.g., Thelen & Smith, 1994) now seems overly pessimistic as well.

Research in computational modeling suggests that the questions at the center of the nativist-empiricist dialogue cannot be settled by a priori considerations of plausibility or parsimony. Theories that seem unparsimonious or implausible under one set of assumptions may appear simple and plausible when background assumptions change. In recent connectionist modeling, we see the germs of new empiricist and nativist theories of the emergence of object perception in infants. Research by neurobiologists and developmental psychologists now can begin to test these theories and their background assumptions.

Object Recognition: Developmental Change and Cultural Variation

However object perception originates, it is clear that a basic process for perceiving spatiotemporally connected and continuous objects arises early in development, without significant tutoring. This process is likely to be universal across human cultures, leading all people to perceive, act on, and talk about the same spatiotemporal bodies.

Consistent with this expectation, all the languages and cultures of the world appear to carve perceptual experience into cohesive and continuous bodies (see Bowerman & Levinson, *in press*, for evidence and discussion).

Despite these universal spatiotemporal principles, important changes in object perception may occur when children begin to categorize parts of visual scenes as objects of specific kinds, such as "dogs" and "cars." If this developmental change is influenced by the child's social and cultural environment, then it may lead people in different cultures to perceive visual scenes quite differently.

Research in cognitive linguistics, cognitive anthropology, and cross-cultural psychology, focusing on cultural variation in people's linguistic and conceptual categories, suggests some possible differences. For example, children and adults in Western industrialized societies tend to call objects by the same name if the objects have similar shapes, even if they differ greatly in size and material composition. A comb is a comb regardless of whether it fits in the hand of a doll or a giant, and regardless of whether it is made of wood, plastic, or gold (see Landau, Smith, & Jones, 1988). Shape, in turn, appears to be represented as an arrangement of geometrical solids (e.g., Biederman, 1987). In contrast, adults in many traditional societies give common names to objects with a common material composition. A pot is not a pot if it is not made of clay; a roof is not a roof if it is not thatch (Lucy, 1992). When shape does influence descriptions in these languages, moreover, it appears to depend on a parsing of objects into parts that are quite different from the geometrical solids that comprise most factory-made artifacts (see Brown & Levinson, 1993; Levinson, 1994). These differences in language may be accompanied by differences in how people sort objects into categories (Imai & Gertner, *in press*; Lucy, 1992; although cf. Markman, 1989). Nevertheless, cultural differences in object representations and recognition processes have not been investigated directly.

The Development of Perception: Themes and Lessons

Studies of the early development of perception echo the themes that emerged from studies of the early development of action. Depth perception and object perception both begin to emerge in anticipation of their functions. Infants perceive a three-dimensional surface layout before they use depth and distance information to guide reaching or loco-

motion, and they organize the surface layout into cohesive, separately moving bodies before they use such information to guide their grasping or manipulation. Like action systems, perceptual systems show continuity over phylogeny and over ontogeny. Infants' perception of depth and objects depends on mechanisms that are shared in part with other animals and that persist over the later course of human development.

In addition to these now familiar themes, the study of perceptual development helps to clarify what it means for an ability to be innate. As Block (1979, 1995) has argued, using very different examples, the claim that an ability is innate in no way implies either that the ability depends on structures coded in the genes or that the ability is impervious to experience. Gallistel (1990) has argued that even in the case of cognitive abilities that appear to be hallmarks of human intelligence (e.g., knowledge of number), claims of innateness do not imply that highly elaborate, special-purpose neural machinery is preformed in the newborn's brain. Studies of perceptual development provide clear and concrete illustrations of these points.

In the development of binocular vision, studies of animals reared in darkness reveal that the basic pattern of neural connectivity underlying binocular functioning arises in the absence of visual experience. In the classic language of the nativist-empiricist dialogue, the pattern is innate (LeVay et al., 1980). Nevertheless, studies in developmental neurobiology reveal that the neural connections underlying binocular functioning arise in animals not by genetic specification but by patterns of endogenously generated activity. Moreover, the same activity-dependent processes that shape the brain in the absence of visual experience also shape the brain in response to visual experience. Binocular functioning therefore provides an example of how a pattern of neural connectivity, and the visual functioning to which it gives rise, can be innate without being either genetically coded or impervious to later experience.

Although the neural basis of object perception is less well understood, studies in connectionist modeling provide a concrete example of how a system for perceiving objects in accord with basic spatiotemporal constraints on object motion might follow from simple and general principles of neural architecture, such as hysteresis and spatiotopic fanning projections. Findings that very young infants perceive objects in accord with these principles need not imply that

infants are endowed with highly elaborate and specific systems of rules.³

More generally, studies in developmental neurobiology and in computational modeling suggest that questions concerning the nature of the brain systems underlying any given perceptual ability are empirical questions that are best addressed through vigorous interdisciplinary research. In particular, it would be a mistake to dismiss the findings of any given study in neurobiology or computational modeling on the grounds that it is based on principles too simple to account for human cognition. It would be equally mistaken to dismiss the findings of any given study of infant perception or cognition on the grounds that it requires neural machinery too elaborate to exist in a young human brain (see Chomsky, 1994, pp. 78–92, for further discussion). Only concerted, interdisciplinary research can reveal what inexperienced humans perceive and the neural computations that underlie their perceptions.

A final lesson from studies of perceptual development comes from very recent research on developmental changes in object perception at the end of the first year of life and on object representation in different human cultures. This research converges to suggest that perception has both universal and culturally specific properties, and that these sets of processes can be distinguished, in detail, through concerted experiments in anthropology and developmental psychology. Humans have an early-developing system of object representation, based on processes for analyzing objects' spatiotemporal properties, that gives rise to the same perceptual organization in all cultures. Humans also have a later-developing system of object representation, based on processes for analyzing other object properties and forming object categories, that may be sensitive to variations in experience and thus may vary from one culture to another.

³ As this chapter was going to press, Elman et al. (1996) published a useful discussion of these issues. They, too, proposed that an ability be considered "innate" if it develops independently of the external environment, regardless of the epigenetic processes involved (pp. 20–23). They further propose that organisms be granted "representations" when the cerebral cortex displays fine-grained connectivity patterns (e.g., p. 25). By these definitions, the findings of Shatz, Rakic, and others reviewed above provide evidence for innate representations, contrary to a central thesis of their book.

Further understanding of perceptual development, therefore, may come from coordinated studies in cognitive anthropology and cognitive development, undertaken with the common goal of teasing apart the constant from the changing and the universal from the variable (see Bowerman & Levinson, in press, and Hirschfeld & Gelman, 1994, for a start).

LEARNING HOW TO TALK

On the face of it, language acquisition would appear to provide the clearest evidence for the purely empiricist side to development. First, languages vary, and children learn the languages they are exposed to. Second, there is developmental change rather than continuity, extending over a lengthy period of early development (measured in years rather than months), and consisting of behavioral output ordered from simple to more complex, as though a great deal of learning were occurring. Nonetheless, some of the most widely known and compelling evidence for nativist approaches to development comes from the study of the acquisition of language. In this section, therefore, we emphasize the evidence for nativism, using the literature on language acquisition to illustrate the issues about nativist views of development that arise in the examination of a system that clearly undergoes learning and developmental change. The themes we wish to emphasize are tightly related to, but slightly different from, those found in the development of action or perception. The evidence for innate factors in language development is extremely strong, but major controversies in the field center around the nature of what is innate: whether there is innate knowledge of language in particular, or whether the innateness derives from perceptual and memorial biases in more general pattern learning, which indirectly predispose the learner toward acquiring languages of certain types. This field therefore illustrates especially well the ways in which empirical enterprises can clarify the ancient nativist–empiricist dialogue.

The basic and most obvious facts about language learning set the stage for these questions. First, every known human culture has a language, each of which is a combinatorial system mapping form and meaning through patterned rule systems that are radically different from any found in nonhuman communication. This dramatic and uncontroversial fact thus demands from the outset a theoretical account

involving evolutionarily specialized developmental mechanisms of some type. At the same time, there are thousands of *different* human languages around the world, and this fact requires that human infants be capable of learning any of them. Although the best studied of these are spoken languages, recent research reveals that thousands more are signed languages, which readily arise in every culture in which there is even temporary functional deafness or muteness (Kendon, 1988). The acquisition of language must therefore be subserved by mechanisms involving *both* innateness and learning, and operating equally well on stimuli from multiple modalities.

Two subparts of the literature illustrate particularly well the types of empirical discoveries and theoretical questions on which we focus: the acquisition of phonetic systems, which has been studied largely in spoken languages, and the acquisition of grammatical systems, which has been studied most revealingly in signed as well as spoken languages.

The Acquisition of Phonetic Systems: Reshaping Auditory Sensitivities into Linguistic Representations

The study of the acquisition of phonetic systems, with which we begin, illustrates several important aspects of the issues raised in language development. First, it is often argued that calling a behavior "innate" may lead investigators to believe they have an explanation, and therefore can deter empirical research into how the capacity is acquired. The history of research on phonetic acquisition, however, shows that, even after an ability has been identified as innate, new findings can radically alter our understanding of the character of what is innate, and one type of nativist theory can readily supplant another. Such a shift of consensus has undoubtedly occurred elsewhere, but this field provides a very striking example.

Second, as we have seen in the development of locomotion, behavioral domains unique to humans may arise from foundational roots common to other species. Phonetic acquisition presents a somewhat different case. Here, a system which in early development is like that of other species gradually changes through exposure into one unique to humans. Its study therefore offers an unusual opportunity for understanding how species-specific plasticity might arise.

The Nature of Adult Phonetic Categories

Listening to one's native language, one has the impression that the speech stream consists of distinct words, each composed of sequences of sounds roughly like the corresponding letters of the alphabet. If one listens to a foreign language, however, this impression is quickly dispelled. The sounds run together and are remarkably indistinct; recurring units are difficult to isolate or identify. This latter impression is in fact closer to the physical array. Even repeated tokens of the same syllable vary acoustically from one another, and tokens of the same individual sound (for example, /b/ or /p/) are acoustically quite different when followed by a different vowel.

This discrepancy between the acoustics of human speech and the way we perceive it has been demonstrated in the literature on adult speech perception, and forms the background to an understanding of the developmental process. Beginning in the 1950s, research on speech perception revealed, surprisingly, that adults perceive speech syllables (for example, "ba" or "pa") as categories in their native language (see Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Lisker & Abramson, 1970, for reviews). Acoustically distinct stimuli varying in the timing of the onset of vocal cord vibration, for example, were perceived either as "ba" (if the voicing began within 30 msec of the onset of the syllable) or "pa" (if the voicing began more than 30 msec after the onset of the syllable); but finer distinctions of voicing onset time, which were not distinctive in the listener's native language, could not be discriminated from one another even in a purely auditory, nonlinguistic discrimination task (Liberman et al., 1967). This phenomenon of *categorical perception* contrasted sharply with the typical ability of perceivers to discriminate many more stimulus contrasts than they could categorize, which appears for both auditory and nonauditory stimuli outside of speech.

The Development of Phonetic Categories

One important question, then, is how this perceptual categorization develops. An obvious possibility is that it is learned, perhaps through some type of feedback about what the language treats as a category. However, this is not what the literature has demonstrated. In a remarkable study published in *Science*, Eimas, Siqueland, Jusczyk, and

Vigorito (1971) used a technique adapted from studies of infant visual perception to ask how infants perceived and discriminated speech sounds. The technique subsequently changed our ability to study foundational capacities in virtually every perceptual domain. Utilizing one of the few expert behaviors of young infants (sucking), they presented a single repeated token of the syllable "ba," contingent on continued sucking, and waited until the infants no longer found this stimulus worthy of their exertion. They could then ask a simple question that was related to the question asked of adult listeners in the categorical perception paradigm: Which other stimuli sound enough like this one that they, like the original "ba," are also unworthy of continued sucking? And, in contrast, which other stimuli, equally physically distant from the original "ba," sound new and distinctive? Remarkably, the infants' answer was like the adults': A new "ba" was boring, while a "pa" was perceptually different, even though the new stimuli differed from the original "ba" by equal physical magnitudes. These findings showed that even 1- and 4-month-old infants perceived speech categorically, long before speech production (and any external feedback for it) was available, and therefore suggested that categorical perception of speech sounds might be innate. More recent research with much younger infants has continued to support this view (for an overview of the relevant findings, see Ch. 4 by Aslin, Jusczyk, & Pisoni, in Volume 2).

The further question occupying subsequent researchers has concerned the nature of the innate abilities. Do infants innately perceive speech in terms of the *linguistic* categories used by languages of the world? This same early research suggested that this was the case: Acoustic stimuli containing the critical onset timing portions of speech stimuli, but which did not themselves sound like speech, were not perceived in this fashion either by adults or by infants (Eimas et al., 1971; Liberman et al., 1967). It therefore appeared that infants entered the acquisition process already equipped with knowledge of the categories of speech sounds that human languages would use.

However, several crucial subsequent studies importantly altered this view. In one of these studies, Kuhl and Miller (1978) showed that chinchillas (which have an auditory system much like that of humans, though, of course, they would not be expected to have particular human linguistic abilities) also perceive speech in the same categories as

human adults and infants. Trained to press a bar discriminatively for individual tokens of "ba" and "pa," chinchillas spontaneously generalized their bar presses to the same range of acoustic stimuli that humans heard as "ba" and "pa." Although researchers were unable to determine any simple physical basis for these phonetic categories, the behavior of chinchillas suggested that it must be present and that its perception was not necessarily based on a specific linguistic capacity. By inference, one could argue that human infants begin the speech perception process with this same *auditory* categorization, which could subserve the categorization of speech sounds but was not itself yet particular to language.

In accord with this work, Pisoni (1977) and Jusczyk, Pisoni, Walley, and Murray (1980) showed more directly that human adults and infants perceive nonlinguistic stimuli in the same categories found for speech stimuli. Eimas et al. (1971) had not been able to demonstrate this for the 35-msec onset portions of "ba" and "pa." But Pisoni, Jusczyk, and their colleagues synthesized longer (and therefore more perceptible) stimuli, each composed of two tones whose onsets were either simultaneous (like the voicing aspects of "ba") or different by 10 to 60 msec (like the various tokens of "ba" to "pa"). When presented to adult and infant listeners in the same standard paradigms used for "ba" and "pa," these stimuli varying in "tone onset time" were perceived categorically, just like "ba" and "pa," and even shared a category boundary with them at about a 30-msec delay. Together, these findings suggest that the phenomenon of categorical perception occurs for many classes of auditory stimuli, in humans as well as non-humans, and is a property of mammalian auditory systems that precedes language.

On this revised view, how does the perception of speech in particular develop? It begins with a perceptual system that is innately built with certain regions of relative sensitivity and other regions of relative insensitivity. These biases in auditory sensitivity thus form the scaffolding for human speech systems. Languages take as their phonetic categories those regions in auditory space that are relatively perceptible (and within which finer distinctions are difficult to discriminate). Regions that are extremely perceptible (for example, the approximately simultaneous onset of voicing and other aspects of syllable onset, as compared with a 30-msec lag between these acoustic

events) form phonetic categories in most or all languages of the world; those regions that are moderately perceptible form phonetic categories in some languages; and those regions that are extremely difficult to perceive form phonetic categories in no languages. Although this revised account is still a nativist one (that is, it hypothesizes that there are innate perceptual categories underlying the processing of speech), it is not one that invokes specifically linguistic innate knowledge, and it is therefore not seen as objectionable or mysterious (or even nativist) to an antinativist theoretician.

Superimposed on this innate scaffolding, however, is the effect of linguistic experience—an effect which, to date, has been demonstrated only in human perceptual systems. The perceptual categories shown by very young infants (and presumably by chinchillas, though this has not been tested directly) are those underlying the phonetic systems of all the world's languages. Infants younger than 6 months of age discriminate not only "ba" and "pa" (a contrast used in virtually every language), but also "mba" and "ba" (a contrast used in Hindi, but not in English or in many other languages). At some time between 6 and 12 months of age, however, the ability to discriminate categories that are not contrastive in the surrounding language is lost (Werker & Lalonde, 1988; Werker & Tees, 1984). Older children and adults show categorical perception not for the full range of acoustic/phonetic contrasts, but only for those of their particular native language. In addition, the precise boundaries between these categories (for example, at 30-msec voice onset time in English, but at 25-msec onset in Spanish) have been adjusted to those of the native language. Perception of contrasts not used in the native language can, to some degree, be retrained through feedback in the laboratory, but do not persist in the untrained perception of adults (Pisoni, Aslin, Perey, & Hennessey, 1982; for discussion of the details of these findings, see Aslin, Jusczyk, & Pisoni, Ch. 4, Volume 2). These findings thus suggest that the initial perceptual abilities of infant listeners are adjusted and altered through exposure to surrounding speech, and thereby change from the biases of the general mammalian auditory system into the phonetic systems of particular languages. Moreover, the changes take the form of a loss, not a gain, in perceptual categorization. To a first approximation, American infants hear the categories of both English and Hindi. With growth and experience, American children and adults lose

this perceptual ability for Hindi but retain the categories of English.

We are just beginning to understand the mechanisms by which this perceptual adjustment takes place. Do infant perceptual systems respond to the fact that certain sets of sounds signal contrasts of meaning? Or do they respond more fundamentally to the fact that certain sets of sounds occur more frequently, or with greater correlations to others? Exploration of the details of the adjustment from auditory to linguistic perceptual abilities has only recently begun, but the stage for answering these questions has been set by investigators' continued fascination with issues of nature and nurture, and with the search for how our most unique abilities have arisen evolutionarily. The picture we have obtained thus far has important similarities to the development of specialized abilities in other animals, in which the innate tendencies of systems common to many species become adapted in species-specific ways, through evolution or through evolved abilities to learn from particular aspects of external experience.

In the next section, we review these issues in perhaps their most dramatic form: the acquisition of grammatical systems. Of all the behaviors we study in human infants, the acquisition of grammatical capabilities presents the arena in which questions about what is innate and what is learned have been the most explicit and central.

The Acquisition of Grammar

Undoubtedly, the most well-known discussion of nativism in the acquisition of grammar has been provided by the work of Noam Chomsky (1965, 1975, 1988). Chomsky has framed this discussion in terms of both a formal linguistic theory and a logical argument about development. His linguistic work over the past three decades has centered on providing evidence that, although the languages of the world appear to vary widely in their grammatical properties, they are in fact quite similar to one another, and they share a large set of universal principles of grammatical structure. The enterprise of modern linguistics, as framed by him, is to formalize these principles precisely. Chomsky's accompanying contribution to development has taken the form of a logical argument: Given the existence of universal principles across unrelated languages, and also the great distance between these principles and their instantiation in the physical signals from

which a language must be acquired, it could not be the case that languages are in any serious sense "learned." Rather, the universal principles underlying languages must be innate, and most of language development must reflect the emergence of these principles in some articulatory form. On this view, the linguistic environment serves the function of triggering and, in limited ways, of setting some detailed parameters on the instantiation of these principles in a specific language.

This set of arguments is, in some ways, breathtakingly at odds with the obvious facts. As already noted, languages appear to differ fairly wildly—enough so that Chomsky's predecessors used their very differences to argue the opposite of Chomsky's view: "Walking, then, is a general human activity that varies only within circumscribed limits as we pass from individual to individual. . . . Speech is a human activity that varies without assignable limit as we pass from social group to social group, because it is purely a historical heritage of the group, the product of long-continued social usage. . . . Walking is an organic, instinctive function . . . speech is a non-instinctive, acquired, 'cultural' function" (Sapir, 1921, p. 4). Under Chomsky's guidance, however, the field has amassed quite a large number of surprising principles of uniformity, which underlie and structure the apparent diversities.

Still, language development certainly appears to involve what any reasonable person would identify as "learning": a lengthy period of gradual mastery, some rather protracted and different-looking stages along the way, and usually some rather striking resemblances between what the child comes eventually to do (e.g., speak English) and what the child's environment presents (e.g., English). But close empirical examination of these phenomena has supported, at least in general outline, some version of Chomsky's claim. The acquisition of language is heavily shaped by innate tendencies of the learner to acquire languages of particular types, in particular ways.

As we have seen in earlier sections, the question of whether there is some innate component to a developmental process is logically distinct from identifying what precisely is innate, how the innate propensities are enacted in the course of development, and to what degree these propensities are specialized to a particular behavioral domain. In the field of grammatical acquisition, however, this distinction has sometimes been overlooked, and evidence for a nativist approach to the acquisition of syntax is

often misinterpreted as evidence in favor of Chomsky's particular nativist theory. In the present review of the literature, we attempt to separate the evidence into two parts: (a) research suggesting that there is an innate component to the acquisition process, and (b) research investigating the nature of the underlying mechanisms of acquisition.

Evidence for Innateness in Learning

Along with Chomsky's formal work on languages and their acquisition, much of the strongest evidence for innateness in the acquisition of grammar comes from comparative studies of children and adults learning languages around the world, under varying circumstances of input and maturational state. As we will see, these studies show that children learn their apparently differing languages in remarkably similar ways, suggesting that they are guided in this process by some type of internal predispositions.

Uniformity in the Course of Acquisition. Lenneberg (1967) was the first to note that language acquisition proceeded through a reasonably fixed set of stages, or milestones, whose nature and timing were stable even when the linguistic environments were varied. As Lenneberg reported, children universally pass through cooing, babbling, first words, two-word sentences, and then more complex syntax, with each milestone appearing at ages roughly as predictable as those of getting teeth or developing motor abilities. Since the publication of his book on this topic, we have learned that there is a similar course of development for exotic as well as familiar spoken languages (Slobin, 1985, 1992), and even for signed languages (Newport & Meier, 1985; Petitto & Marentette, 1991). Perhaps most surprisingly, deaf children who are not effectively exposed to any conventional language devise words and sentences from gesture, and pass through at least the early stages of "acquisition" on their own (Feldman, Goldin-Meadow, & Gleitman, 1978; Goldin-Meadow & Mylander, 1984). Such regularity of development despite varying environments suggests that internal maturational factors heavily dictate the course of acquisition.

Not All Learners Look the Same. Young human children look remarkably similar to one another as they learn languages, but not every organism exposed to the same linguistic environments displays the same behaviors in response. Dogs and cats produce neither spoken nor signed

sentences and understand, at most, a few simple words, even when they are addressed for years with the most loving and tailored forms of speech (Hirsch-Pasek & Treiman, 1982). Devoted caretakers of chimps and gorillas, our nearest evolutionary relatives, have noted in them, at most, some simple elements of human language (Premack, 1976; Savage-Rumbaugh, 1991; although cf., Savage-Rumbaugh et al., 1993). But perhaps the clearest evidence that learning language requires a particular native endowment comes from studies of human adult language learners.

In the same book that noted the regularities of human children's acquisition of language, Lenneberg (1967) suggested that this process, like the development of many other species-typical behaviors (for example, imprinting in birds and ducks, or the acquisition of song in sparrows), might be limited to a maturationally bounded critical period, early in life. It has, however, required several subsequent decades for investigators to determine how to put his hypothesis to empirical test. Lenneberg himself provided a review of the neuropsychological literature, suggesting that reacquisition of language, after damage to the left hemisphere, was successful only in childhood. But this evidence showed only a possible critical period for the acquisition of language by the right hemisphere, and did not address the learning capacities of the intact brain over maturation.

The well-known study of Genie, conducted by Susan Curtiss and her colleagues (Curtiss, 1977), examined the acquisition of English by a girl who was deprived of linguistic exposure (and many other aspects of a normal human environment) until after puberty. In accord with Lenneberg's hypothesis, Genie did not acquire English syntax and morphology normally, even though she did succeed in learning a vocabulary.

Several studies have recently been conducted on deaf adults who were first exposed to American Sign Language (ASL) as their native language at ages ranging from birth to well past puberty (Emmorey, 1991; Mayberry & Fischer, 1989; Newport, 1990). Each of these studies has shown a decline in the ability to learn and process ASL syntax and morphology as the age of first exposure increases.

Finally, several studies have examined the acquisition of English as a second language by adults who were first exposed to it, through immersion in the United States, at ages ranging from 3 to 40 years (Johnson & Newport, 1989, 1991; Johnson, Shenkman, Newport, & Medin, 1996;

Krashen, Long, & Scarcella, 1982; Long, 1990; Oyama, 1978; Patkowski, 1980; Slavoff & Johnson, 1995). Again, each of these studies has shown a decline in the ability to control various aspects of English syntax and morphology as the age of first exposure increases.

These studies thus confirm Lenneberg's hypothesis of a critical period for learning language. In certain details, their results are different from those anticipated by Lenneberg. Human adult language learners do not totally fail to learn new languages. In fact, as any second-language learner knows, human adults are capable of learning quite a bit about a language late in life, and some adults are particularly talented at late-learned languages (Birdsong, 1992; Coppeters, 1987). It is thus perhaps more accurate to say that human language learning shows a sensitive, rather than a critical, period (although virtually every behavior displaying maturational changes in plasticity also shows them in a less-than-absolute form, so such a distinction may not be worth making). Nonetheless, these changes in the ability to learn languages over age are perfectly adequate for making the present point: Not every learning device acquires human languages; only some, with particular internal characteristics we cannot yet specify, are capable of learning languages as children do.

Learners Do Not Always Learn Their Input. Some of the best evidence for innate tendencies in human language learners comes from cases where the learners do not acquire the language to which they are exposed, but rather acquire a system that is structured more like a natural human language. Only tiny fragments of such a phenomenon appear in most language learning; in the ordinary case, children are exposed to a language governed by rules and patterns of the universal sort, and they acquire one that is pretty well indistinguishable from the one to which they were exposed. Under these circumstances, native instincts are hard to discern; a mechanism that had principles of its own, and one that more slavishly followed its input, would both arrive at the same outcome. Only rare but interesting childish errors (for example, the overproduction of rules like adding -ed to form the past tense of irregular verbs) give hint of the tendencies of learners to impose patterns of a particular type.

The more crucial cases for examining the innate tendencies of learners arise in circumstances where the input is

not an ordinary human language. Suppose, in the extreme, that a human learner were exposed to well-formed Martian. That is, suppose that the input language did not observe or illustrate the principles universal to human languages. Under these circumstances, a learner natively endowed with tendencies to observe these principles should acquire a language with the properties universal to human languages nonetheless. Such an outcome would provide especially strong evidence for the existence of such innate tendencies, and might even help to articulate what these tendencies are.

Surprisingly, several phenomena with similarities to this scenario have come under empirical study in recent years. One such phenomenon has been claimed to occur in language *creolization* (Bickerton, 1981, 1984; Sankoff & Laberge, 1973). In cases where adult speakers regularly interact across mutually unintelligible languages, they may develop a simple pidgin, which borrows a limited vocabulary from one of the surrounding languages and forms sentences using a few word-order rules, or the differing rules of each of the surrounding languages. Pidgins are, by definition, no one's native language, and they do not display either the consistency or the grammatical complexity of any ordinary natural language. In a small number of cases, pidgin speakers marry, and the pidgin becomes the primary language to which their young children are exposed. Under these circumstances, the language acquired by the first generation of children is called a *creole*; the new term is coined because, it has been claimed, the language of this new generation is strikingly different in structure from the one from which it was formed. Unlike their antecedent pidgins, creole languages are both more consistent and more complex in grammar, and, over subsequent generations, may take on all the properties of ordinary natural languages. Bickerton (1984) and certain other creolists have suggested that these changes arise from the innate predispositions of child language learners. Unfortunately, however, the process of creolization has almost never been observed in progress (though see Sankoff & Laberge, 1973) and is typically reconstructed from the differences in speech among speakers of different ages many years later. Because both the pidgin and the creole arise in regions where large numbers of other languages are spoken, it is difficult to separate language innovation from language borrowing, and creolists often disagree about which of

these is most responsible for the structures that appear in the creole (see the commentary attached to Bickerton, 1984). Nonetheless, creolization studies provide exciting opportunities for empirical research on extraordinarily important cases of language acquisition.

Fortunately for researchers, phenomena like creolization (but without some of the complicating factors) have been found to arise much more commonly in individual deaf children learning signed languages, and even in large deaf communities. Most congenital deafness occurs within otherwise hearing families, where signed languages are typically not used by adult models; in these circumstances, deaf children may develop simple family "home sign" systems, which have some of the grammatical characteristics of early languages (see the earlier subsection, "Uniformity in the Course of Acquisition"). It is believed that full signed languages—for example, ASL (now used by deaf people throughout the United States)—developed spontaneously from these roots, when many deaf children were brought together by the establishment of schools and other organizations that created communities of signers (Fischer, 1978; Woodward, 1978). This process has occurred only recently in Nicaragua, where the creolization of Nicaraguan Sign Language has been observed and recorded by linguists and psycholinguists interested in language acquisition and linguistic structure (Kegl, Senghas, & Coppola, in press; Senghas, 1995). Senghas's landmark dissertation has shown that young deaf children entering this community over a period of 10 to 15 years have gradually added more complex linguistic structure to the community language, even though the input they received was much less grammaticized. Unlike spoken-language creoles, Nicaraguan Sign Language could not have borrowed its linguistic devices from surrounding languages. Because its users were isolated from oral Spanish by their deafness and illiteracy, the language could only have derived its linguistic complexity from the internal tendencies of its users themselves.

Singleton and Newport (1994; Newport, in press; Singleton, 1989) have also documented the acquisition and grammaticization of a signed language by a single child, whose input models they recorded and closely analyzed. The child they studied had deaf parents who used ASL, but who themselves had been exposed to ASL only during adulthood. Because they were late learners of ASL, the parents used only the simpler structures of the language, and used

even these with great irregularity. No one else who knew ASL was available to provide additional input to the child. Despite this reduced and inconsistent input, their child acquired a more complex and highly structured form of ASL. Again, this creole-like phenomenon could only have occurred because of the tendency of children to learn languages of particular types.

Taken together, these occurrences of creolization and its relatives, in spoken and signed language communities around the world, provide striking evidence that children are highly biased learners. The acquisition of language is not a slavish reproduction of environmental forms; rather, it is the systematization and reorganization of these forms into patterns, according to the native tendencies of learners.

The Nature of an Innate Mechanism for Learning Languages

The various studies we have reviewed provide empirically detailed and theoretically powerful evidence for Part One of a nativist view of language development: There is indeed a significant contribution of innate factors to the acquisition of language. Because of these studies, some version of Chomsky's hypotheses about language and its acquisition has been accepted, at least in general outline, by most researchers in the field. Probably every student of language acknowledges that there are surprising commonalities among unrelated languages of the world, and that language acquisition takes place in humans, at least in part, because of innate predispositions. But there is, nonetheless, widespread disagreement on Part Two of the nativist question: *What* is innate, and *how* does innately guided learning occur?

The current state of the art provides surprisingly little evidence about the nature of what is innate in the acquisition of language. Because we know that children are capable of learning any language, as long as it conforms to human language principles, it cannot be the case that children innately know any particular language, or even any particular linguistic constructions. Rather, they must be prepared innately to learn languages of the proper kind. Chomsky has suggested that this is accomplished by the child's innately knowing what is universal about languages, and also knowing the dimensions along which languages may vary. But no empirical evidence has been provided that this is the best or only way to construe a nativist account of acquisition, and it is certainly not the only way biology

builds innately guided systems. Feasible (though relatively unarticulated) possibilities include learning mechanisms that do not "know" anything about linguistic universals and variation, but rather perceive, remember, or analyze linguistic input in ways that bias certain outcomes indirectly. As we have argued throughout this chapter, the business of nativist approaches to development is articulating and testing these alternatives.

Theories of Innately Guided Learning

What types of mechanisms are capable of accounting for these phenomena? Two important issues arise in moving toward a model of language acquisition. First, how does one account for the obvious and protracted changes in linguistic behavior over age? Are they an artifact of changing performance abilities, with an underlying continuity of fundamental capacities (as in the development of locomotion), or is there a genuine change, through maturation or learning, in the nature of linguistic capacities? Second, how does one reconcile the evidence for innate factors in the development of language with the obvious evidence for experiential sensitivity? What types of developmental mechanisms might a theorist invoke to account for both innate and experiential aspects of acquisition?

Continuity, Maturation, and Learning

If important innate factors account for the acquisition of language, why does the learner change so dramatically over a period of 4 to 5 years? Until recently, this question received little direct attention in the field. However, in the past few years, several positions have been offered on this issue.

One possibility, termed by Pinker (1984) the "continuity hypothesis," is that both the principles underlying linguistic knowledge and the mechanisms for learning particular languages are unchanging over development, and they constitute a continuous set of core or fundamental capacities that pertain throughout development. On this view, the changing appearance of linguistic behavior must arise from the content of what is learned over time. What is not entirely clear in this position is why the learning process should take so long or should show the recurrent stages that appear; presumably, these arise in large part because of the complexity of the linguistic details to be mastered, and the inherent grading of complexity across constructions.

(Other reasons might include developmental changes in the planning or production of speech itself; see Gerken, 1994, for discussion.) It is of interest to note that the continuity hypothesis is often adopted by researchers whose own view of language acquisition makes the learning of language-particular constructions a fairly trivial part of the acquisition process (see, for example, Hyams, 1986); but the protracted appearance of language in the young child would instead suggest that this learning process is quite significant, and therefore worthy of more attention in the research literature than it has received.

A second possibility is that there is substantial maturational change in some or all parts of the acquisition mechanism, analogous to the (partly) endogenous maturation of other aspects of biological growth. This could involve either maturation within a specific linguistic mechanism (Borer & Wexler, 1987; Chomsky, 1988), or the maturation of nonlinguistic abilities that alter the learning process as development progresses (Newport, 1990). The evidence cited above for a sensitive or critical period in language acquisition suggests that there is indeed a maturational decline, throughout the learning period (see as early as ages 4 to 6), in the ability to acquire a new language; whether there is maturational change during this time (or earlier) that affects the ongoing acquisition of a language encountered from birth remains to be investigated empirically.

Proposals for Integrating Nativism with Experiential Sensitivity

The major theoretical issue that pervades the literature on language acquisition, but has been the subject of surprisingly little empirical research, concerns the character of mechanisms for acquiring language that show both innate propensities and experiential sensitivity.

The best-known proposal on this topic is that of Chomsky (1965, 1981, 1988), who suggests that these two aspects of acquisition correspond to two (or perhaps three) underlying separate mechanisms. The innate restrictions in Chomsky's theory arise from an innate and domain-specific knowledge of the universal properties of linguistic systems. Human children are thought to know innately the primitives out of which languages are built (for example, such concepts as *noun*, *verb*, *subject*, *object*), and the principles by which they may combine to form sentences (for example, that word classes much combine in limited ways to form certain types of phrases; that phrases are always

structured with their major elements in either the first or last position; and that sentences are always comprised of the same phrase types). The experiential sensitivity in this proposal is provided by two other mechanisms: one that knows certain very limited parameters on which the innate principles may show variation (for example, whether the major elements of phrases are in the first or last position) and acquires the appropriate value from "triggering" linguistic input; and one, not described in this theory, that somehow acquires from input the much more variable aspects of languages (such as the particular words). Little research has been conducted on children's acquisition of languages to determine whether this type of proposal is an empirically correct description of development; rather, the main supporting research consists of extensive linguistic analyses of languages of the world (suggesting that they do indeed vary in parametric ways), and studies of acquisition that assume the theory as a framework and then investigate its application to particular languages.

As an alternative, a less well-developed literature suggests that language acquisition may be performed, at least in part, by more domain-general learning mechanisms. The difficulty for this approach lies in accounting for the particular and apparently innate characteristics of languages and their learning, which are stipulated as specific knowledge in the Chomskian proposal. A potential direction of this alternative literature, however, is that the innate characteristics of language learning may result from indirect biases inherent in the nature of children's learning. This literature thus raises an issue we have seen in our earlier discussion of perception: the possibility that nativist approaches can encompass not only genetically determined outcomes (which are in some ways like the Chomskian approach to language acquisition), but also outcomes that result from more indirect, but still innate, predispositions. Below, we review this literature in two parts, focusing first on models of statistical learning, and subsequently on potential sources from which predispositions, or biases, in such learning might be derived.

Connectionist Models and Statistical Learning. In recent literature, an approach to language acquisition called "statistical language learning" has arisen independently in many of the subfields studying natural language, including not only language acquisition, but also sentence processing and computational linguistics. The common

influence for these developments is the prominence of connectionist models of language, and most especially the widely discussed connectionist model of the acquisition of the morpheme *-ed* (Rumelhart & McClelland, 1986) and its equally widely discussed critiques (Lachter & Bever, 1988; Pinker & Prince, 1988).

Rumelhart and McClelland's model of the acquisition of *-ed* took as its focus the question of whether a connectionist device, composed of interconnected units that stored in a superimposed fashion the thousands of tokens of past-tense forms of verbs in English, could succeed in acquiring a simulation of the "Add *-ed*" rule without explicitly acquiring a "rule." Their model argued (somewhat implicitly; this wording is ours) that the superimposed frequency of forms that end in *-ed*, distributed widely over verbs of English whose stems were quite variable, could form the basis for the learning of an apparent rule, and even for its overgeneralization during early stages of acquisition. Pinker and Prince (1988) subsequently argued convincingly that this simulation was accomplished incorrectly. It exploited a distribution of tokens that changed over the course of learning and contained at critical moments a frequency distribution uncharacteristic of actual language learners. In addition, Pinker and Prince (1988) and Lachter and Bever (1988) showed that the connectionist device in question contained within it architectural features that mimicked linguistic rule-learning mechanisms, and, where it did not, that it could not acquire the correct properties of natural languages. Rebuttals of these critiques, and rebuttals of the rebuttals, continue (Daugherty & Seidenberg, 1992; MacWhinney & Leinbach, 1991; Marcus et al., 1992; Marcus et al., 1995; Pinker, 1991; Plunkett & Marchman, 1991, 1993).

However one views the outcome of this interchange, it has provided important stimulation for rethinking the role of statistical information (including the frequency of word forms as well as more complex statistics, such as their co-occurrence or conditional probabilities) in the acquisition process. This is in fact an old issue; statistical descriptions of natural language structure (called "distributional analysis") formed the core of linguistics and psycholinguistics in the 1930s to the 1950s (Bloomfield, 1933; Harris, 1955; Miller, 1951), and critiques of this approach were the topic of Chomsky's earliest linguistic work (Chomsky, 1955, 1957). In the enthusiastic embracing of Chomsky's important critiques, however, the potential contributions of sta-

tistical information to the learning of languages have until recently been neglected. Recent studies of linguistic input taken from the CHILDES database (MacWhinney & Snow, 1990) have shown that the statistical features of input corpora may provide potentially rich information for the induction of grammatical categories and other linguistic structures (Brent, 1996; Finch & Chater, 1992; Mintz, 1996; Mintz, Newport, & Bever, 1995; Morgan, Shi, & Allopenna, 1995; Redington, Chater, & Finch, 1993; all of these studies follow up on important suggestions made by Maratsos & Chalkley, 1980). In addition, recent empirical studies of infants' and children's learning from input structured solely in terms of statistical information have shown that they are surprisingly adept at acquiring such information (Goodsitt, Morgan, & Kuhl, 1993; Morgan & Saffran, 1995; Saffran, Aslin, & Newport, 1996; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997).

The problem for statistical approaches to language acquisition, noted by Chomsky (1955, 1957, 1988) and others from the 1950s to the present, concerns what might be called "the richness of the stimulus" (Gleitman & Newport, 1995; "the poverty of the stimulus problem," mentioned in earlier sections, is in some sense another way of stating the same difficulty). There is an infinite number of statistical computations that learners might in principle calculate over a body of environmental input. How do real learners hone in on just the right ones? Extant models of acquisition in a connectionist or statistical framework, when they work, are thus far built by hand-tailoring into the model just those computations that solve the problem under study; in this regard, they could be argued to instantiate domain-specific knowledge of linguistic principles (the position on acquisition they attempt to eschew). In the long run, a successful mechanism will need to incorporate just those procedures or architectures that are assumed to be involved in learning (and no others), and to make explicit claims about the nature of these limitations.

Moreover, how can we account for creolization and similar phenomena reviewed in earlier sections, which show that language learners often build a structure that is not represented in the input corpora from which they learn? Again, models either will have to stipulate innate linguistic constraints to solve such problems, or they will have to provide an account of the architectural features of a general learning device that produce the right outcomes.

In the next section, we consider some tentative directions in the search for limitations, biases, or architectural constraints that might provide solutions to these problems.

Inherent Biases in Learning. Several proposals have suggested that the tendencies of language learners to develop universal features of linguistic systems may arise, at least in part, from inherent biases in the way young children learn seriated, patterned information, rather than from direct knowledge of the way languages must be organized. For example, Bever (1970) and Slobin (1973) suggested that learners may be subject to perceptual or memorial constraints on the encoding of sequential auditory information (for example, a greater ability to notice or remember the ends of units rather than their beginnings). Such constraints might result in the appearance, in languages of the world, of grammatical structures that accord with these constraints (for example, a more widespread appearance of suffixes than of prefixes in word formation rules). Newport (1988, 1990) and Elman (1993) have suggested that the processing limitations of young children in working memory may change the data to which they have access in language learning, and therefore may shape the character of the structures that can be acquired. Surprisingly, both investigators have shown that certain types of complex linguistic structures are learnable only when learners begin their acquisition processes in such limited states (Elman, 1993; Goldowsky & Newport, 1993). Newport has called this the "Less is More" hypothesis. More generally, Turkewitz and Kenny (1982) have hypothesized that many aspects of development may be shaped by the fact that altricial organisms begin learning during a period in which their capacities are particularly limited, and that the slow maturation of these capacities may provide a series of changing opportunities to be affected by selected aspects of experience.

Each of these proposals only hints at the possibility that innate constraints on language learning may arise from forces other than direct knowledge of linguistic principles; none is well enough articulated to account for the detailed structures and constraints that appear in linguistic theories. Nonetheless, the proposals may remind investigators of how little attention has been devoted to the range of ways in which innate factors may direct development, and may suggest directions in which further theorizing and empirical research should be pursued.

The Development of Language: Themes and Questions

The acquisition of language provides a somewhat different type of example for the discussion of nativist-empiricist issues than those we have seen thus far. For each of the other topics we discuss—the development of locomotion, depth and object perception, and spatial knowledge—there has been extensive empirical controversy about whether there is innate knowledge, what form it takes, and how it interacts with experience. Because in each of these arenas the core behaviors are in some clear and obvious ways uniform over members of our species, however, it is possible, at least in principle, to imagine how innate knowledge might organize the developmental process. In the domain of language, the clearest and most obvious fact is that there is diversity, and therefore that development in this arena must involve learning. Children exposed to French learn French, children exposed to Hindi learn Hindi, and children exposed to American Sign Language learn ASL, a communicative system that employs input and output media that are entirely different from those of French or Hindi. If there is a nativist account of the acquisition of language, it must involve a natively based *learning* mechanism, one that operates with equal ease on highly different types of environmental input. Our review of this literature has focused on illustrating the particular types of questions and issues that arise in considering nativist concerns in such a case.

Like the development of action, perception, and spatial knowledge, certain core abilities of humans for the perception of language appear to be shared with other species, and are evident as early in development as researchers have discovered how to test for them. Infants begin their acquisition of the sound systems of natural languages with auditory categories like those of other mammals. But unlike development in these other domains, language development is primarily about the enormous changes that occur from this initial state. With linguistic exposure, infants gradually diverge from nonhuman mammals, and acquire phonetic and grammatical systems that no other species displays. Nonetheless, the character of this experiential sensitivity suggests that innate factors are involved. Children acquire only certain types of languages, sometimes even when their environmental input is highly degraded. Language development thus exemplifies the fact that continuity is not the only form that behavioral domains influenced by innate factors might display; maturation and constrained learning—what

Marler (1991) calls an "instinct to learn"—can also be developmental courses that reveal nativist components.

The study of language acquisition also clearly demonstrates that nature–nurture questions have at least two distinct parts: First, is there a significant contribution of innate factors to the development of the capacity? Second, what is the character of the innate factors? Are the initial abilities that organize the domain particular to language, or are they more general? Is there innate "knowledge" of the structures of languages, or are there instead innate biases in the way the learning mechanism acquires whatever structures it is exposed to? Perhaps most important, how might one empirically distinguish these closely related alternatives from one another? These two parts to the nature–nurture question have not always been clearly distinguished, particularly in grammatical acquisition, where research has focused almost entirely on the first question and has sometimes confused an answer to this question with an answer to the second. In the long run, however, empirical answers are needed for both of these sets of questions.

We believe a further point is illustrated by this field. In our discussion of perceptual development, we noted that innateness is not the same as genetic determinism, and we described cases in which neural circuitry might arise from indirect (though still innate) internal mechanisms, rather than from direct genetic specification. A related issue runs through the literature on language acquisition. As we have described, nativist accounts in this field take either of two forms. One hypothesizes that there is direct stipulation of the possible languages that children can learn, and the other hypothesizes that there may be constraints on learning and these constraints more indirectly lead to these outcomes. These alternatives exemplify two different ways that biology may build developing systems. Our best current understanding of development in other species and for other domains is that the ways in which organisms acquire their species-typical behaviors varies. In some cases, particular developmental outcomes are prespecified in some detail and in terms of representations specific to the domain. One well-known example is the acquisition of song in sparrows. Sparrows are thought to enter the learning environment with an innate template of their species song, and to use this template both to select the stimuli from which they learn and to organize the aspects of these stimuli which are acquired (Marler, 1970, 1991). In contrast, in

other cases, particular outcomes are achieved through combining more general perceptual biases or tendencies with dependable species-typical experiences from which the biased organism will learn. An example of this type of alternative appears in accounts of imprinting (Bateson, 1979; Hess, 1973). Ducks and birds begin their learning with an innate propensity to follow moving objects, a set of preferences for the stimuli they will follow (e.g., a sphere is preferred to other shapes), and maturational limits both on when they start to locomote (which begins the critical period) and when they begin to fear novel objects (which ends the critical period). In a natural environment, these biases and tendencies will result in early imprinting to species members, without an initial innate representation of the species. Given these two different types of innately guided development in other organisms, it is sensible to expect that either of these two methods might underlie the development of biologically significant behaviors in humans as well, and that empirical debate between comparable alternatives in the acquisition of language is the sign of healthy science in progress.

Perhaps most important, recent findings in language acquisition suggest at least the beginnings of answers to these questions. It is often argued that nativist accounts are non-explanatory, and that, by labeling a phenomenon "innate," they serve only to deter empirical investigations into how the capacity is acquired. (The other half of this argument is, of course, that empiricist accounts are therefore preferable, even if the truth is not yet known.) The study of language development, however, provides particularly instructive examples of how empirical findings may inform nativist accounts. Over the past 25 years, new findings have led one type of nativist explanation to be modified into another that is equally nativist but quite different. In the case of speech perception, claims of an innate, species-specific sensitivity to the sounds of language have been replaced by claims of an innate, species-general sensitivity to certain kinds of auditory patterns. In the case of syntax, claims of innate knowledge of grammatical principles now vie with claims of innate predispositions to discover or impose certain kinds of patterns on input data. Rather than bringing empirical investigation to a halt, nativist arguments in language acquisition have provided inspiration to a remarkable range of empirical enterprises, and have given us a new understanding of both the plasticity and the inflexibility of the human capacity to learn. What remains for future work

is to clarify the types of mechanisms that might underlie this capacity, and to provide further empirical evidence indicating which of these mechanisms has evolved in human infants to subserve the acquisition of communicative systems.

ABSTRACT KNOWLEDGE: SPACE

Conceptual knowledge is a vast topic, comprising knowledge of categories of objects such as animals or artifacts, events and routines such as school days or picnics, the material world and its behavior, people and their actions, and abstract entities and relations such as number or ownership. We discuss just one content domain within the last category: spatial knowledge. We focus on this example because spatial knowledge has been studied at many levels, from tacit knowledge of the environmental layout to explicit knowledge of formal geometry, and because the development of this knowledge has been a central topic within the nativist-empiricist dialogue from classical times to the present day.

Geometrical knowledge presents a challenge to any naturalist. The objects of Euclidean geometry—dimensionless points, lines of infinite extent and no thickness—cannot be perceived by any biological system. At the base of Euclidean geometry, moreover, are propositions whose truth cannot be verified by experience or deduced from other verifiable propositions. Principles such as Euclid's fifth ("parallel") postulate cannot be proven true, and yet people who think about geometrical relations typically find them intuitively correct.

What are the sources of these intuitions? Socrates suggested that geometrical knowledge is innate in humans and is evoked through a process akin to recollection. He probed this process by conducting what may have been the first study of the development of geometrical knowledge. Plato (1961) recounts his famous interview of a young slave, which elicited geometrical knowledge (for example, knowledge that the area of a square quadruples when the length of a side doubles) purely by posing questions. Because the youth had never studied geometry, Socrates concluded that the knowledge revealed by his questioning was already present in the youth's mind.

Arguments for the innateness of geometric principles were extended as the nativist-empiricist dialogue progressed. Descartes (1641/1971c) considered how one

comes to know that the three angles of any triangle together equal two right angles. Because such truths extend beyond concrete experience with any particular figures, Descartes concluded, "My mind is assuredly so constituted that I cannot but assent to them . . ." (p. 102). Kant (1781/1964) considered the origins of spatial knowledge by asking what kinds of creatures humans must be in order to gain such knowledge. Pure creatures of sensation, for whom the world evokes no ideas of space, time, or causality, could never come to conceive of a world with these properties, he reasoned. Experience, moreover, may bring knowledge of how the world *is* but not of how it *must necessarily be*; experience therefore cannot account for the intuition (e.g.) that the three inner angles of a triangle necessarily sum to 180° . Because humans do have knowledge of a spatially extended world, and because some of this knowledge has necessary force, some geometrical knowledge must be *a priori*.

Empiricist replies to these arguments resound through the dialogue. Arguments for the innateness of geometrical knowledge were challenged by Berkeley (1710/1975a), who denied that humans truly have such knowledge. When one talks of triangles, he suggested, the abstractness of this concept derives from the abstractness of the words used to describe experience. For Berkeley, the acquisition of human language therefore is central to the growth of ideas about space.

Helmholtz later challenged Kant's argument that humans have *a priori* knowledge of Euclidean geometry by appealing to developments in mathematics and physics that began shortly after Kant's writing (see Hatfield, 1990). The discovery of a family of non-Euclidean geometries, based on a denial of Euclid's fifth postulate, showed that humans can construct systems of spatial representation in which this axiom does not hold. The later discovery that the universe is non-Euclidean showed that humans can even learn that their most basic geometrical intuitions are false. If it is possible to learn that the world is non-Euclidean, Helmholtz argued, then human "knowledge" of Euclidean geometry cannot be *a priori*. Why not suppose that humans initially learn to perceive and represent space in ways that give rise to Euclidean intuitions?

Like Socrates, Helmholtz viewed this last possibility as an empirical hypothesis: If one could find a way to raise a child in a strongly non-Euclidean environment, one could test whether the child developed geometrical intuitions in

accord with Euclid's fifth postulate. Although this experiment is neither practically nor ethically possible, studies of animals and children reared in natural environments have shed considerable light on the normal development of spatial knowledge. We begin with the development of the basic representations underlying navigation and object localization. Then we consider the development of abilities to represent space through two symbolic systems: language and maps. Finally, we discuss the development of the explicit geometrical intuitions whose sources have so intrigued contributors to the nativist-empiricist dialogue.

Spatial Representations for Navigation

Any animal with a stable home must find its way homeward after venturing out to locate food, secure a mate, or defend its territory. Species as diverse as ants, geese, rats, and humans solve this problem, in part, by representing the direction and extent of their locomotion and computing their changing position relative to home. This process of "path integration" (Mittelstaedt & Mittelstaedt, 1980; Muller & Wehner, 1988) or "dead reckoning" (Gallistel, 1990; McNaughton, Knierim, & Wilson, 1995) allows an animal to return home directly from any point in its travels, in the absence of visible landmarks. Dead-reckoning is subject to errors that accumulate over time, however, and require correction through some other process. Most animals correct these errors and reorient themselves by drawing on representations of the environment. We consider each of these processes in turn.

Dead Reckoning

Dead-reckoning abilities testify to perhaps the most basic of spatial representations and computations: the representation of where one is and how one's position changes as one moves. Both the existence and the nature of this representation have been investigated in desert ants, who search for food by traveling from the nest on tortuous paths and then return home directly from a distance of 100 meters or more (Wehner & Srinivasan, 1981). Displacement experiments in which the ants are taken from the nest and released at different points within their territory indicate that they cannot reliably find the nest by perceptual cues, for they wander at random when released further than about 2 meters away (Wehner & Flatt, 1972). Foraging ants therefore must rely on an internal representation of the nest's distance and direction, and so further experiments

tested the precision of this representation. In one series of studies, ants walked freely from the nest to a food source and then were carried to new terrain before beginning their homeward march. The ants moved on a straight path of nearly the same distance and direction as the path that would have led them home had they not been displaced, testifying to a strikingly accurate representation of the nest's location (Wehner & Srinivasan, 1981; see also Muller & Wehner, 1988).

Desert ants are remarkable because their navigation depends on dead reckoning almost exclusively. As we will see in later sections, birds and mammals are more influenced by perceptible landmarks when they navigate and search for objects. Nevertheless, all mobile animals appear to be capable of dead reckoning (see Gallistel, 1990, chapter 4, for a sweeping review of the relevant evidence). For example, rodents have been shown to navigate by dead reckoning in the dark, when perceptible cues to the nest's location are minimized (Etienne, 1987; Mittelstaedt & Mittelstaedt, 1980). Indeed, dead reckoning sometimes overrides immediate perceptual information for the nest location. If a female rodent's nest is moved, she will go to its reckoned position even if her young nestlings plainly can be heard at the new location (Mittelstaedt & Mittelstaedt, 1980).

How does the dead reckoning system develop? Do animals learn, by trial and error, the relation among their current position, current velocity, and resulting position? As far as we know, this question has been addressed experimentally only in avian species, who appear to develop dead-reckoning abilities after minimal locomotor experience. St. Paul (1982) led young alpine geese, who had never left the vicinity of their nest, to a location on the far side of a mountain, where she released them. Most of the goslings took off in the direction of home, on a path that deviated considerably from the circuitous path by which they had arrived. Further experiments involving invisible displacements of the geese (similar in logic to Wehner's displacement experiments with ants) showed that they were not guided by perceptible landmarks in choosing their homeward direction but rather by an internal representation of the home direction that they, like ants, updated as they moved through the layout. Because this representation was computed by goslings who had never previously left the home area, we may conclude that geese do not learn to dead reckon by trial and error. Laboratory studies of 2-day-old chicks, who show appropriate navigation toward an unseen object on the very

first trial of a detour experiment, support the same conclusion (Regolin et al., 1995b).⁴

The dead-reckoning abilities of insects and birds are surprising from the perspective of human cognition, for human adults often have trouble determining their position in the larger spatial layout, and nautical navigators spend many years learning to make such calculations explicitly (see Gallistel, 1990, Chapter 3; and Gladwin, 1970). From a different perspective, however, the existence of an early-developing system for dead reckoning should be expected, because such a system is essential for the survival of any animal that forages beyond the bounds of the environment that is immediately perceptible from home. If animals had to learn to dead reckon by trial-and-error wanderings, it is unlikely that many would survive their first journey. Mechanisms for representing one's current position relative to home, and for updating this representation over motion, are an ecological necessity.

Does a system for dead reckoning exist in humans at the time children begin to locomote? The limited research directed to this question suggests that it does. In a study that resembled experiments with ants (Muller & Wehner, 1988), adults and children (aged 2.5 to 3.5 years) were blindfolded and then were walked on linear paths between a starting position and three other locations. Then they were walked from the starting position to one of the other positions and were encouraged to walk to a third position (Landau, Gleitman, & Spelke, 1981). Both the children and the adults performed this task with above-chance accuracy. Indeed, children were no less accurate on the new paths than on the paths on which they had been trained, suggesting that their errors stemmed from limitations on locomotor performance, not from errors in the dead-reckoning computation itself. Nevertheless, children's and adults' accuracy was not as high as that of ants, and further studies have revealed that errors in dead reckoning can be considerable (Loomis

et al., 1993; Newcombe, Huttenlocher, Drummey, & Wiley, 1997).⁵ Dead reckoning by adults is quite accurate, however, under certain conditions (e.g., Fukusima, Loomis, & Da Silva, in press).

Repeated testing of a congenitally blind child between the ages of 2.5 and 4 years revealed the same abilities found in sighted children and in other animals. After walking away from a single location on two linear paths, the child returned to that location on a more direct path. As in the case of ants, displacement experiments indicated that the child wandered helplessly and randomly when she was passively lifted and placed at a given location in the room (Landau, Spelke, & Gleitman, 1984). This finding provides evidence that the child's active navigation was not guided by detectable landmarks in the room, contrary to the suggestions of some investigators (Liben, 1988; Millar, 1994). Like sighted children and other animals, the child evidently represented the changing egocentric distances and directions of locations in the room as she locomoted actively. Human children's dead reckoning therefore can survive certain forms of perceptual deprivation. Nevertheless, not all blind people adeptly use this system of spatial representation (see Thinus-Blanc & Gaunet, 1997, for review). Because 2.5-year-old children have walked independently for well over a year, Landau's experiments were consistent with the possibility that locomotor experience underlies the development of dead reckoning.

Further research with younger children has addressed this possibility (Bremner, Knowles, & Andreasen, 1994; Keating, McKenzie, & Day, 1986; Lepecq & Lafaite, 1989; Rieser, 1979). Lepecq and Lafaite (1989) investigated the dead-reckoning abilities of 7- to 19-month old infants during

⁴ Although the dead-reckoning system appears to develop without trial-and-error learning during large-scale navigation, it remains possible that it is calibrated by experience gained during small-scale travels around the nest area (see McNaughton et al., 1994). In addition, perceptual experience may serve to calibrate the perceptual systems that give input to the dead-reckoning system, at least in some species. In humans, for example, perception of the distance and direction of one's locomotion can be altered through adaptation experiments in which the normal relation between forward locomotion and optical flow is changed (Rieser, 1990).

⁵ The experiments of Landau et al. (1981) and of Loomis et al. (1993) differed from that of Muller and Wehner (1988) in certain respects. In particular, Landau tested children's dead reckoning among four locations rather than three, in a situation in which no single location had the priority that the nest may be presumed to have for an ant. In addition, human subjects were tested in a situation lacking any clear perceptual cues to direction; ants rely heavily on directional information from the sun or wind in computing changes in direction and holding a course while returning home. Either of these differences may account for the lower accuracy of human performance. In particular, the absence of a perceptible directional signal may explain why children's paths in Landau et al.'s (1981) experiments were not straight (cf. Millar, 1988).

a continuous, passive rotation in a featureless, cylindrical environment. Children's ability to keep track of their displacement in this environment was inferred from their ability to turn their heads in the direction in which a visible and audible event had previously appeared. Beginning at 11 months, infants showed reliable head orientation in the appropriate direction, providing evidence that they were able to keep track of their own facing position despite the passive turning. Although younger infants failed this task, they have succeeded at similar tasks in more structured environments (e.g., McKenzie, Day, & Ihlen, 1984).

The findings described above have met with considerable skepticism among developmental psychologists, for they make no sense if one believes that spatial knowledge is wholly constructed as the child locomotes (Liben, 1988; Millar, 1994). From a comparative perspective, however, the conclusion that children represent their own position in space at the beginning of locomotion, and that they update this representation as they move around, is not improbable but expected. In the hunter-gatherer societies that existed throughout most of human evolution, our ancestors were central-place foragers, like ants and rodents, and could ill afford to become lost during their long travels from home in search of food. Comparative studies and evolutionary considerations therefore converge with developmental studies to suggest that humans are biologically predisposed to represent their changing position in the layout. This representational capacity emerges early in development, either synchronous with or in anticipation of the development of the navigation performance that it subserves.

As with all the other developmental phenomena that we have considered, the existence of an early-developing dead-reckoning system does not imply that this system is impervious to later experience. Indeed, studies in cognitive anthropology suggest that experience has considerable effect on the extent to which people rely on dead reckoning. Many adults in industrialized societies appear to maintain little or no sense of orientation as they travel, finding their way through the environment by memorizing routes or landmarks. In contrast, people who live in societies lacking maps, street signs, or extensive means of passive transport often rely strongly on dead reckoning to maintain their sense of where they are in relation to distant, significant locations, even when they travel in novel or relatively featureless environments (e.g., Gladwin, 1970; Levinson, *in press*; Lewis, 1976). Although a dead-reckoning system appears to be present in all people, the extent to which this

system is used may vary greatly, depending on one's culture and experience.

Reorienting

As we noted, dead reckoning is subject to cumulative errors. Birds and mammals correct errors in their reckoned position by drawing on representations of the environmental layout. Evidence both for dead reckoning and for reorientation in accord with the perceptible environment has been provided by research with hamsters (Etienne, 1987), which learned to find food by traveling from a home nest at the edge of a circular arena to the center of the arena, from which they carried the food back to the nest. On a series of test trials, the arena and nest were rotated after the animal's outward journey, so that the direction of home specified by dead reckoning conflicted with its direction within the environmental layout. When these test trials were given in darkness, the animals carried food in the direction specified by their own path of travel, guided by dead reckoning. When the rotation occurred in a lighted environment with a wealth of visual information for the nest's geocentric direction, the animals carried food in the direction specified by the visible environment. This finding suggests that visual information for the environmental layout served to recalibrate the animal's dead-reckoning.

Further experiments have revealed that rats reorient themselves in accord with the shape of the surrounding layout but not with its nongeometric properties (Cheng, 1986; Margules & Gallistel, 1988). If a rat is disoriented in a rectangular room with distinctive odors and patterns at each corner, it uses the shape of the room to reorient up to a 180° ambiguity, but it does not use smells or patterns in the room to resolve this ambiguity. Reorientation in accord with the shape of the environment is highly effective in natural settings, because this information is least likely to change over time. Although the locations of odors and the colors and textures of the terrain often are variable, the shape of the spatial layout—its hills, valleys, and ravines—remains constant through an animal's lifetime. A predisposition to reorient by geometry therefore may maximize the chance that animals will determine their position reliably.

Rats also reorient preferentially in accord with stable features of the environment. In experiments by Biegler and Morris (1993; see also Etienne, Lambert, Reverdin, & Teroni, 1993; Knierim, Kudrimoti, & McNaughton, 1995), rats searched for food that was buried in a chamber in a

constant geometric relation to two landmarks. In different conditions, the landmarks either occupied constant locations in the room or they moved together from trial to trial. Rats learned to find the food in the condition with stable landmarks. In the condition with movable landmarks, however, they learned to search near the landmarks but not at the correct location. Reorientation in accord with stable, geometric information also occurs in 12-day-old chicks, although chicks do not rely on geometric information as exclusively as do rats (Vallortigara, Zanforlin, & Pasti, 1990).

In light of these findings, we may ask whether humans also possess a system for reorienting in accord with the most stable, geometric information, and if so, how this system develops. Although considerations of evolution and ecology suggest that the system found in birds and rats might exist in humans, the experiences of many adults suggest otherwise. Adults in Western industrialized societies who are disoriented in a known environment (for example, upon emerging from a subway in a familiar city) may reorient by drawing on nongeometric information that no rat could use, such as the pattern on a building or the name on a street sign. Human adults therefore may reorient quite differently from adult birds and rats.

Studies of the development of reorientation in human children offer a resolution to these conflicting suggestions (Hermer & Spelke, 1994, 1996). Hermer investigated the reorientation processes of 18- to 24-month-old children in a situation much like that used with rats. The children watched a favored object being hidden in a corner of a rectangular room, then were disoriented by being lifted and turned with eyes covered, and finally were allowed to reorient and find the object. Children searched with high and equal frequency at the object's location and at the geometrically equivalent opposite location, despite the presence of nongeometric landmarks that distinguished these locations. Like rats, young children appear to possess a basic system for reorienting in accord with the shape of the environmental layout.

Although rats and children fail to reorient in accord with nongeometric information, experiments have shown that both rats and children detect, remember, and use nongeometric information for other purposes. For example, young children use the distinctive coloring and patterning of a container to locate a hidden object when the container moves, but they do not use the same properties to reorient themselves when the container is stable (Hermer & Spelke, 1996). These contrasting findings suggest that reorientation depends on a system that is task-specific (that is, it

functions only to guide reorientation) and informationally encapsulated (that is, it operates on a subset of the information that the child detects and remembers). Because task specificity and informational encapsulation are central features of modular systems (Fodor, 1983), these findings support Cheng and Gallistel's suggestion that reorientation depends on a "geometric module" (Cheng, 1986; Gallistel, 1990).

To date, research has not probed the developmental processes underlying the emergence of reorientation abilities in children or in other animals. Because the laboratory animals and American children in these studies have not spent their lives in outdoor environments where hills and valleys uniquely specify object positions, but rather in rectangular environments where many symmetries make geometry-based reorientation prone to error, it is likely that this process has been shaped more by evolutionary history than by learning. Nevertheless, such plausibility arguments are no substitute for research. Studies of precocial animals or dark-reared rats, parallel to Gibson and Walk's studies of the visual cliff, may shed significant light on this question.

Unlike rats and young children, human adults can use a nongeometric landmark to locate a hidden object in Hermer's tasks. Their superior performance suggests that some of the limitations of the child's reorientation system are overcome during development. Nevertheless, adults continue to reorient by geometric information, and their ability to do so may depend on a more basic, robust process than their ability to reorient by nongeometric information. Hermer, Spelke, and Nadel (1995) tested adults in a reorientation task while they engaged in a simultaneous interference task in which they attended continuously to a spoken text and repeated what they heard. These participants, like children and rats, reoriented in accord with the shape of the layout but not its nongeometric properties. A basic process for representing one's own position in relation to the stable shape of the layout appears to emerge by the age of 18 months, if not earlier, and to persist throughout human life. With development, however, children may overcome the central limitations of their encapsulated reorientation system.

Representing Object Locations

In addition to representing their own position in the environment, humans and other animals represent the positions of objects. Representations of object positions relative to

the self ("egocentric" representations) guide actions such as reaching, and representations of object positions relative to other objects or to the larger layout ("allocentric" representations) guide navigation and object localization from novel points of observation.

A large variety of birds and mammals use allocentric representations in preference to egocentric representations when they attempt to locate hidden objects. Perhaps the most striking demonstrations of allocentric representations come from studies of food-storing birds (see Krebs, Hilton, & Healy, 1990, for review). Observations and experiments reveal that such birds retrieve food that they previously buried in thousands of caches by drawing on memories of the locations of the caches relative to a geometric configuration of landmarks—a classic example of an allocentric representation (e.g., Vander Wall, 1982). In rats, the priority of allocentric over egocentric representations has been demonstrated in experiments that compared the animals' ability to learn to find a hidden object whose location was specified either allocentrically or egocentrically. One experiment (Sutherland & Dyck, 1984) was based on the finding that rats submerged in a cylindrical tank of water containing a hidden platform will seek to escape from the water by climbing on the platform (Morris, 1981). In different conditions of the experiment, the platform was hidden either at a constant allocentric position within the tank or at a constant egocentric position. Although rats quickly learned to find the platform when its allocentric position was stable, they were slower to learn to locate the egocentrically specified platform and never learned to swim to it directly. In this situation and others (e.g., Montgomery, 1952; Olton & Samuelson, 1976; Tolman, 1948), adult rats appear predisposed to represent object locations in allocentric coordinates.

Developmental experiments reveal that the ability to represent the allocentric position of a hidden object emerges at about the same time that rats begin actively to explore environments, at about 3 to 4 weeks of age. Exploration emerges quite abruptly at this time, suggesting that its emergence depends in part on a maturational change in the animals, possibly timed to the onset of weaning (Nadel, 1990).

Like rats, human infants represent both the egocentric and the allocentric positions of objects (e.g., Keating et al., 1986; McKenzie et al., 1984; Rieser, 1979). In experiments by McKenzie et al. (1984), for example, 6- and 8-month-old children learned to look toward a given allocentric location

from two different facing positions. When they were subsequently rotated to a novel facing position, the infants turned in a novel egocentric direction so as to look for the event at a constant allocentric position. When infants are trained to localize an object from just one starting position, however, their performance contrasts with that of rats and shows no preference for allocentric representations. For example, Acredolo (1978) trained 6-, 11-, and 16-month-old infants to anticipate, on hearing a bell, that a person would appear in a particular spatial location. When the children were turned to face in the opposite direction and the bell sounded, nearly all the youngest children looked in the familiar egocentric direction to a new allocentric position. Egocentric responding continued to occur at the older ages, although its frequency declined with age. This research suggests a developmental shift, over the first 2 years, from preferential reliance on egocentric spatial representations to preferential reliance on allocentric representations.

Numerous experiments have investigated the factors that influence young children's choice of reference systems (see Acredolo, 1990, for review and discussion). Egocentric behavior increases when children perform the same response repeatedly (Bremner & Bryant, 1977), move passively from one location to another (e.g., Acredolo, Adams, & Goodwin, 1984), or are tested in a symmetrical environment (Keating et al., 1986). A developmental increase in reliance on allocentric representations coincides with the onset of independent walking (Acredolo, 1990; Bertenthal, Campos, & Barrett, 1984) and is enhanced by experience in a walker (Bertenthal & Campos, 1990). Because prelocomotor infants already have the ability to form allocentric representations, however, this ability evidently does not depend wholly on the experiences children gain by moving actively through the layout.

Spatial Language

Language gives children the means to talk about space. Terms such as "left of" and "north of" capture the spatial relationship between two objects in egocentric and allocentric coordinates, respectively, and terms such as "in" and "on" capture such relationships in object-centered coordinates. It has been suggested that spatial language has universal properties, including a restricted vocabulary capturing qualitative relationships between the major axes of objects but ignoring spatial details of the objects or metric

properties of the spatial relation. For example, English has terms such as "across" and "near," but no language appears to have terms that might be translated as "across a cylindrical object" or "less than one inch away from an object" (Talmy, 1983; see also Bloom, Peterson, Nadel, & Garrett, 1996; Landau & Jackendoff, 1993). Despite these universals, languages also differ in the ways they capture certain spatial relationships, and some investigators have suggested that these differences influence a speaker's nonverbal spatial representations (Choi & Bowerman, 1991; Levinson, 1996). The latter claim resonates with empiricist theses, suggesting that spatial representations are changed by the experience of learning a language and therefore can differ across different cultures. Here, we focus on research supporting the empiricist perspective.

Consider first how languages represent the spatial relationship between two horizontally separated objects. In languages such as English, this relationship of one object to the other is described most often by the egocentric terms "left," "right," "front," and "back" (e.g., "The ball is in front of the tree"). In a number of languages indigenous to Australia, Central America, and Asia, in contrast, horizontal configurations of objects are described most often by geocentric terms similar to "north" and "east" (e.g., "The rock is south of the tree"; Levinson, 1996). As Levinson has pointed out, each of these systems has advantages and disadvantages. A compass-point system has the virtue of assigning invariant spatial terms to any objects whose positions do not change, irrespective of the viewpoints of speakers and listeners, and a left-right system has the virtue of assigning invariant terms to anything that moves with the reference object (e.g., "my left arm") (see Levelt, 1989, for further discussion).

Recent research by Levinson and his collaborators has shown that these differences affect how people remember and act on spatial relationships. When speakers of a compass-point language gesture, for example, their gestures tend to preserve geocentric directions of motion, whereas the gestures of speakers of left-right languages tend to preserve egocentric relations (Haviland, 1992). Speakers of the two kinds of languages also perform in systematically different ways when they must reproduce the positions of objects from novel viewpoints. Speakers of compass-point languages tend to perform such tasks by preserving compass-point relations, whereas speakers of egocentric languages like English tend to preserve egocentric directions (see Levinson,

1996, for review). Finally, speakers of a compass-point language may rely on dead reckoning more than speakers of a left-right language, maintaining their orientation in the absence of focused attention or strong perceptual support (Levinson, *in press*). Nevertheless, Levinson notes that speakers of both kinds of languages understand both sets of geometric relations. This observation suggests that the same representational abilities are present in all people, and that language highlights a subset of these representations.

A more radical effect of language on spatial representation has been suggested by Hermer (1994; see also Spelke & Tsivkin, *in press*), based on her studies of reorientation. Recall that young children reorient themselves only in accord with the stable, geometric properties of their surroundings, whereas adults rely on a wealth of nongeometric information. Hermer suggested that adults' more flexible performance may depend on the acquisition of spatial language, which provides a medium of representation in which information from distinct, encapsulated systems can be combined. When a child learns expressions such as "left of" by mapping words to a set of spatial representations, and terms such as "truck" by mapping words to a set of object representations, the child may gain the ability to conjoin these terms to create representations such as "left of the truck." These new representations, in turn, may guide the disoriented adult's search for objects. If Hermer's hypothesis is correct, then there may be a grain of truth to Berkeley's proposal that geometrical knowledge depends on language. The acquisition of a specific language may permit the development of certain new representations that conjoin information from initially modular systems. To date, however, no evidence bears directly on this hypothesis.

Although research on language and spatial representation has hardly begun, the above studies suggest a picture of the nature and development of spatial representation and of its universal and variable features across cultures (see especially Bloom et al., 1996; Bowerman & Levinson, *in press*). All people appear to be born with the same propensities to develop a set of representations of space: task-specific egocentric and allocentric representations that capture specific properties of the environment and that serve to locate the self or other objects. Spatial language has universal properties, both because of the universal properties of language itself and because children only learn words for spatial relationships that they can represent (Landau & Jackendoff, 1993; Talmy, 1983). Despite these

universals, each language captures only a subset of the spatial relationships that are represented by preverbal children. Where different languages capture different subsets of relations, speakers of those languages may differ in the prominence they assign to different spatial relations and in their abilities to represent conjunctions of spatial and non-spatial information. Communication between speakers of different languages initially may go awry as each interprets the behavior of the other in terms of the relations privileged by his or her own language. At bottom, however, all speakers build their representations of the environment from the same set of core systems.

Making and Understanding Maps and Models

The human species is unique not only in its ability to use language to represent space but also in its ability to construct and use maps and models of the environment. Like spatial language, children's use of maps develops gradually, well after they begin to navigate and represent the positions of themselves and of objects. Here, we discuss only one part of the large literature on the developing use of maps and other spatial representations; we focus on children's emerging understanding of these representations (see Liben, 1988, for a more complete review).

Experiments by DeLoache provide evidence for a striking developmental change in young children's understanding of scale models (see DeLoache & Burns, 1993, for review). Beginning at about 3 years of age, children are able to locate an object that is hidden in a room after viewing the corresponding location of a miniature replica of the object in a scale model of the room. Younger children do not benefit from a scale model in searching for an object. After watching the hiding of a miniature object in a scale model of a room, for example, young children find it much easier to find the miniature object hidden in the model than to find the real object hidden in the room (DeLoache, 1987).

Why do scale models pose difficulties for young children? One possibility is that geometric transformations, such as the change in size from a large room to a smaller-scale model, are problematic for children: Children may fail to detect the spatial relations that are invariant over these changes. A different possibility is that children detect the relevant geometric invariants but fail to understand that a model is a representation that provides information about the environment.

An ingenious study by DeLoache, Miller, Rosengren, and Bogart (1993; see also DeLoache, 1995) tested these two possibilities by presenting young children with a task whose solution required the detection of the same geometric invariants as in the scale model task but required no understanding of models as representations. Children were introduced to a machine that was said to make things smaller, and the shrinking machine's abilities were demonstrated on a toy. Then the children were shown a full-size room in which the toy was hidden, they were told that the machine would shrink the room and toy, and finally they were shown the scale model, which was described as the shrunk room. In these circumstances, children readily found the hidden object in the model. Because this task preserved the geometric component of the original task but removed the symbolic component (i.e., children were led to view the model as a transformation rather than a representation of the room), children's success suggests that their difficulty with models stems from limits on their understanding of representations, not limits on their sensitivity to geometric invariants.

DeLoache's experiment illustrates how studies addressing focused versions of the questions central to the nativist-empiricist dialogue, probing both the capacities that emerge as children begin to use maps successfully and the capacities that exist prior to this development, shed light on the nature of the processes by which children develop an understanding of spatial representations. Her research suggests that an understanding of representations undergoes developmental change in early childhood, but that an understanding of certain geometric transformations (similarity transformations in this case) predates this change. This finding opens the way to further study of the sources of older children's changing understanding and use of representations—a central ability that appears to separate humans from other animals.

Explicit Knowledge of Geometry

At the pinnacle of human spatial knowledge is explicit, storable knowledge of formal geometry. For most Western adults, this knowledge includes all the axioms and some of the theorems of three-dimensional Euclidean geometry, as well as some theorem-proving procedures from elementary logic. For some adults, knowledge extends to certain non-Euclidean geometries and higher-dimensional spaces. What are the sources of this knowledge: Does the 6-year-

old child, who is unable to prove the simplest theorem of Euclidean geometry, nevertheless have the intuition that certain theorems are true? How do students extend their geometrical intuitions over the development of formal geometrical reasoning, and what causes these changes?

The experiment by Socrates can be viewed as an attempt to answer these questions. Socrates' experiment was limited in scope, however, and few investigators have followed in his path (although see Piaget, Inhelder, & Szeminska, 1960). Here, we consider one recent extension of Socrates' experiment: an interview study of the geometrical intuitions of 6- and 7-year-old children who, like the young slave, had received no training in geometry (Silberstein & Spelke, 1995).

Children were asked a series of questions designed to elicit their intuitions about points and lines. First, they were shown a rough sketch of a line segment with one dot on it and one dot off to the side, and they were asked to imagine that the segment represented a small part of a straight line that went on and on without turning and that was so thin it had no thickness. Children also were asked to imagine that the dots on the paper represented points so small that they too had no thickness. Children younger than 6 years did not appear to understand these requests and interpreted the questions as pertaining to physical markings on paper.⁶ In contrast, 6- and 7-year-old children appeared to understand the requests and served as subjects in the full experiment.

Children first were asked a series of yes/no questions probing their intuitions about some of the central relations captured by Euclid's first four postulates. In accord with those postulates, children judged with near unanimity that two points could always be joined by a straight line, that three points sometimes could not, that many different straight lines could pass through a single point, and that only one line could pass through two distinct points. Children often paused and reflected before responding, but they answered with no prompting, no experimentation with objects or drawings, and no correction.

Because of the significance of Euclid's fifth postulate within the nativist-empiricist dialogue, further questions probed children's intuitions about parallel lines. Children were shown a sketch of two short, nonparallel, nonintersecting line segments, were told that each segment represented a

small part of a straight line of indefinite extent and no thickness, and were asked a series of questions about the extensions of these and other lines. Almost without exception, children judged that the two segments represented lines that would cross on the side where they were closer together, that some pairs of straight lines would never cross, and that no pairs of straight lines would cross more than once. Most children reported that if two lines never crossed and a third line crossed one of them, then it would cross the other line. Again, children typically reflected before answering these questions but then answered, with no prompting or further material aids, in accord with Euclid's fifth postulate.

In an additional part of the interview, children were asked questions about the behavior of lines on one type of non-Euclidean surface: a sphere. They were shown a ball on which a point and a line segment were roughly marked and were asked to imagine a line that continued on the spherical surface without turning. Then the children were asked the same questions about points and lines as for the line on the plane. (Note that in spherical geometry, many answers are different; in particular, all pairs of straight lines intersect twice.) About half the children were able to answer questions about lines on the sphere correctly, but they invariably manipulated the sphere and sometimes drew additional lines before answering. As Helmholtz would predict, children were able to gain knowledge of non-Euclidean spatial relationships by active manipulation of the sphere.⁷ In line with the expectations of nativists from Socrates to Kant, however, this knowledge did not arise as readily as knowledge of the behavior of lines on the Euclidean plane.

The findings of these studies support Socrates' conclusion that some geometric intuitions can be attained by children without instruction. At the time when children first begin to communicate about geometric objects such as points and lines, they already share a number of the intuitions that are at the core of Euclidean geometry. Contrary to Socrates' radical suggestion that all geometric knowledge inheres in the human mind, however, the studies suggest that only a subset of our culturally sanctioned geometric knowledge is present prior to the onset of formal training in mathematics. Interestingly, this subset appears

⁶Young children's failure may stem from their inability to distinguish material from immaterial entities (see Carey, 1991; Keil, 1979; Smith, Carey, and Wiser, 1985).

⁷This conclusion is not certain, however, for children may have considered the marks on the sphere as circles in three-dimensional Euclidean space, rather than as straight lines in two-dimensional spherical space.

to include all of the axioms and some of the key theorems of Euclidean geometry as it was first formalized.

Silberstein's studies raise many questions about the origins and development of formal geometric knowledge. For example, where do the earliest intuitions about points and lines come from: Do they arise from experience perceiving and imagining and spatial layout, from navigation, or from some other source? What changes occurring at about 6 years of age allow children to talk about abstract geometric objects for the first time, and what later changes allow them to develop ways of extending and testing their geometrical knowledge by proving theorems? How do children develop new conceptions about the properties of points and lines, such as the properties of lines on a sphere? Finally, how do children or adults go beyond their Euclidean intuitions and come to understand that these are not inevitably true? As in the case of locomotion, depth perception, and language, the discovery of initial knowledge within a given cognitive domain does not close off inquiry into developmental change but rather focuses such questions and raises new ones.

Developing Knowledge of Space: Themes and Suggestions

The varied phenomena comprising the development of spatial knowledge illustrate each of the principal themes that emerged from earlier sections of this chapter: Like action and perception, spatial representation depends in part on abilities that emerge in anticipation of their function, that are constant over human development, and that are shared by other species. Like the development of perception and language, the development of spatial cognition appears to depend partly on maturational processes and partly on experience. In addition, studies suggest that initial spatial knowledge is the product of a set of relatively separable cognitive systems, and that developmental processes allow children to transcend the limits of these systems. We focus here on two of these themes—phylogenetic continuity and cognitive modularity—because they run counter to prevalent conceptions of human cognition and cognitive development.

Phylogenetic Continuity and Ecological Adaptedness

Studies of the development of spatially oriented behaviors such as navigation, reorientation, and object localization suggest striking commonalities between the representational capacities of humans and other animals. Although only humans make maps, talk about space, or codify their knowledge

into axiomatic systems, spatial knowledge appears to build part on cognitive systems that other animals share. Unique human forms of spatial representation may arise not from some basic system possessed only by humans but from distinctive ways in which humans elaborate on the systems representation that they share with other animals.

We believe that evidence for common representation systems in humans and other animals should not be surprising, for two reasons. First, during human evolution, systems for representing the environment appear to have been subject to many of the same ecological demands as in other animals. Like ants, geese, and rats, for example, humans foraged by venturing from a persisting home, to which they needed to return. Second, human action systems and perceptual systems show deep homologies at all levels with those of other animals. In light of these homologies, it would be surprising if human and animal cognition should turn out to be built from radically different foundations.

Insofar as common representational systems exist in humans and other animals, studies of those systems can proceed in two directions. First, investigators can probe the cognitive capacities common to humans and other animals by bringing to bear a powerful array of converging tools—not only the tools of the cognitive psychologist and cognitive developmentalist, but also those of the behavioral ecologist and the neuroscientist. This convergence has led to striking progress in understanding of action and perception, and it is beginning to advance understanding of spatial cognition (see Gallistel, 1990; Krebs et al., 1990; McNaughton et al., 1995; O'Keefe & Nadel, 1978). Second, investigators can probe in more focused ways those aspects of spatial cognition that are unique to humans, by viewing our distinctive cognitive performance against a background of shared, phylogenetically older abilities. Like studies of locomotion and perception, studies of the representational capacities that are common to humans and other animals will allow investigators to define with greater clarity the ways in which human cognition goes beyond those capacities, yielding unique forms of reasoning.

Cognitive Modularity

Research on the development of spatial representation suggests that some early-developing systems of representation are task-specific and informationally encapsulated. The representations by which children reorient themselves, in particular, do not serve to relocate movable objects, and they capture only a subset of the information

about the environmental layout that children perceive and remember. Early in development, human cognition does not appear to depend on a single, general-purpose system for intelligent learning but rather on a collection of more special-purpose cognitive systems. This collection of systems may provide the building blocks for human intelligence and cognitive development (see also Cosmides & Tooby, 1994).

If human knowledge of space begins with a set of separable, task-specific, and encapsulated cognitive systems, the later development of spatial knowledge shows an openness and flexibility that modular systems lack. The discovery by mathematicians and physicists of the non-Euclidean structure of the universe testifies most dramatically to humans' cognitive flexibility, but all humans show this flexibility in mundane ways by reorienting in accord with nongeometric information, talking about space, and drawing maps. Human children and adults evidently move "beyond modularity" in spatial reasoning, and transcend the limits to initial systems of knowledge (Karmiloff-Smith, 1992).

At the time of this writing, research supports only the most tentative suggestions concerning the processes that underlie these developmental changes. (See Carey & Spelke, 1994; Karmiloff-Smith, 1992; Rozin, 1976; and Spelke & Tsivkin, *in press*, for examples.) Nevertheless, studies of the ways in which children overcome the limits on their initial systems of knowledge may hold a key to understanding the highest, uniquely human forms of cognition. The most distinctive aspects of human cognition may not lie in the core systems of knowledge with which we are endowed, but rather in the processes by which we extend these knowledge systems beyond their initial bounds. The human penchant for extending knowledge by combining distinct cognitive systems may distinguish humans from other primates most clearly (see Gibson & Ingold, 1993), and it even may be responsible for the rapid and multifaceted changes in human cultures that evidently occurred over the past 50,000 years (Mithen, 1996). As others have suggested (Gopnik & Meltzoff, *in press*; Karmiloff-Smith, 1992), research on cognitive development in children, grounded in an understanding of children's initial systems of knowledge, may provide insights into the nature of these processes.

PERSPECTIVES ON THE DIALOGUE

In each of the domains we have examined, research arising from the nativist-empiricist dialogue provided insights into

the sources of human knowledge. The outcomes of these inquiries are not always the same and indeed, we have selected these examples precisely because they shed somewhat different light on the questions of nativism and empiricism. Here, we briefly underline both the recurring and the unique points that we believe these examples offer.

Our current understanding of the development of action, perception, and spatial reasoning reveals several themes. In each of these arenas, human development appears to stem from a set of core capacities that emerge independently of experience and are constant over age and across species. In many cases, these early capacities appear to form the building blocks for later, more culturally specific skills. Although cognitive performance may change considerably over development in each of these domains, the striking continuity of the core abilities that underlie these changes suggests that biology plays a strong role in the growth of knowledge.

The development of language offers a somewhat different perspective on the same issues. Here, capacities are largely neither constant over age nor common across species; human communication systems are enormously different from those of other species and are acquired gradually, over a relatively lengthy period of human development. Nevertheless, the character of this species-specific and protracted acquisition process suggests additional ways in which innate propensities may emerge: through maturational processes, as well as through natively directed learning from experience. Innate capacities do not always appear in earliest development; as in the case of language acquisition, they may be revealed in remarkable capacities to learn, or even in the diminishing ability to learn over age. In this case, the relative independence of acquisition from striking variations in environmental input, the selectivity of what is learned, and the restriction of this learning to a maturationally significant period in development together provide evidence for an innate component to the developmental process.

Finally, research on perceptual development and language development offers particularly interesting examples of what the concept of innateness might mean. Shatz's (1992) elegant work on the development of neural connectivity in the visual system provides a case in which activity, and not genetic determination, shapes the course of development. The activity in question, however, is provided by processes internal to the organism, not by exposure to the visual world. This example demonstrates that nativism does not reduce to the more limited concept of genetic

specification of a developmental product, but rather includes a variety of internal mechanisms that predispose development in certain directions, independently of external experience. Similarly, the effects of spatiotopic fanning and hysteresis in models of object perception, Turkewitz and Kenny's (1982) hypothesis of the developmental consequences of early perceptual limitations, and Newport's expansion of this proposal in the "Less is more" hypothesis for language learning all provide examples illustrating that innate predispositions may include a wide range of possibilities—both direct stipulative mechanisms and indirect ones.

Taken together, we believe that recent research in these four domains, as well as many others, presents a rich and complex picture of what can be learned by pursuing questions of innateness and learning. Rather than stifling investigation into the nature of development, the nativist-empiricist dialogue has provided engrossing topics for the scientific study of human knowledge and its acquisition. In light of this progress, one might expect treatments of this dialogue to figure prominently in current discussions of human development. Contrary to this expectation, the nativist-empiricist dialogue has become nearly anathema in contemporary psychology.

Arguments against Nativism

In this section, we explore some of the reasons that are offered for rejecting this dialogue. Because most arguments against the dialogue have been directed against the nativist side, our discussion begins with arguments against nativism. We discuss six widely cited reasons for rejecting nativist claims in developmental psychology. According to these arguments, nativism is (a) conceptually incoherent, (b) empty, (c) unparsimonious, (d) false, (e) denying of human flexibility and potential, or (f) socially and politically dangerous. After examining these arguments and finding none of them compelling, we turn to positive reasons for pursuing research that is guided by the assumption that ground the nativist-empiricist dialogue.

Nativism Is Incoherent

It is commonly argued that both nativist and empiricist claims are incoherent, because all phenotypic characteristics, including the mechanisms underlying behavior, are products of genes and environment. There is no such thing as a genetically determined characteristic or behavior, be-

cause the genome is inert in the absence of an appropriate biochemical environment to activate particular genes in particular spatiotemporal patterns. All biological characteristics therefore depend on indissociable interactions between genes and their surroundings (see Elman et al., 1996; Lehrman, 1970; Oyama, 1985; Thelen & Smith, 1994).

Contrary to this argument, research on gene-environment interactions is irrelevant to the nativist-empiricist dialogue on one reading of the neurobiological findings, and it is supportive of the dialogue on a second reading. Gene-environment interactions are irrelevant to the questions at issue in the nativist-empiricist dialogue, because the dialogue is not about the role of genes in development but about the ways in which both intrinsic structure and a structured, external world shape mind and action. In asking whether knowledge of Euclidean geometry was present in the mind of an untutored youth, for example, Socrates was not asking whether such knowledge is encoded in the human genome but whether it arises in human beings without any shaping by their external environments—in particular, without instruction in geometry. In asking whether abilities to perceive depth, organize scenes into objects, or represent allocentric positions are innate, one is not asking whether these accomplishments depend on neural connections specified directly in the genes, but whether they are independent of learning that the external world is in fact a three-dimensional layout of solid, material bodies at enduring locations. Would a human infant with a normal course of fetal development, but born into a world with a different geometrical and causal structure, perceive and reason about objects and space in the ways that infants born into our world do? These questions are not undermined by studies of epigenetic interactions in morphological development.

Research on the development of ocular dominance columns provides a clear example of the separability of questions of genetic determination from those of innateness and learning. Neurobiological experiments suggest that central features of the organization of the visual cortex in newborn animals depend on spontaneously generated, spatiotemporal patterns of activity in the fetal visual system. Although the patterns of neural connections that result from this activity are not coded directly by the genes, they form without any shaping by the visual world. Insofar as these patterns of connectivity give rise to perception of depth and objects, this research suggests a neurobiological mechanism that could create perceptual abilities that are innate but not genetically determined.

Although the nativist-empiricist dialogue is not about the nature and limits of genetic determination, studies of the processes by which genes and gene products interact in development are relevant to the dialogue at a different level, and they suggest that the dialogue is a rich source of empirical hypotheses. Developmental neurobiologists have created exquisite techniques for teasing apart contributions of genes and their environment to development, from embryonic transplants (e.g., Constantine-Paton et al., 1990) to neural rewiring (e.g., Roe, Pallas, Kwon, & Sur, 1992). As these experiments unravel the epigenetic interactions giving rise to the development of particular phenotypic features, they return ever more precise answers to the question of how organisms of exquisite complexity come to be. Psychologists might well be heartened by the progress of this field and encouraged to probe, in our own distinctive ways, the contributions of intrinsic structure and environment to the development of cognition.

Nativism Is Empty

Perhaps the most common criticism of nativist theories by developmental psychologists is that such theories are not explanatory. The reasoning behind this dismissal can be illustrated by example. Suppose one wanted to understand how high school students come to appreciate that points on a line are infinitely dense: a geometric relationship that young children do not appear to grasp in their verbal reasoning (Piaget, Inhelder, Szeminska, 1960). A nativist would propose that this knowledge is wholly innate. The evidence for this proposal might be provided by studying young babies, devising ever more sensitive tests for their capacities, and finding that babies can answer every question about the infinite density of points on a line that successful high school students answer. In this scenario, however, the psychologist's work has not explained what knowledge of point density is or how students become able to answer questions about it.

This argument can be joined by a parallel argument that empiricist claims are not explanatory. Concerning the development of knowledge of point density, an empiricist might propose that this knowledge is wholly learned. Evidence for this proposal would be provided by devising ever more sensitive tests for learning in children, and finding that all the knowledge manifested by children of all ages results from the same set of learning processes. Again, the psychologist's work would not explain what knowledge of point density is or how it arises. The pure nativist and the pure empiricist can give names to a mystery—knowledge

of point density is a collection of "innate ideas" or "associations," and it arises through "evolution" or "learning"—but neither theorist can describe what students know, predict what further questions students will and will not answer, or explain how students came to have these particular conceptions and not others.

The problem with this argument is that it misconstrues the nativist-empiricist dialogue. The dialogue rests on the thesis that human knowledge is rooted partly in biology and partly in experience, and on the promise that successful explanations of the development of knowledge will come from attempts to tease these influences apart. Return for the last time to students of geometry and to the imaginary career of a third psychologist, working in the tradition of the nativist-empiricist dialogue. This psychologist attempts to disentangle the knowledge that students bring to the learning task from the knowledge they take from it. Studies of infants may reveal an innate system for representing approximate numerosity and exact small numbers (but not large ones), an innate system for representing lines and perceptibly separate points on those lines (but not the infinite density of such points), and a collection of propensities that allow children to learn language and other culture-specific symbolic systems. Further developmental studies may reveal that, as children learn counting, they come to bring some of the machinery in their language system to bear on their knowledge of numbers, generating representations of large numbers and the intuition that the natural numbers have no upper bound (Bloom, 1994; Spelke & Tsivkin, in press; Wynn, 1990). As children learn to represent points and lines with marks on paper or on a blackboard, the latter representations may become linked to the number system through the device of the number line, facilitating developing knowledge of fractions (Gelman, 1991). Finally, children's developing understanding of the density of fractions on a number line may give rise to an understanding of the density of points on the line (Carey & Spelke, 1994).

This speculative account roots knowledge of the infinite density of points on a line in a specific set of innate systems of knowledge, each of which constitutes a small part of mature knowledge of geometry, number, language, and symbols. The account proposes that these separate systems come to grow and change, giving rise to new knowledge, as they interact in specific ways. The account surely is false in detail, and it may be altogether wrong. Our point, however, is that it offers an explanation of the development of knowledge of point density which, if true, would reveal something

about what this knowledge is and how it arises. Accounts of development rooted in the nativist-empiricist dialogue both explain development and yield insight into the nature of developing knowledge.

Nativism Is Unparsimonious

Many developmental psychologists have suggested that the most parsimonious theories are those that provide the simplest account of the initial state of development (e.g., Fischer & Bidell, 1991; Thelen & Smith, 1994). Theories with a nativist component are unparsimonious, in this view, because the claim that the newborn infant is a blank slate will always be the most parsimonious claim *about the newborn infant*. Let us call this parsimony principle the "blank-slate assumption."

The blank-slate assumption does not reflect the traditional conception of parsimony in science. Parsimony is a measure that applies to theories as wholes, and the most parsimonious developmental theory provides the simplest account of the *development* of some capacity, not the simplest account of its initial state. A theory attributing minimal capacities to the newborn may not be more parsimonious than a theory attributing greater initial capacities, because all developmental theories need to arrive at same end state—mature knowledge. Indeed, theories offering more parsimonious accounts of the initial state of development may offer less parsimonious accounts of developmental change.

The last consideration suggests a different parsimony principle: If several theories account equally well for the same developmental phenomena, the more parsimonious theory is the one that posits the least amount of developmental change from infant to adult. As we noted, Pinker (1984) advanced this "continuity assumption" in the case of syntactic development, arguing that one should prefer characterizations of children's speech that accord with the grammatical categories of adults' speech in the absence of evidence to the contrary. The continuity assumption also has been urged by Banks and Shannon (1993), writing of the development of sensory processes such as mechanisms for coding color and spatial pattern. These authors consider the evidence for trichromacy in infant color vision, noting that infants' spatial acuity is too low for activity of one of the color channels to be detected by ordinary psychophysical methods. In the absence of evidence for this channel, they suggest, it is most plausible to assume that the channel is present in infants, because it is known to be present at

older ages. For these authors, the burden of proof in developmental theories falls on those who propose change. Insofar as the complexity of initial state descriptions and the complexity of descriptions of developmental change are inversely related, different researchers adhering to these two different parsimony principles will arrive at opposite conclusions from the same data.

We are wary of both the blank-slate and the continuity assumptions, and indeed of any conclusions about development based on burden-of-proof arguments. In a field as young as cognitive development, theories should stand on evidence, not on methodological arguments. This is especially true today, because developmental psychologists now have a wealth of tools for collecting such evidence. Once knowledge of specific developmental phenomena is rich and detailed, psychologists may need to confront questions of parsimony in distinguishing rival theories. At that time serious work will be needed to develop simplicity metrics for developmental theories, weaving an appropriate course between the blank-slate and the continuity assumptions so as to assess the parsimony of theories as wholes, not just their nativist or empiricist components.

Nativism Is False

Many accounts of research in cognitive development offered by textbooks and review chapters give the impression that experience has rich and manifold effects on development. Against a detailed portrait of the learning child, one is told about a few slender threads of evidence for initial knowledge and developmental continuity. Conclusions based on the latter evidence may be treated as uncertain (as they and all other conclusions are), as indicative of earlier learning processes (as they may be), or as local exceptions to the general principle that development is change driven by learning. According to this portrait, nativism is wholly or almost wholly false.

This portrait does not capture the current state of knowledge about development. The impression that development studies provide rich evidence for learning and meager evidence for initial knowledge stems, we believe, from two fundamental errors of interpretation of developmental data. The first error is based on a logical fallacy that pervades the study of development: In the absence of evidence for a capacity, investigators are apt to conclude that the capacity is absent. The second error is based on an unwarranted conclusion about developmental change: Learning often

claimed to produce developmental changes, and to underlie the emergence of new abilities, in situations where the only relevant data concern the fact that a change has occurred. When these errors are corrected, we believe a more accurate portrait of the current state of knowledge about cognitive development reveals evidence for innate and learned capacities in approximately equal measure, as well as vast areas where less is known than the standard portrait suggests.

In the history of developmental psychology, examples of the first error abound. The failure to observe visually guided reaching in infants below about 4 months of age, for example, was routinely taken as evidence that younger infants could not use vision to guide their reaching, until the experiments of Hofsten (1982) and Amiel-Tison (1985) showed otherwise. Similarly, the failure to observe differential responses by newborns to stimuli at different distances was taken as evidence that newborns failed to perceive depth, until evidence bearing on newborns' depth perception was collected (e.g., Slater, Morison, et al., 1990). As a last example, the failure to observe search for hidden objects in the spontaneous activities of infants below 8 or 9 months was taken as evidence that younger infants were incapable of acting on representations of objects, until infants' reaching was observed in the dark (e.g., Hood & Willats, 1986).

The fallacy of interpreting an *absence of evidence for a capacity* as *evidence for the absence of the capacity* can be seen in current discussions of the development of explicit memory. In the past 10 years, cognitive psychologists and neuroscientists have developed tools for probing explicit and implicit memory processes in normal and neurologically impaired adults. Although investigators disagree about the nature of the memory systems these tools reveal, there is growing evidence for some distinction between explicit, conscious memory on one hand and implicit, unconscious memory on the other (see Mandler, Ch. 6, Volume 2, for further discussion). Turning to the infant, memory capacities have been documented at early ages by a number of methods. Unfortunately, no one has yet found a way to adapt for infants the tasks that reveal explicit memory in adults (but see McKee & Squire, 1993, and McDonough, Mandler, McKee, & Squire, 1995, for an approach to these questions). Given this situation, one might expect accounts of the early development of memory to conclude that researchers do not know whether young infants are capable of explicit memory. Contrary to this expectation,

one frequently reads that young infants' performance reflects only implicit memory and knowledge.

The second error has been equally frequent. For example, the discovery of developmental changes in patterns of search for hidden objects was routinely interpreted as evidence for effects of experience on search skills, until studies of the development of object search in other vertebrates pointed to the importance of maturational factors (Diamond, 1990; Regolin et al., 1995b). Faced with evidence that sensitivity to a variety of Gestalt relations emerges late in infancy, Spelke (1990) concluded that sensitivity to these relations is learned as well, a conclusion that newer studies all but demolish (Johnson & Aslin, 1996; Regolin & Vallortigara, 1995).

These examples do not show that learning does not take place or cannot be studied. Before one interprets a developmental change as evidence for learning, however, one must tease apart effects of maturational change, exercise, motivation, and other factors on performance. Thelen's studies of stepping, kicking, and walking provide a model of how to do this and a background for studying diverse effects of experience on action. A second kind of evidence for learning comes from studies relating systematic variability in children's or adults' knowledge to systematic differences in their experiences. Studies of children learning different languages, of cultural differences in spatial memory, and of patterns of attention and spatial representation in children with different locomotor competence provide examples. A third kind of evidence comes from experiments in which the environment of a child or animal is systematically altered and the effects of the alteration are assessed or analyzed. Examples include studies of dark-reared cats on the visual cliff, or of students in accelerated science education programs.

If one accepts nativist or empiricist claims only on the basis of evidence, rejecting claims based on default assumptions, faulty logic, or experiments with inadequate controls for alternative explanations, how should one assess the current state of knowledge about cognitive development? We suggest that the development of knowledge does not appear to be sharply skewed toward either pole of the nativist-empiricist dialogue. Some evidence supports nativist claims, documenting capacities that emerge before they are needed under conditions in which alternative explanations of their development can be rejected. Some evidence supports empiricist claims, documenting capacities

that differ as a function of specific prior experiences, in ways that cannot be explained as effects of exercise, motivation, or other ancillary factors. Development is both constancy and change, invariance and variability, nature and nurture.

Nativism Denies Flexibility

It has been popular for some time to gloss nativist claims as claims about "constraints on learning" (e.g., Gelman, 1990; Keil, 1981; Spelke, 1990). The claim that children have innate knowledge of language is rephrased as the claim that they are constrained to learn as a primary language only a subset of the logically possible systems of symbolic communication. Similarly, the claim that children have innate knowledge of objects is rephrased as the claim that they are constrained to represent only certain kinds of entities behaving in certain ways.

These rephrasings tend to obscure two related features of human cognition. First, knowledge is always extendable. There appear to be no practical limits to the number of motor skills an athlete can command, the size of the vocabulary a speaker can attain, the number of faces or objects a perceiver can recognize, or the number of scientific theories a thinker can devise. Second, cognitive scientists posit innate cognitive structures in an effort to understand how humans come to know the things they do. The goal of explanation within the nativist-empiricist dialogue is to account for the development of human knowledge. The finding that certain logically possible actions, perceptions, or languages are not readily attained by humans is of interest only insofar as it sheds light on the actions, perceptions, and languages humans do attain. Nativist and empiricist claims are not denials or assertions of flexibility but ways of characterizing and accounting for the distinctive qualities of flexible human thought.

Research grounded in the nativist-empiricist dialogue, probing both the constant and the changing features of human cognition, helps to delineate the circumstances that will maximize flexibility and enhance development. That is why questions at the heart of the nativist-empiricist dialogue have long been considered, with justice, to be central to the development of effective programs of education (for example, see Carey, 1985; Gelman, 1991). Answers to the questions at issue between nativists and empiricists serve as signposts to educators, guiding the design of curricula that build on children's core cognitive capacities and use their existing knowledge to extend that knowledge.

Nativism Is Dangerous

"There are . . . social reasons to be wary about simple innatist interpretations. Scientific claims about the genetic origins of human intelligence and culture have often been misused to justify discriminatory social policies (Lewontin, Rose, & Kamin, 1984). Scientists therefore have a responsibility to proceed with great caution in developing and disseminating theories of this kind" (Fischer & Bidell, 1991, p. 202).

We are tempted by two responses to this argument. The first response is that the job of science is to discover what is true (Scarr, 1993). Science can serve society by providing information, not propaganda. Providing information, in turn, requires that scientists pose questions openly, without prejudice. Political concerns should not affect a scientist's evaluation of theories or evidence.

We are tempted, however, by a different response. Although investigators may aspire to provide information impartially, scientists cannot eliminate social and political considerations from their choice of questions to ask. The considerable energy and resources currently directed to understanding how children learn mathematics, or how children's thinking grows in different social environments, can be justified not only by the inherent interest of these questions but by the likely social benefits that their answers will provide. The renewed interest in measuring racial differences in IQ can be criticized not only because this research has no clear theoretical importance but also because it is unlikely to provide information of any social value to any pluralistic, nonracist society. If the study of constancy and change in cognitive development were devoid of social benefits and plagued by potential ill consequences, perhaps psychologists should stop asking these ancient questions.

A further reason for considering the larger social and political implications of research guided by the nativist-empiricist dialogue is that these considerations always have been prominent in the minds of the participants in the dialogue, and they explain in large part why scientists and laypeople alike find questions of nature and nurture so important. How different would our children and grandchildren be if we changed the society in which we and they lived? How different are people from one another, and how different are the thoughts and values of the members of different cultures, religions, or social groups? Stripping these questions from the nativist-empiricist

dialogue impoverishes that dialogue and deprives it of much of its interest. To accept these questions, however, is to accept the possibility that research addressed to the nativist-empiricist dialogue could have consequences beyond the community of scientists. What are those consequences?

First, we must be clear about one consequence that this research does *not* have: The findings of research on the nature and nurture of human knowledge have no implications for accounts of individual differences in knowledge or cognitive abilities. The claim that some body of knowledge is innate in the human species does not entail, or even suggest, that *differences* in knowledge and cognitive performance between different members of the species are innate as well. Individual differences in knowledge and cognitive processes may depend wholly on differences in the opportunities available to different people to elaborate on their common, biologically given knowledge systems. (This is close to our view of the matter.) Similarly, the claim that some body of knowledge is learned in the species is consistent with the thesis that individual differences in the extent of this learning stem from biologically based differences in learning capacities. (This seems to be the view of many modern investigators who argue for innate individual differences in intelligence.) For better or for worse, research such as that described in this chapter does not speak to debates over the sources of individual differences in cognitive performance.⁸

Nevertheless, research in the tradition of the nativist-empiricist dialogue does foster understanding of individual differences in intelligence in two indirect ways. First, insofar as basic research in cognitive development supports theories with a strong nativist component, providing evidence for elaborate systems of knowledge that are common to all people and constant over development, this research suggests that the differences between people detected by instruments such as IQ tests or college entrance examinations are unimportant. If all normally functioning people are endowed with the same rich and intricate systems of knowledge, then individual differences in cognitive performance likely reflect only minor variations in the ways these knowledge systems are elaborated or put to use (see Pinker, 1994). Second, as research in cognitive development in-

creasingly sheds light on the origins and growth of human knowledge, it allows educators and social planners to act more effectively to enhance people's abilities to deploy and extend their knowledge. In this way, studies in the nativist-empiricist tradition indirectly can change the very database of individual variation whose sources are being debated (see Block, 1979).

If evidence for innately coordinated actions, innate perceptions of depth, innate syntax, or innate knowledge of points and lines does not bear on claims about the genetic basis of human differences, does it have any implications for how one views human nature? In the final section of this chapter, we consider a possible implication of such research for how people view themselves and members of other cultures.

The Nativist-Empiricist Dialogue in a Multicultural World

How different are two people from different cultures, with different languages, religions, and social practices? Critics of the nativist-empiricist dialogue, as well as many other modern thinkers, conclude that this is a meaningless question. The universal and the variable can never be disentangled, and so one can never know how similar or unfathomably different the members of different cultures are. In this intellectual vacuum, many people have considered the obvious differences in the appearances and behavior of people in different cultures and concluded that the gulfs separating human beings are immense. Thus, a person of one religion may justify indifference toward those of a different religion because "They don't think of human life the way we do." Or, students may request a university living center open only to members of their culture "so that we can live with people who share our concepts and values." When we asked the authors of these statements to describe the differences in thoughts and values that separated them from others, their responses included a large measure of bewilderment, as if the differences were too great to express or understand.

In the best of times, the belief that the thoughts and values of the members of other religions, races, or cultures differ immeasurably from the thought and values of one's own ethnic group may lead to a patchwork of isolated, homogeneous societies—not a very interesting world. More often, this picture of human difference is more pernicious; always, it is a barrier to understanding others and oneself.

⁸Block (1995) discusses further reasons why the genetics-of-IQ debate is logically independent of the nativist-empiricist dialogue, centering on the distinction between nativist explanations and genetic explanations.

Research in the tradition of the nativist–empiricist dialogue suggests that the commonsense assumptions embodied in the above quotations and enshrined in the postmodern and multicultural intellectual movements are false. People from different cultures are not immeasurably, unfathomably different. Rather, people differ in specific, understandable ways. Beneath these differences, the knowledge, beliefs, and values of all people build on a common foundation.

There is no mystery to why the commonsense thinking of 20th-century humans favors the view that people of different cultures differ immeasurably, just as there is no mystery to why the commonsense thinking of 10th-century humans favored the view that the heavens rotate around a stationary earth. People from different cultures act differently on the surface. They utter different sounds so as to produce mutually incomprehensible languages. They eat different food, wear different clothing, and (at least until recently) listen to different music. They also go to different churches, marry different numbers of people under different sorts of arrangements, hold and transfer property differently, and abide by different and sometimes mutually incompatible conventions. Appearances favor the view that people differ profoundly, just as the appearance of the sky favors the view that the sun circles the earth.

Appearances can be misleading, however, and research once again has revealed that they are. People differ from one another in some ways and are the same in other ways. The universal foundations of human cognition provide a common ground on which the differences between people can be described, understood, and bridged.

Where nativist claims have been shown to be true, they illuminate the cognitive abilities that all humans share. By finding and clarifying this cognitive common ground, research in the nativist–empiricist tradition points the way to a set of bonds that unite people across cultures and give each person knowledge of all others. Because the abilities shared by all humans form much of the foundation for the abilities that distinguish us, the most divergent practices of people in different cultures are built largely on a common foundation. Culturally specific practices therefore reveal capacities that are to some degree latent in all humans, and an understanding of the practices of any group of people sheds light on the capacities of everyone. Linguists have appreciated this point for some time, for their research on languages such as Mandarin or Walpiri has served to reveal

previously obscure features of languages such as English. The same point applies to other cognitive abilities. For example, the Australian who travels great distances without map or compass, maintaining with exquisite accuracy a sense of his own changing position, exhibits a capacity for dead reckoning that all humans possess, although many of us make little explicit use of it. In the context of the nativist–empiricist dialogue, human universals and human differences are mutually illuminating, and contact with people from different cultures sheds light on one's own culture and cognition.

Where empiricist claims have been shown to be true, we have reason to believe that people in different cultures could genuinely differ. Research in the tradition of the nativist–empiricist dialogue enables us to discover what those differences are, what has produced them, and what, in principle, would change the conceptions that flourish in one's own culture into conceptions that flourish elsewhere. Despite Americans' predilection for "left" and "right," for example, Americans can understand what Mayan villagers mean when they speak of "the house to the north of the village" and can even understand the advantages of the Mayan terms. The differences between members of different cultures are not unfathomable but rather are describable and explainable in terms of differing experiences of quite specific kinds. These differences can be bridged—always in principle and sometimes in practice—because the members of a different culture are oneself as one would have been, had one's parents made the sound contrasts of their language, or described object positions with respect to the compass points. Describing and demystifying cultural differences do not deny or deprecate those differences. It does become harder to argue, however, that the differences are worth killing and dying for.

Because this is a landmark handbook, appearing on the cusp of the third millennium and calling on its authors to attempt, in a necessarily myopic way, to chart a course for future research, we close by indulging our imaginations and offering a vision for the study of human development. We envisage a developmental psychology that acknowledges, with respect and humility, an intellectual tradition that extends back to the beginning of recorded human inquiry. In this field, questions about the inherent and the acquired, the inevitable and the coincidental, the constant and the changeable, the universal and the variable, are asked openly and are answered not by prejudice or preconception but by evi-

dence. We envisage a flowering of that evidence, as developmental psychologists use the tools already at their disposal to address the questions raised by the nativist-empiricist dialogue, and as the answers they receive open the way to new and better methods for pursuing the next generation of questions. In our vision, advances in developmental psychology will occur in concert with advances in the allied disciplines of biology, cognitive science, and anthropology, so that a panoply of methods and perspectives can shed converging light on human nature and human knowledge. Finally, we envisage a developmental psychology whose findings lead future generations of people to look back on the conceptions that have fueled the ethnic, cultural, and religious conflicts that are closing the second millennium and to say what we now say about the conceptions of the heavens that closed the first: These ideas seemed reasonable at the time, but science has shown that they are wrong, and so has opened new worlds of progress.

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