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development of perception in infancy

THE CRADLE OF KNOWLEDGE REVISITED

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DEVELOPMENT OF PERCEPTION IN INFANCY

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Preface

In 1998, we published *The Cradle of Knowledge: Development of Perception in Infancy*. In that book, we drew on infant perception research to evaluate a number of philosophical issues regarding perception and the origins of knowledge. We discovered a great deal about the early capacities of young infants, and we were able to clarify some age-old questions. At the same time, many questions remained unanswered. Our goal for this book is to revisit these philosophical issues and outstanding questions more than 15 years later. As will be shown, many advances have been made in the intervening years. Moreover, new areas of inquiry have been tackled. At this juncture, we see the field standing firmly on an understanding of the basic capacities of infants at different ages (e.g., acuity, motion detection, and intermodal perception) and asking what infants do with this information—perceive people, objects, and events.

Our treatment this time is much the same as before. We first introduce each topic from philosophical and historical perspectives, and then we evaluate each issue relying on research with infants. When possible, we address mechanisms of change, in addition to describing what infants can do when. Our theoretical perspective continues to be informed by the work of J. J. and E. J. Gibson. From such a perspective, we focus on the information available for perception, when it is used by the developing infant, the fit between infant capabilities and environmental demands, and the role of perceptual learning.

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Introduction

More than three centuries ago, the philosopher John Locke (1690/1971) recounted the query he received from his friend William Molyneux:

> Suppose a man born blind, and now adult, and taught by his touch to distinguish between a cube and a sphere .... Suppose the cube and sphere placed on a table and the blind man to be made to see: ... [could he] by his sight, before he touched them ... distinguish and tell which is the globe, which the cube? (pp. 121–122)

Locke and Molyneux answered in the negative. In their view, only by learning to interpret the sensation of vision and associating them with touch could visual sensations become connected to a notion such as *form*.

How we obtain knowledge through the senses has long intrigued philosophers and scientists. Many have sought to understand the nature of perception by asking how it begins, and their answers have anchored conceptions of human nature and formed the foundations of theories of knowledge.

It is striking that Molyneux posed his question about what untutored perception might be capable of in reference to an *adult*. Given that the experiment was imaginary, why not ask about perceptual responses un-influenced by a lifetime of thinking and learning; why not ask about a human infant? Apparently, the idea of assessing perception in the helpless human infant was considered too far-fetched even for thought experiments. In this regard, not much had changed in 1947 when Austin Riesen wrote, "The study of innate visual organization in man is not open to direct observation during early infancy, since a young baby is too helpless to respond differentially to visual excitation" (p. 107).

The study of human perceptual development turned out to be possible after all. Researchers have discovered windows into the human infant's perceptual world. Although unable to speak, point, or locomote, even newborn infants respond in subtle ways that reveal aspects of their sensory and perceptual experiences. Through diverse and often ingenious efforts, researchers have exploited these responses to reveal perceptual competence, test hypotheses about processes, and infer neural mechanisms. Some of the answers they have uncovered would have surprised Lock and Molyneux, as they have surprised modern researchers.

Why do we care about how perception develops? The reasons are those that have kept these questions in the forefront of intellectual debate for centuries.

The beginnings and workings of perceptual knowledge bear on fundamental questions of both epistemology and psychology: What links ideas in our minds to external reality? Are perceptual processes that connect the mind to the world inherent in the mind or are they constructions from experience? Today, we know these questions unfold at several interacting levels. How does energy carry information and how can it be extracted by perceptual systems? To what extent has sensitivity to structured information, and the neural circuitry that carries out perception, developed through the evolution of perceptual systems, and how much does perception become organized through experiences of the individual? Do the basic processes of perception differ across individuals depending on their personal histories?

It is sometimes argued that questions of nativism versus empiricism are misguided—that all development is an interaction between organism and environment. Perceiving organisms must of course eat and breathe, and their perceptual systems will deteriorate if not stimulated. These interactions with the environment, however, do not answer questions of whether organisms come equipped innately or maturationally to pick up information and represent their environments in meaningful ways. The study of perceptual development can and, as we will see, often has answered such questions.

We also care about perception as a prerequisite to understanding other aspects of human cognitive and social development. The developing infant's interactions with the physical and social worlds are both enabled and constrained by what can be perceived. What has recently been learned about perception, we suggest, requires a new account of development. The discovery that human beings begin the path of development at quite a different place than previously suspected has many consequences.

Finally, the study of perceptual development sheds light on the character of perception itself and its place in the mind. Early in the 20th century, the Gestalt psychologists contended that relationships are most important in perceiving and that intrinsic mechanisms in the nervous system respond to these. Still today, this lesson is not fully appreciated. Students of cognitive science, neuroscience, and psychology often think in terms of sensation (or basic filtering of stimulus energy attributes) and cognition—general inferential processes that "recognize" or "make sense of" sensory inputs. However, a wealth of evidence points toward autonomous perceptual mechanisms that stand between sensation and cognition. More than half of the cerebral cortex appears to be dedicated to perceptual information processing. This massive allocation of brainpower may serve primarily to extract stimulus relationships and produce abstract, meaningful descriptions of reality. There may be no better way to acquire an appreciation of the character and function of perception than by studying its development.

In writing this book, we have stayed close to the methods and data of scientific research on infant perception. A simpler and neater story could have been told with fewer details; no doubt such a story would have better suited some purposes.

On the other hand, the story of infant perception research is one in which experimental findings are replacing centuries of conjecture about the origins of the mind. Like conjecture, interpretation of data has pitfalls, and these are not easy to prevent or remedy without keeping in view the methods and results on which conclusions and generalizations depend.

1 Views of Perception and Perceptual Development

INTRODUCTION

Perception forms the portal between reality and knowledge. It is the gateway through which matter and energy in the physical world lead to ideas in the mind. An enigmatic bridge, it appears as biological activity from one end and conscious awareness from the other. In the theater of the mind, it is the opening scene.

In giving us contact with the world, human perception is proficient and unobtrusive. The world simply appears to be there, in all its dimensions and detail, from even a brief glance. To walk, we place our feet on some surface whose location and solidity are obvious. To grasp, we reach to where an object is located. We turn toward a speaker, knowing before turning where and often who the speaker is. The accuracy and transparency of perception mislead the casual observer, and sometimes the expert, into thinking that knowing through the senses is uncomplicated.

In the development of the individual, perception is pivotal. Learning about the physical and social worlds and acquiring language rely on the products of perception. To the extent perceptual ability is lacking at the beginning of life, these tasks must be postponed. Developing perception becomes the central task of early development, as many theorists have suggested (e.g., Piaget, 1954).

In seeking to understand perceptual development, we encounter several key questions. How does perception get started? It is easy to demonstrate that the senses function from birth. But do they reveal a world of objects, situations, and events? Or do they serve up at first only the "blooming, buzzing confusion" suggested by William James (1890)? When perceptual knowledge is attained, how does the process work? To explain how a quantum of light absorbed by a photoreceptor in the eye initiates an electrical signal in the nervous system involves many complexities. Equally mysterious, however, are processes that determine from many rays of light—each carrying no information about how far it has traveled—the position, size, and shape of an object several hundred feet away. Moreover, perceptual abilities are not static; they change with development and experience. Which of these changes depend on simple growth or the maturation of new mechanisms, and which depend on learning to interpret the inputs to the senses or acquiring skill in selecting information? How do perceptual changes cause and result from changes in other cognitive and motor abilities? To begin to pose such questions, we need first to consider the character and function of perception.

ASPECTS OF PERCEPTION

One reason the study of perception is so fascinating and complex is that it involves questions of fundamentally different kinds. We can discover these different aspects by considering almost any perceptual phenomenon and asking what needs to be explained.

Issues of Representation and Process

Consider the display in Figure 1.1A. We see five objects varying in shape and color. The same five areas are rearranged in Figure 1.1B. Now things look different. We notice three objects, not five, and the objects have acquired some interesting qualities and relationships. The circle on the left has become translucent; we can see part of another object through it. The circle on the right is pierced by the middle object. The middle object is seen as a whole despite having two visible parts separated by a gap on the right and a differently colored part on the left.

This example illustrates that perceptual experience is not a simple inventory of stimulus inputs. Both Figure 1.1A and Figure 1.1B may be straightforwardly described as containing five regions of certain colors at certain positions on a flat surface. Indeed, this is exactly the type of description used by the computer on which the displays were created to send instructions to the printer. There is no depth, nothing transparent, and no interpenetrating objects. Your perceptual system handles these inputs very differently, mapping the five simple regions into three objects, one of which is translucent and one pierced by another.

In this example, the transformations between the stimulus inputs and what is perceived depend on relationships in the stimulus. As the Gestalt psychologists argued long ago, perception is not merely a response to local stimuli; it depends on *patterns* in space and time. A crucial part of the task of understanding perception is finding out what dimensions, features, and relationships we extract from the inputs. We seek to determine how these are represented and what further processing is required to produce the objects, scenes, and events of our experience. These questions address the level of *representation and process* in the study of perception.

We might set out to study perception in the infant or the adult with this goal alone. By manipulating stimulus inputs and measuring what is perceived, we can obtain data allowing us to build theories about perceptual processes. This task is central but not sufficient. One limitation is that in pursuing this task alone, we would end up with a catalog of curiosities. On receiving stimulus pattern *a*, the visual system engages processes *b* and *c*, leading to our perceiving *d*. We would lack a deeper understanding of our catalog of transformations. We could say nothing of why a visual system should take pattern *a* and end up with percept *d*.

Issues of Ecology

Let us look again at Figure 1.1. It is remarkable that this arrangement of color patches on a piece of paper should evoke the perception of one object passing through another, or five patches making three objects. But consider the following: If three

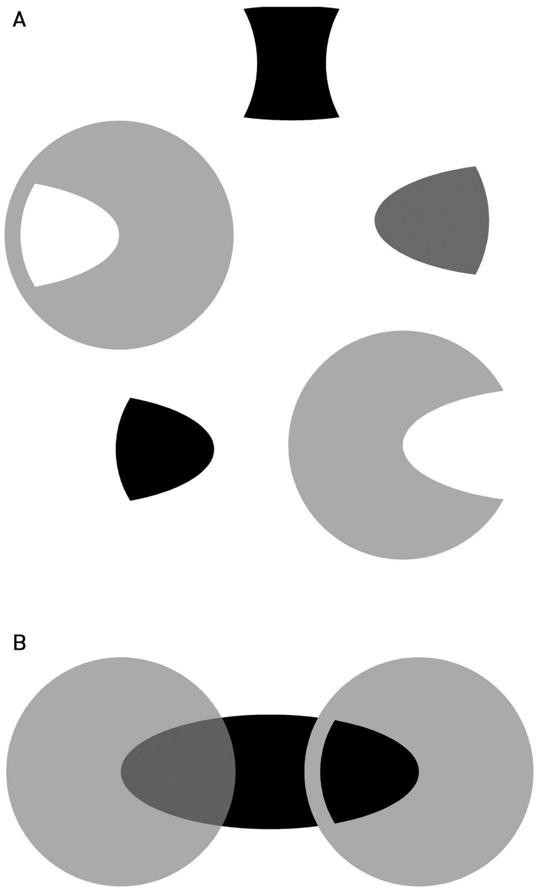

FIGURE 1.1
Organization in perception. The five visible areas in part A appear as three perceived objects in part B. Source: Created by P. J. Kellman.

objects were positioned in space in the proper way, and if one were translucent, then the projection to the eyes could be the same as what we get from the picture. Where one object passed behind the translucent one, that part of the display would appear different in surface lightness, whereas its boundaries maintained their continuity with those not covered by the translucent object. In other words, the percepts rendered by the visual system are physically plausible—that is, they could be caused by a suitable physical arrangement in the world, given the laws of optics.

A stronger claim can be made. The technology for placing precise arrangements of ink on paper is a relatively recent human invention. In the natural world, the one in which animals evolved over millions of years, if your eyes received the patterns in Figure 1.1, you would almost certainly be confronting an arrangement of a translucent object and two others—the scene your visual system says is there. To make such a claim, we need to know a great deal about the ecology—about what goes on in the physical world and how it produces patterns of light sent to our eyes. Stated informally, it would be very improbable for five separate physical objects to come together in such a way that their boundaries displayed the continuity we see in Figure 1.1. Moreover, certain lightness relations in the scene are exactly right for a translucent surface, and certain positional relations are exactly right for one object penetrating another, but these relations would be quite coincidental otherwise.

We now see that our understanding of perception must involve—in fact, must begin with—the study of the world to be perceived. We call this the *level of ecology* in the study of perception. Although sensation and perception have been studied systematically for several hundred years, a clear understanding of the importance of this level has emerged only in the latter part of the 20th century (Gibson, 1950, 1966, 1979). The first stop on the road to understanding perception is a rigorous analysis of the *task* of perception—what is to be perceived—and the ways in which environments make *information* available to accomplish the task.

Issues of Biological Mechanism

To capture, represent, and transform information requires mechanisms of considerable complexity. How does perceptual processing take place in the nervous system? This is the question of the level of *biological mechanism*. When we consider nonbiological information-processing systems (machines) along with biological ones, we might prefer Marr's (1982) label—the *level of hardware implementation*. In some ways, this level requires the least introduction. Everyone knows that to understand vision, for example, we need to know about the retina, about rods and cones, and about where optic nerve fibers project in the brain. If one develops a vision problem, the facts of biological mechanism are most relevant to its causes and treatment.

Although we may speak of this level as a single category, it encompasses various levels of its own. Each sense involves specialized receptors and associated neural mechanisms designed to bring to the receptors a particular form of energy from the outside world. In vision, for example, the lens and cornea refract incoming light rays onto the retina, and several different muscle groups allow the eyes to be pointed, focused, and converged, to optimize the pickup of information. Beyond the receptors, neural structures are wired to register key features in energy patterns; these in turn feed into various neural streams specialized for extraction of higher-order information. Still other neural mechanisms must integrate information from different processing streams and different senses to produce our coherent experience of objects and events.

MULTIPLE LEVELS IN THE STUDY OF PERCEPTION

We have now introduced three levels important in understanding perception—the level of *ecology*, the level of *representation and process*, and the level of *biological mechanism*. Table 1.1 indicates the kinds of questions asked at each level. In this section, we take a closer look at each level to sharpen the issues within and between levels that guide our study of infant perception.

Table 1.1 Three Levels of Analysis in the Study of Perception

Level of Ecology	*Level of Representation and Process*	*Level of Biological Mechanism*
What is the perceptual task? What information is available for perceiving? What constraints simplify the task?	How is information extracted? How is information represented? What computations are performed?	What biological mechanisms accomplish the extraction, representation, and processing of visual information?

The Level of Ecology

What are the tasks of perception, and what information is available to do these tasks? Gibson (1966, 1979) noted the central importance of these questions and argued that answering them requires study of the way environments interact with energy to provide information. In vision, he called this enterprise *ecological optics.* The term *ecological* designates facts at a level relevant to perceiving organisms. Not every fact about the physical environment is relevant. We are concerned with the physical world within certain spatial and temporal ranges. In spatial terms, our concerns lie primarily between approximately one-tenth of a millimeter and 10,000 meters. In this range, the texture and topography of surfaces and the shapes and sizes of objects are relevant to our activities. At one end of this range, we may be concerned with minute variations that make a surface rough or smooth or with tiny markings on visible surfaces. At the other end, we can set and maintain a course with reference to distant mountains. The physical distances between stars and the distances between molecules, in contrast, may be preconditions for our existence but are not ecologically relevant for guiding behavior. Our perceptual concerns are likewise confined in time. Organisms may apprehend and react to changes or events in the environment unfolding in milliseconds or hours but not to those occurring in nanoseconds or centuries.

Within these ranges, what sorts of information about the physical world are important? Complex perceptual systems belong exclusively to mobile organisms, and we can understand much about perceptual function from that simple fact. In the first place, the task of moving through the environment requires selectivity and guidance. We need to know about surfaces of support in the world, about footholds and drop-offs, and about obstacles and passageways. To maintain posture and balance as we locomote, we need ongoing information about our own position relative to surfaces of support and to gravity. Next, there are the aspects of the physical world—including objects, events, and the spatial layout—that we need to apprehend if we are to do anything useful by moving. Objects, which are coherent, bounded, material units, often are inanimate, such as rocks, plates, and pillows. Many of their properties are important to our interactions with them, including their forms, sizes, rigidity, and composition. Other entities we perceive, such as people, cats, and spiders, are animate and may pose danger or provide protection, comfort, and companionship. With those of our own species, it is important that we perceive emotion, demeanor, action, and intention, as well as spoken language. Analogous to the boundaries in space that specify surfaces and objects, we perceive *events*—sequences of motion or change that are in some sense coherent and separate from other goings on.

This brief description of the subset of the physical world relevant to perception is illustrative, not exhaustive. Certain ways of thinking about perception lead to the possibility that its full scope is surprisingly wide. Besides surfaces, objects, people, and events, connections among physical events—causality—and among social ones—social intention—might be detected by perceptual mechanisms rather than constructed from learning about the world. After understanding more about perception and its development, we will be in a better position to consider these possibilities.

Ecology and Information

What about the *optics* in *ecological optics*? Information, like objects and events, must be appropriate to spatial and temporal scale. Thus, Gibson argued that ecological optics is not fundamentally concerned with trackings of single rays of light or the absorption of quanta by molecules emphasized in traditional geometric and physical optics. Instead, we attempt to identify information produced by interactions of volumes of light with objects and surfaces at a scale relevant to perceiving organisms.

Marr (1982) emphasized the need for formal *computational* accounts at this level. How can the objects and events of the physical world be determined mathematically from informational variables available to the perceiver? Often, obtaining a unique and accurate answer requires the use of *constraints.* A constraint is an assumption about the way the world works that may be incorporated into perceptual computations to restrict their possible outcomes. The most powerful constraints derive from general and enduring features of our physical world. For example, objects in our world have spatiotemporal continuity. In order to move from one place to another, they must pass through positions in between. Objects do not appear at one place, vanish, and materialize some distance away. A perceptual system that incorporates this premise will exclude percepts of discontinuous objects that would otherwise be compatible with available information.

As another example, consider perception of object size. What information is there for perceiving size? The projection of a viewed object takes up a certain portion of our field of view; we call this *projective size* or *visual angle*. Projective size is a poor guide to physical size because it varies with viewing distance. However, there is an invariant relation between physical size, projective size, and distance: The ratio formed by the object's real size and its distance is the tangent of the visual angle. Figure 1.2 illustrates. The projection of the object onto the eye can be obtained by drawing straight lines from points on the object through the nodal point[1] of the eye to the retina. If distance can be registered, a perceptual processor

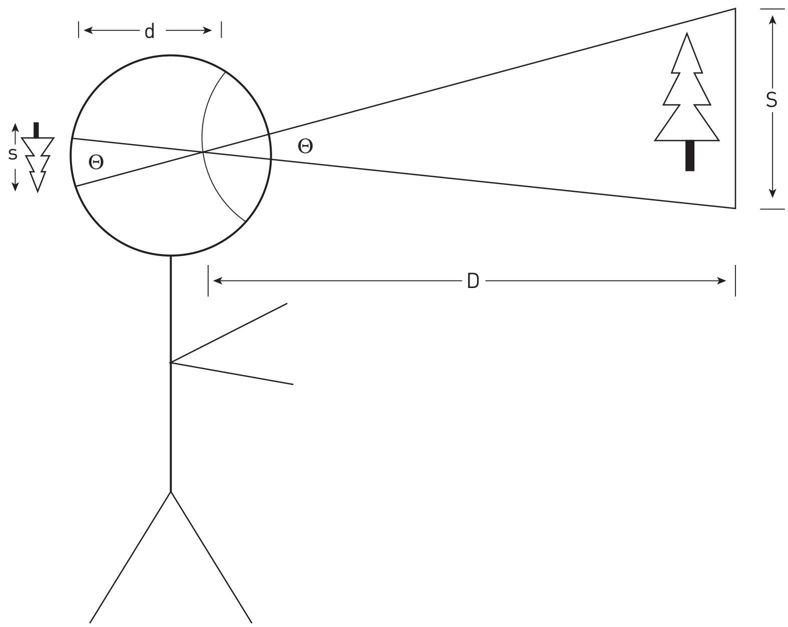

FIGURE 1.2
Size and distance relations. *S* is the real object size, *D* is its distance from the observer, *s* is the projected size at the retina, *d* is the distance from the nodal point of the eye to the retinal surface, and Θ is the visual angle projected by the object. The inverted tree to the left of the eye depicts the retinal image. Source: Created by P. J. Kellman.

that incorporates this relationship can compute a real size from visual angle, available at the eye of the observer, and register distance. This mathematical relationship concerning size and distance is a fact about the world in which we live—that is, a fact about optics and projective geometry. An important part of the study of perception is to determine when such relationships are incorporated as constraints in perceptual processing. Such constraints may be inborn or maturational, presumably resulting from evolution under consistent conditions (Gibson, 1966; Johansson, 1970; Shepard, 1984). On the other hand, some theorists have suggested that constraints may be discovered through learning by the individual (Goldstone, 2003; Helmholtz, 1885/1965; Wallach & O'Leary, 1982).

This example of size perception can be extended to illustrate the importance of thorough ecological analysis. Although it was long believed that physical size could be recovered perceptually only by using distance information, Gibson (1950) noted a relational variable that offers size information without using distance. On a textured surface whose texture elements are relatively uniform in size, the visual array projected to the eye contains a *texture gradient*. The projective sizes of texture elements decrease as the surface extends father away from the observer. Gibson noted that an object resting on a textured surface will occlude the same number of texture elements no matter what its distance. Object size, then, might be perceived in relation to texture element size. Seeing two objects at different distances as being the same size might not require using equations about size and distance; rather, they can be directly compared to the texture elements at their location.

The relation between projective size and distance applies equally to viewed surface texture and viewed objects, allowing us to obtain size by their relation without using distance information. The usefulness of this relation also depends on the fact that, due to gravity, most objects in our environment rest on ground surfaces.

The example underscores the primacy of the level of ecology in understanding perception. Many advances in understanding perception have come from the discovery of stimulus relationships (e.g., decreasing texture size with distance) that provide more direct information about some physical property (e.g., depth) than do simple variables. If we have limited or misleading notions about information, we may not understand what is detected and computed by perceptual systems. Even where many details are known about the neurophysiology of perceptual systems, an understanding of which details are relevant and what brain mechanisms need to extract and compute depends on a clear ecological or computational account of perception.

The Energy World

We have thus far said little about the role of *energy* in sensation and perception. In terms of function or tasks, we have emphasized not perception of energy, such as seeing light, but perception of physical structure, such as objects and surfaces. In terms of means, we have emphasized the pick-up of information. But how does information become available? We are able to perceive only because the material environment around us is awash with energy. We are constantly immersed in seas of acoustic vibrations, electromagnetic waves, chemical and temperature gradients, and much more. Only some of this energy is available to our senses. It is sobering to realize that while standing in your living room, thousands of cellular telephone calls, air traffic control transmissions, commercial radio and television broadcasts, and wireless Internet traffic are passing undetected through your body.

Energy links the physical world of material structures and events to the perceptual world in which objects and events are represented. We see a table not by direct contact but by means of the light it reflects. Due to the evolution of specialized systems for receiving them, we are sensitive to certain forms and ranges of energy.

There is no question that perception begins with energy interactions at sensory receptors. This first step, however, has given rise to many misconceptions about perception. One is that we can understand perception by understanding local responses to energy. Another misconception is that what we *perceive* is energy. Perceiving properties of energy is in fact a means, not an end. Perception informs us more about matter than energy, by means of patterns in ambient energy. In the final outputs of perception—what we experience or represent—our knowledge about energy per se is generally poor. For example, in a lighted room, we perceive the layout of surfaces of varied reflectance, but we have little or no sense of how much light, in absolute terms, comes to the eye from each surface (Gilchrist, Delman, & Jacobsen, 1983).

It is so intuitive that what we hear is sound and what we see is light that to suggest otherwise may be shocking. But these notions are arbitrary, as we can readily grasp by thinking about the casual chains involved in perception. Consider the following: Causal interactions of objects with light send patterns of light to the eyes. A pattern of light as it hits the retina is the last step in the causal sequence of sight that lies in the physical world, *outside* of our biology. Perhaps this fact underlies the idea that what we see is light. But the causal chain continues. Light goes no further into the nervous system than the retina, where it gives rise to electrical signals. Significantly, no one would claim that seeing occurs in the retina; it occurs in the brain. The light is left behind as subsequent electrical events take place en route to later destinations in the nervous system, where perceptual representations and conscious experiences are produced. In this causal chain from objects to light patterns to electrical signals to perception, what should lead us to single out light as the thing that is perceived? It makes no more sense to say we see light than that we see electrical signals in the retina.

The causal chain of perception carries information about all of the steps. Patterns of cortical activity contain information about light patterns *and* about retinal electrical patterns *and* about objects in the world. Singling out one of these as what we perceive is arbitrary, except on functional grounds. In the use and evolution of these causal sequences in biological systems, the important properties extracted are usually far along the causal chain: objects, spatial layout, and events. Sometimes a property of energy is a salient output of perception, such as when a sound is loud enough to cause pain. What we most often find in the descriptions we obtain from perception, however, are behaviorally important aspects of the physical world's material structure, not its energy characteristics.

Explaining perception, then, must include accounts of the catching of energy by receptors. But it requires much more. As our description makes clear, perception is determined by events that occur both earlier and later. Perceiving what is in the world is possible because interactions of energy with objects produce patterning across space and time. These patterns in spatial temporal relationships are often not even definable in terms of local receptor activity. Discovering and specifying precisely patterns in energy that provide information to perceptual systems is our task at the level of ecology.

The Level of Representation and Process

The function of perception is to provide accurate representations of the world to organisms and to guide their action. These representations and the processes that derive them comprise what we labeled the *level of representation and process*. Much of what needs to be explained in perception is what these representations contain and how well they correspond to the physical world. In the study of infant perception, we compare the scope, accuracy, and detail of the infant's perceptual world to the physical world as well as to the perceptual world of adults.

In calling the outputs of perceptual processes *representations*, we use the term broadly. We certainly mean to include characterizations of the outputs of perception as *descriptions* of the environment (Marr, 1982; Pylyshyn, 1973). We do not mean to imply, however, that the outputs of perception are always accessible to consciousness. Some theorists view the outputs of perception as leading to the adjustment of ongoing action in perception–action loops, rather than as comprising explicit descriptions to be thought about, remembered, and so on (Gibson, 1966; Turvey, Shaw, Reed, & Mace, 1981). A standing person, for example, makes periodic postural adjustments to compensate for detected sway. The visual or vestibular registration of sway is seldom conscious. For our purposes, registration of knowledge about the environment (or self) will count as part of the perceptual world, whether or not it is conscious or accessible to other cognitive processes. Although the differences among these cases are interesting, they are not particularly well illuminated by studies of infant perception. It is often tractable to test an infant's registration of some aspect of the environment, but it is much more difficult to distinguish whether it has been registered implicitly or made explicit in the infant's awareness.

The first step in understanding representation and process is some account of infant perceptual competencies. Much of our focus is on research revealing these. What aspects of the environment are perceptible by infants? Which of the multiple sources of information used by adults are usable by infants? Prior to the 1960s, these questions were sources of speculation and controversy but not of experimental research. In this book, we show that these questions have been answered to an impressive extent in many perceptual domains.

Direct Versus Algorithmic Perceptual Processing

How to characterize representation and process in perception has been controversial. Marr (1982) argued that perceptual processes are "algorithmic," in the sense that the outputs of perceptual processes depend on a sequence of representations and operations on them. Our label is more neutral about the character of perceptual processes. Some processes seem aptly described as algorithmic. In other instances, perception may involve not a sequence of representations but, rather, a more direct mapping from stimulus relations onto perceptual outcomes, as emphasized by Gibson (1966, 1979) and others (Cornman, 1975; Epstein, 1982; Hochberg, 1974; Johansson, 1970; Runeson, 1977; Turvey et al., 1981). A related issue is whether perception must be described as inferential in the sense of requiring assumptions about the world to constrain the possibilities consistent with the input (Fodor & Pylyshyn, 1981). An example may help illustrate these issues in understanding the character of perception.

Consider an object approaching an observer at a constant velocity. The size of the object's optical projection increases as it comes closer. Knowing when the object will contact the observer, however, might seem to require calculation. At a certain instant, the object projects a certain size on the retina of each eye. If the object is familiar, its distance may be calculated using the same geometry we considered previously. The real size of the familiar object is retrieved from memory. Distance to the object may be computed from the projected size (visual angle) and the real size. Another distance calculation taken after a known time interval could be used to calculate velocity. Then, if velocity is constant, the *time to contact* could be derived from the object's last position and its velocity. This algorithmic approach would require acquiring, storing, and comparing projective sizes and distance estimates along with accurate timekeeping. The sensed visual angles, as well as the distance estimates, are intermediate representations used to obtain the final result. The inferential character of the process is less obvious.

Lee (1974) provided an alternative analysis of this problem. Omitting mathematical details, the main result is that time to contact is specified directly by a higher-order optical variable. This variable is a ratio of the optical position of the approaching object's boundary and its first temporal derivative (*optical velocity*). The latter refers to the rate at which a contour or feature changes position on the retina. The upshot is that a ratio of two variables available at the observer's eyes mathematically specifies time to contact, without any need for computations involving distance and object size.

Now suppose a sensory system is wired so as to function as a detector for this higher-order variable. The only mental representation involved with such a detector might be its output—that is, time to contact. Indeed, empirical evidence suggests that perceptual systems in a variety of species do extract this information, and it is used to guide important behaviors (Lee & Reddish, 1981). It is in this sense that perception may be direct: Properties of the world may be detected by perceptual mechanisms sensitive to relational variables in the stimulus; computations on intermediate representations may not be required.

Studies of infant perception have not settled the question of whether perceptual processes are algorithmic or direct. Such studies suggest that the answer may vary across perceptual domains. We need to ask the question of representation and process separately for different perceptual abilities.

The Level of Biological Mechanism

The study of the machinery in the nervous system that allows us to extract, represent, and transform information is a rich and multifaceted enterprise. Studies of sensory psychophysics seek to define the range and limits of sensitivity of sensory systems to particular dimensions of energy, such as the range of frequencies the auditory system can detect. Taking a developmental stance, we seek to characterize changes in these sensitivities and theorize about their causes in neural maturation, learning, attention, motor development, and so on. Correlated with these efforts is direct investigation of physiological mechanisms underlying sensation and perception in animal subjects. Some of these studies address truly perceptual issues, such as how we detect and represent the positions of objects in space, whereas others are concerned with limits of sensory receptivity that constrain the pickup of information. Some research is undertaken in the hope of understanding and treating defects of perception. This concern involves almost solely the level of biological mechanism. If you wish to build a computer vision system, you will want to understand ecology and the representations and algorithms used in human visual perception. If your vision becomes cloudy, however, you should consult an ophthalmologist.

One of the fundamental insights of the study of information processing is that the levels we have discussed are not reducible to each other. The specialist who understands algorithms for computing depth from differences in images given to the two eyes probably does not also perform cataract surgery, and vice versa. Neither is using concepts and relationships that will ultimately be replaced by the other's. One important reason is that hardware implementation (biological mechanism) is not unique. Given a task, and a process for doing that task, there are many possible implementations. Thus, an account of perception can be scientific and precise at the ecological and process levels but reveal little about the details of the actual hardware.

The converse insight is sometimes less well understood. But it is one key to understanding perception and perceptual development, as well as information processing in general. That is, a detailed account of biological hardware alone does not explain perception. Accounts of ecology and process are not facts about neurons. They cannot be gleaned from ever more precise maps of neural firing and transmitter uptake. In fact, the reverse is true; choosing which observations of hardware are likely to be important rather than incidental requires knowledge of the task and the processes of perception (Chomsky, 1980; Marr, 1982; Putnam, 1975).

In this book, our primary focus is on ecology and process. This emphasis is in part due to the impossibility of treating all of the levels adequately in one book. A truly massive amount of information is available on biological mechanisms alone, and the research has varied goals. Our focus is *perceptual knowledge*—how perceivers come to know the world around them, what processes achieve this knowledge, and how they change over time. But this is a statement of emphasis and not exclusion. Most scientists who work in cognitive science and neuroscience at any level would agree that work at each level informs the others. Indeed, we have enjoyed several remarkable decades in which the facts at various levels connect and constrain each other far more than has previously been the case. Among the reasons are more precise quantitative theories about information and process, along with powerful new techniques for probing brain mechanisms. Accordingly, we have quite a bit to say about physiological mechanisms, but we stress those facts that clearly connect to the acquisition of perceptual knowledge, such as ways in which what we know at the biological level constrains information processing. Chapter 2 is devoted exclusively to this topic, and physiological aspects arise in our treatment of many other topics as well. Where our discussion of topics in the anatomy and physiology of developing sensory systems is less than comprehensive, the reader may consult several excellent sources (Daw, 2013; Møller, 2012).

STARTING POINTS OF PERCEPTION: TWO GENERAL VIEWS

We have seen that understanding perception involves three levels of inquiry—ecology, representation and process, and biological mechanism—and connections across levels. But we have not yet mentioned perhaps the most remarkable fact of all: The landscape is dynamic, not static. From the beginning of each human life (earlier, in fact), it is constantly forming and changing. These are the phenomena of development and learning. In this book, we examine early perception in various domains, such as object, space, motion, intermodal, and speech perception. In each case, we attempt to discover the starting points and paths of development of important perceptual abilities. In most cases, two general views compete to describe how perception begins and develops. One family of views—which we label *constructivism*—is empiricist in spirit, emphasizing the construction of perceptual reality through extended learning.[2] The other family of views—which we label *ecological*—encompasses a more nativist approach, emphasizing the role of evolution in preparing human beings to perceive. We introduce and examine each view in turn.

Constructivist Views of Perceptual Development

How might we know the world through our senses? The general answer given by constructivists has dominated theorizing about perception in philosophy and experimental psychology for more than two centuries. Constructivist views begin with the fact that sensory receptors, such as rods and cones in the eye, do not apprehend objects directly; each responds to a tiny region of impinging energy. As a result of their activation, receptors give rise to characteristic sensations, such as brightness at a particular location on the eye. Perception—knowing something about the objects and events in the outside world—consists, in constructivist views, of somehow making sense of these sensations. The process is like an inference: We must guess, hypothesize, or imagine what external objects might produce our sensations. Because many possible objects could give rise to particular sensations, the process can succeed only through learning. We learn which sensations co-occur and succeed one another, what visual sensations predict about tactile sensations, and so on. Drawing on memories and associations of past sensations, we construct a coherent interpretation of the causes of our sensations. This construction is the world we perceive. From this perspective, perceptual development must consist of an extended period of learning to interpret sensations before meaningful perception of coherent objects and events is possible.

Constructivist views about the building of perception out of sensation originated with British empiricist philosophers (Berkeley, 1709/1910; Hobbes, 1651/1974; Locke, 1690/1971; Reid 1785/1969). These views were further elaborated by key figures in early experimental psychology (Helmholtz, 1885/1965; Titchener, 1902; Wundt, 1862), by modern perceptionists (Hochberg, 1981; Wallach, 1985), and by developmental theorists (Harris, 1983; Piaget, 1954, 1976). The specific ideas of these theorists differ somewhat but share the main features of our schematic account.

The arguments for constructivism were originally logical ones. Two are particularly instructive for understanding both the constructivist stance and departures from it. We label these arguments the *ambiguity* and *capability* arguments.

The Ambiguity Argument

In his 1709 *Essay Toward a New Theory of Vision*, Berkeley (1709/1910) asked how we might possibly obtain reliable information through the visual sense. Berkeley pointed out that the projection of an object onto the retina of a single eye is inherently ambiguous; an infinite number of variously sized and shaped objects in the world could give rise to the same retinal image. If visual patterns are ambiguous, some nonvisual information is needed to disambiguate them. Berkeley suggested that the nonvisual information was provided by the oculomotor cues of accommodation and convergence. *Accommodation* refers to changing of the thickness of the lens to bring images at different distances into focus. *Convergence* is the turning inward of the eyes so that the two eyes image the same point in space. In each case, the muscular contractions required to accomplish the task would correlate with physical distance to the target, and these muscle sensations might also start out as meaningless but could come to signify depth by association with experiences of reaching for and contacting objects.

The Capability Argument

The growth of experimental physiology in the 19th century gave rise to perceptual theorizing rooted in knowledge of basic sensory capacities. Progress in sensory physiology centered on basic elements, such as individual sensory receptors and electrical conduction in individual nerves. An almost inevitable consequence was a strong emphasis on local activity in sensory nerves in attempting to explain perceptual knowledge. Particularly influential was the formulation advanced by Johannes Müller (1838/1965). Müller, often considered the father of experimental physiology, was concerned with the physiological basis for differences in sensory qualities across the senses. When the eye is stimulated, normally by light but also by pressure or other means, we have sensations of brightness and color. As the example illustrates, characteristic sensations are a function less of the external stimulus than of the particular sensory apparatus affected. Müller called this idea the *specific energies of nerves.* The qualities possible in each sense derive from specific properties of the particular sensory nerves. (We now know that the nerves themselves do not differ in the various sensory systems; Müller's insight accordingly is transferred from the nerves themselves to the separate brain areas to which different sensory nerves project.) Müller's notion of specific nerve energies is profound in making clear that sensations inhere in the observer and not the world.

It suggests a way of thinking about perception, however, that is less fortunate. Consider a few of Müller's doctrines (Müller, 1838/1965):

> I. In the first place, it must be kept in mind that external agencies can give rise to no kind of sensation which cannot also be produced by internal causes, exciting changes in the condition of our nerves.
>
> III. The same external cause also gives rise to different sensations in each sense, according to the special endowments of its nerve.
>
> V. Sensation consists in the sensorium's receiving through the medium of the nerves, and as the result of the action of an external cause, a knowledge of certain qualities or conditions, not of external bodies, but of the nerves of sense themselves; and these qualities of the nerves of sense are in all different, the nerve of each sense having its own peculiar quality or energy.
>
> VIII. The information thus obtained by the senses concerning external nature, varies in each sense, having a relation to the qualities or energies of the nerve. (pp. 27–33)

We recount Müller's doctrines in detail to give a sense of the logic of a sensation-centered view. Any sensory effect could have multiple causes and moreover reflects more the properties of the nerve affected than anything else. Taken together, we can call these doctrines the *capability* argument. By their nature, the senses have only the capability of producing one kind of product—sensations. These characteristic sensations of each sense reside in the observer, not in the world.

Taking the capability argument at face value, it becomes baffling how we might move from having sensations to having knowledge about the external world. To the philosophically unsophisticated, it seems that perception puts us in contact with objects and events in the outside world. Given the capability argument, this cannot really be so. At best, we construct, guess at, or imagine the world. We do so by cataloguing, associating, and reasoning about sensations. Achieving perceptual knowledge must consist of inferring the causes of our sensations. We might even be predisposed to do this. In Müller's (1838/1965) words, "The imagination and reason are ready to interpret the modifications in the state of the nerves produced by external influences as properties of the external bodies themselves" (p. 27).

The ambiguity and capability arguments are not entirely distinct. Berkeley's (1709/1910) claim that a ray of light striking the retina carries no information about how far it has traveled can be viewed as a capability argument. However, the arguments are somewhat different. Berkeley's argument concerns the patterns (images) coming to the eye, irrespective of the sensory apparatus from the retina on. The capability argument is an argument about sensory mechanisms. It is in the nature of the sensing process that all the observer can really acquire are sensations, and these are results of specific neural activity within the observer.

In subtle or overt form, this inference from the capabilities of individual receptors or neurons to explanations of perceptual capacity still characterizes much work in sensory physiology and perception. It also characterizes some descriptions of perception by cognitive scientists. Specifically, it is often assumed that the senses deliver some raw or uninterpreted data that is then worked into meaningful form by cognitive processing, incorporating expectations and prior knowledge ("top-down" processing) to obtain the result.

Constructivism: Dissent and Modernization

Problems with the classical constructivist view have often been noted. Kant (1781/1902) questioned how our representations of the world could ever originate from sensory input alone. The fact that we have coherent experience presupposes modes of mental organization, such as the dimensions of space and time, into which our sensory experiences are arranged. A different sort of dissent came from the physiologist Hering (1861–1864), who emphasized the functioning of the two eyes as an integrated system that apprehends depth directly. Binocular disparity—differences in retinal positions in the two eyes stimulated by a target—might allow direct detection of depth without learning. Hering's claims attack both the capability argument, because the perceptual system can be seen as responding to relationships rather than local stimulation, and the ambiguity argument, because the characterization of the visual stimulus in terms of single retinal images is considered to be mistaken.

Despite these dissents, extreme constructivist views dominated experimental psychology until the early 20th century. At that time, the Gestalt psychologists mounted a comprehensive attack on the notion that percepts are built up from local sensations. Their demonstrations and arguments suggested that *patterns* are fundamental to perception, whereas sensations are incidental. Form or pattern, they asserted, is not a sensory concept at all. The Gestaltists made this point using a variety of demonstrations of *transposition* phenomena. Consider a square made of solid red lines. From the constructivist perspective, the total experience of viewing the square is the collection of various sensations of discriminable locations and the redness and brightness at each. Thus, "the whole is the sum of the parts." The Gestaltists noted that one can easily change all of the sensations, however, while preserving the form of the square. A square constructed from black dots, changed in size and positioned elsewhere on the retina, is nevertheless a square (Figure 1.3). Thus, "the whole is different from the sum of the parts." A melody illustrates the concept for temporal patterns. One can change the constituent notes while preserving the melody, as long as certain relationships among the notes are preserved. Conversely, presenting the original sensations in jumbled order destroys the original form.

Despite its telling arguments and demonstrations, the Gestalt critique was unsuccessful at dismissing constructivist views of perception's origins. Part of the problem was the lack of a successful alternative view. Perceptual organization, the Gestaltists suggested, resulted from the activity of field forces in the brain, a notion that received little support and has since been abandoned. In addition, constructivist views evolved to meet some objections while retaining their emphasis on learning in perception. The modified views elaborated Helmholtz's (1885/1965) notion that experience might lead not only to stored sensations but also to the

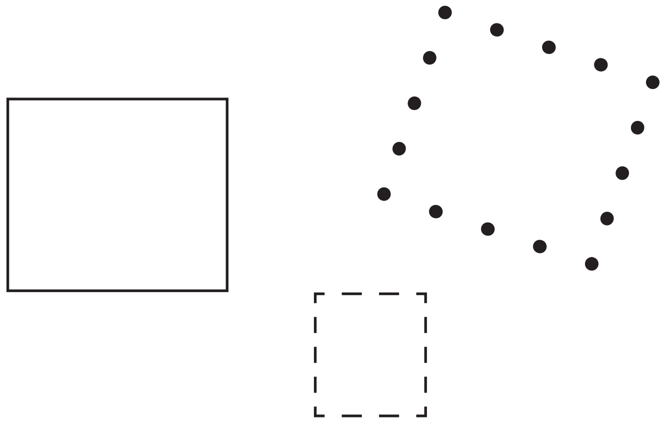

FIGURE 1.3
The three objects are perceived as squares despite changes in elements that define the shape, size, and orientation. Source: Created by M. E. Arterberry.

abstraction of perceptual rules that could be used in the interpretation of future sensory impressions (Brunswik, 1956; Hochberg, 1978). Brunswik, in particular, argued that the Gestalt laws of perceptual organization could be learned by experiences with objects. Such neo-Helmholtzian views have remained influential to the present time (Harris, 1983; Hochberg, 1981; Nakayama & Shimojo, 1992; Rock, 1983).

Ecological Views of Perceptual Development

A different perspective on perceptual development—an ecological view[3]—starts from radically different premises about perception. Its basic ideas were elaborated by J. Gibson (1966, 1979) and E. Gibson (1969, 1984; see also Johansson, 1970; Shepard, 1984). Here, we develop an ecological view that is generally consistent with the viewpoint elaborated by both J. Gibson and E. Gibson; however, some particulars are closer to the positions elaborated by Johansson (1970), Braunstein (1976), and Shepard (1984).

A basic premise of ecological views is that the perceiving organism is awash not only in energy but also in information. Ambient energy is structured by its interactions with objects, surfaces, and events. These interactions are lawful, resulting in a detailed correspondence between patterns in ambient energy and the structure of the environment. The specificity of the patterning of energy by the physical layout makes the environment knowable via detection of structure in the array of energy (J. Gibson, 1966). A second major premise is that perceptual systems evolved not to allow the organism to have meaningless sensations but, rather, to pick up information in energy patterns. The focus is on the perceiving apparatus as an integrated system for information extraction rather than on activity at single receptors or even simple summing of such activity in multiple locations. Receptive elements and individual nerve fibers are parts of larger devices whose circuitry is set up to extract useful information.

The organism is considered to be *actively* involved in the pursuit of information. Take the visual system as a case in point. More than a passive array of retinal receptors, it is an active, highly coordinated, information-seeking system. Ciliary muscles change the shape of the lens, focusing light on the retina. The two eyes turn inward or outward to place the same point in space at the center of each. The eyes may turn as a unit to follow the moving stimulus or focus on a particular feature of an object. The head may also turn, or the observer may move her body to improve her view of a scene. These attunements are closely linked to events in the environment and the perceiver's behavior. The organism's behavior allows it to actively extract information, and this information in turn guides ongoing behavior (J. Gibson, 1966).

On this view, perceptual development begins with meaningful contact with the world, although some perceptual systems may mature after birth, and skill in picking up particular information may improve with practice. This developmental starting point differs conspicuously from that in the constructivist account. If perceptual systems have evolved to pick up meaningful information, perceiving objects and events may not require a long learning period. Perceptual systems may no more have to "learn to interpret" sensations than they have to learn which portion of the electromagnetic spectrum interacts informatively with objects. Perceptual systems may be richly structured devices specialized to take patterns as inputs and produce meaningful and functionally useful descriptions of objects and events as outputs.

To be plausible, ecological views must incorporate some answers to the ambiguity and capability arguments of constructivism. Let us consider these answers. As before, we use visual perception as our example because it has been most central in debates about these issues.

Answering the Ambiguity Argument

Berkeley's (1709/1910) analysis of ambiguity is technically correct if one considers only the information available in a momentary image projected on a single retina. Human perception, however, does not work that way. First, as Hering (1861–1864) described, the two eyes can work together as a system to detect depth from differences in the optical projections to the two eyes. More important, perhaps, the best information available to perceivers is extended in time, and perceptual systems are equipped to utilize such information (J. Gibson, 1966). Looking with a single eye through a peephole, a three-dimensional scene may be indistinguishable from a photograph or photorealist painting. When the observer views a real-world scene or photograph while walking, however, the optical transformations across time differ drastically. Assuming the environment to be at rest, the pattern of optical changes furnishes unequivocal information about the three-dimensional spatial relationships in the scene, with the relations between optical transformations and the real scene specified by the laws of projective geometry. It has been claimed that this *kinematic* information given by observer or object motion is fundamental to ordinary perception. The momentary retinal image considered by Berkeley may be a degenerate input to perceptual systems (J. Gibson, 1966, 1979; Johansson, 1970).

Answering the Capability Argument

The reply to the capability argument is complementary to the reply to the ambiguity argument. J. Gibson (1966) argued that perceptual systems are geared to detect structure in ambient energy rather than properties of the energy itself (e.g., intensity or wavelength of light). Although the separate senses have their characteristic sensations, "sensation is not a prerequisite of perception, and sense impressions are not the 'raw data' of perception—that is, they are not all that is given for perception" (J. Gibson, 1966, p. 48). Perceptual systems actively extract higher-order information from incoming stimulation. The specialization of perceptual systems to detect information about the environment (and about the self) is the result of evolution (J. Gibson, 1966; Johansson, 1970; Shepard, 1984). Over evolutionary time, perception has come to exploit enduring regularities or constraints of the physical world.

The ecological rejoinders to constructivism undermine the *logical* case for learning in perceptual development. Empirical investigations become central. Does perception give a meaningful representation of the world from the beginning? Can available information that is abstract and extended in space and time be used by naive perceivers? Despite available information and the possibility of evolved mechanisms of information pickup, the meanings of sensory patterns might nevertheless be learned, and the most optimal information might not be utilized. Moreover, the facts might differ for different perceptual abilities: Development might conform to the ecological view for some capacities and fit a constructivist account in other cases. We cannot decide by logic alone; we must pursue these questions by observation and experiment.

PERCEPTUAL CHANGE

Perception changes with age. Details of surface texture obvious to an adult are invisible to a 2-month-old infant. The same infant makes no use of differences in the projections to the two eyes, although these specify vivid depth to a 5-month-old. Through the lifespan, perceptual change continues. A student pilot peers out the window, unable to locate the airport in the midst of roads, buildings, and streams, while her instructor spots it effortlessly. Perceptual skills attained through experience underlie expert performance in many domains (Kellman & Massey, 2013).

Less apparent is what exactly changes. How does the infant perceiver differ from an older child or adult? What is the role of learning? Of maturation? Is there only one kind of perceptual learning or several? Are processes of change in early perceptual development similar to or different from the perceptual changes that occur later in life as adults develop expertise in particular domains?

One class of change—perceptual change due to *maturation* of the nervous system—may be unique to the first year of life. We will encounter many examples, including visual acuity and stereoscopic vision, in Chapters 2 and 3.

Against this backdrop of maturing sensory capacities, we attempt to assess the role and characteristics of learning in perception. Investigators of every theoretical persuasion agree that learning changes perception. What is hotly disputed are the nature and implications of the changes. In particular, from the two general views of perception come two different answers—answers that imply radically different understandings both of the learning process and of the experienced perceiver. J. Gibson and E. Gibson (1957) called these opposing views of perceptual learning *differentiation* or *enrichment* theories. These two notions of perceptual change will be useful as landmarks as we consider early perceptual development. We explore them in turn.

Enrichment: Perceptual Learning in the Constructivist View

Enrichment describes the notion that meaning must be added to the raw data brought in through the senses. What we mean by *meaning* is reference to the environment. Thus, perception can furnish knowledge about the environment (or misunderstandings of the environment from misperception). Sensation does not implicate an external world. The notion of enrichment is a necessary companion to classical ideas about the starting point of perception. If the senses deliver to the observer only meaningless sensations, some process must add meaning for knowledge of the outside world to be attained.

Different possible enrichment processes have been proposed. Constructivist views have often emphasized associations based on contiguity in space or time and also similarity. Such associations apply both to current stimuli and to stored memories of earlier sensations. For example, when the observer is presented with an apple, the various locations at which red is sensed are linked by continguity in time and space and by similarity. These sensations can call up earlier ones, based on similarity and perhaps recency in time. Association with sensations of touch has often been accorded special status, as in Berkeley's (1709/1910) famous dictum, "Touch educates vision."

Knowledge of an external object is composed of a combination of current sensations and those called up from memory. In structuralist psychology, the former was called the *core* and the latter the *context*; meaningful perception was held to be possible only by adding the context to the core (Titchener, 1902). One of the most famous accounts of perceptual knowledge as enrichment was given by Helmholtz (1885/1965) and has become known as Helmholtz's rule: "Such objects are always imagined as being present in the field of vision as would have to be there in order to produce the same impression on the nervous mechanism " (p. 152).

The world we perceive comes about as an act of imagination using current sensations and associated ones from memory. Helmholtz also emphasized another aspect of enrichment—namely the abstraction of general rules from experience. He contended that perceptual experience leads inductively to the formation of abstract perceptual rules. These rules, in turn, function as premises in inference-like perceptual processing; thus, perception has the character of *unconscious inference*.

The most detailed view of enrichment, and the one most influential in theories of infant development, is Piaget's theory (1952, 1954, 1976). Reality is constructed out of sensorimotor experience. At first,

> there is not involved, it goes without saying, any interest of the child in the objects themselves that he tries to watch. These sensorial images have no meaning, being coordinated neither with sucking, grasping or anything which could constitute a need for the subject. Moreover, such images have neither depth nor prominence . . . . They therefore only constitute spots which appear, move, and disappear without solidity or volume. They are, in short, neither objects, independent images, nor even images charged with extreme meaning . . . . Still later . . . the visual images acquire meanings connected with hearing, grasping, touching, with all the sensorimotor and intellectual combinations. (Piaget, 1952, pp. 64–65)

Unique in Piaget's analysis is the idea that interpretation of sensations comes about not merely from association with other sensations but with *action*. Connecting self-initiated movements and their sensory sequences forms the basis of the growth of knowledge about oneself and the world.

Differentiation: Perceptual Change in the Ecological View

Ecological views suggest that meaningful contact with the environment is possible without the necessity of enrichment. There is no stage in development in which the senses yield an uninterpreted product; perception is always directed to the external environment. Ecological views do not, however, assert that perception is unchanging through the lifespan. In fact, perceptual changes with experience are dramatic, both in early development and in later life. The type of change is what Gibson and Gibson (1955) termed *differentiation*. The environment provides a wealth of information, far too much to be extracted all at once. Moreover, the new perceiver lacks skill in information extraction. With experience, perceivers develop selective skills. Perceptual learning considered as differentiation learning is the development of precision and speed in the pickup of information.

In her classic work *Principles of Perceptual Learning and Development*, E. Gibson (1969) described these changes: With experience in a particular domain comes increasing specificity of discrimination, more optimal deployment of attention, and discovery of higher-order perceptual structure. E. Gibson and Pick (2000) further emphasize that the active perceiver discovers invariants of events, objects, layouts, and *affordances*, or the properties of events, objects, and layouts as they relate to the perceivers' capability for using them. Perceptual development, then, is the process of learning meanings for what can be perceived and learning the information that distinguishes one event, object, or layout from another.

An interesting feature of perceptual learning is that it sometimes seems to occur without explicit reinforcement or even feedback. Mere exposure may be sufficient. E. Gibson also advanced an interesting conjecture about the content of perceptual learning. Learning primarily consists of learning *distinctive features.* These are attributes within a stimulus set that are relevant to distinguishing members of a set. What is interesting about this claim is that not all aspects of objects are said to be learned from exposure to the objects. Rather, the contrasts among members of a stimulus set come to the fore in perceptual learning. This idea makes interesting predictions about exposure to particular stimulus sets and transfer of what is learned.

PROSPECTUS

In what follows, we examine experimental research on the development of perception to determine the ecological and constructivist foundations of perceptual competence, the character of perceptual processes, and the sources of change. Research in infant perception has already shed considerable light on these issues. We will find that some claims of constructivist and ecological views must be abandoned or modified, whereas others have received strong support. There may even be some hope of reconciling key ideas from conflicting general views of perception into a single coherent whole. We return to these issues in Chapter 12, after we have more thoroughly explored the infant's perceptual world.

NOTES

1. The *nodal point* is the point of intersection of all rays that pass through the optical system of the eye undeflected. Other rays of light leaving in slightly different directions from a given object point will arrive at the same image point, but they will get there by being deflected due to refraction by the eye's optics.
2. In other domains of cognitive development, constructivism may have other connotations and contrast strongly with, rather than subsume, associationist accounts.
3. Although the terms are similar, it is important to distinguish the *level of ecology* in the study of perception from *ecological views of development*. The level of ecology refers to facts and concepts about how physical environments make information available for perception. It is theory-neutral in the sense that any theory of perception must include analyses at this level. Ecological views of perceptual development embrace the idea that perceptual mechanisms have evolved to pick up information about functionally important properties of the environment. The closeness in terminology reflects a shared emphasis on lawful relations in the physical world as crucial to understanding both how perception works and how it evolved.

2 Physiological and Sensory Foundations of Perceptual Development

INTRODUCTION

More of the human brain is devoted to perceptual information processing than to any other function. Vision alone, it is estimated, involves more than 30 different areas and 40–50% of the entire cerebral cortex. Adding other senses, it appears that the bulk of cortical processing serves functions of perception.

Even so, the whole brain weighs only several pounds and could be held in our two hands. Thinking of the brain this way, as a small object, we might suspect that focused scientific effort would readily reveal how it works. Unfortunately, inspection at a finer grain gives us a different view of the difficulty of the task. Neurons—the units of information transmission in the brain—number approximately 100 *billion*. Their functions are realized in their connections with other neurons, and these *synapses* number approximately 10^{14}, or approximately 1,000 for every neuron. Connectivity on such a scale makes possible awesome computational power but also makes the task of describing in detail how computations are carried out in the brain a daunting challenge. Most visual areas, for example, are known to be connected to each other, and the hypothesis that each is connected to every other cannot be ruled out by existing data. It is no wonder that the human brain has been claimed to be the most complex device in the known universe.

When we seek to understand the brain early in life, we add to this complexity the dimensions of growth and change. Whereas some plasticity can be found at later ages, never are the changes so extreme and rapid as in the infancy period. Before birth and beyond, the vast neural machinery of perception is under construction. Its status at any given age inevitably decides the potentials and limits of perception in the infant.

Based on their status at birth, animal species are classified as *altricial*, meaning helpless and immature at birth, or *precocial*, comparatively mature, mobile, and functional at birth. In such a classification, *Homo sapiens* is designated as altricial. Although not born with its eyes closed, as are kittens and many other altricial species, the human newborn is nonetheless relatively immobile and long dependent on its parents for care. These are just the outward manifestations. On the inside, the newborn has an incompletely developed brain, and other parts of its nervous system continue to mature for some time after birth.

Yet the extent of postnatal development should not obscure the fact that much perceptual machinery is already in place at birth (Stiles, Brown, Haist, & Jernigan, 2015). Compared to other altricial species, humans are perhaps unique in that all sensory systems become functional before birth (Gottlieb, 1971). The newborn opossum, by comparison, is born without eyes or ears (the eyes open approximately 55–79 days postnatally). Gottlieb considers humans and other primates as "unique in having combined the precocial pattern of sensory development with the altricial pattern of motor development" (p. 118).

In this chapter, we consider aspects of physiological development and sensory limitations that make possible and constrain the acquisition of perceptual knowledge. The division of labor between this chapter and our later topics comes from distinguishing two types of questions and research on infant sensory and perceptual development.[1] In later chapters, our primary focus is on perceptual knowledge—knowledge of objects, spatial layout, and events. Our present concern is with sensory limits and changes in them caused by physiological development. These outer boundaries of receptivity, such as visual acuity, do not directly reveal what is perceived and represented, but they place constraints on it. Sensory maturation in human infants has implications for early perception, for development in general, and, as a practical matter, for attempts to study infants' capabilities.

THE HUMAN INFANT'S NERVOUS SYSTEM

Linking the infant's physiology to sensory and perceptual functioning is a difficult undertaking. We are limited by what is known about physiology and perhaps even more by our modest knowledge about how structures and events in the nervous system carry out perceptual processing. On the behavioral side, measures of sensory and perceptual function in infants are somewhat blunt instruments. The result of these compounded uncertainties is that our conclusions about specific physiological limitations on perception must be tentative. More encouraging is the fact that progress is occurring rapidly in all of the domains relevant to understanding brain and behavior. As a result, hypotheses about neural links to perception, and their developmental patterns, are becoming more plausible, precise, and testable than they were even in the recent past.

Neural Development

Soon after conception, development of the nervous system begins. Cortical neurons begin to form at 10 weeks of gestation and are completed at approximately 18 weeks (Casaer, 1993). Once neurons form, they migrate, under the guidance of chemical gradients and of glial cells (discussed later), to genetically programmed sites in the nervous system. Formation of the cortical layers occurs from the deepest layer out toward the surface of the cortex (Jacobson, 1991). On reaching their destinations, neurons begin a branching process that allows each to form 1,000 or more connections with other neurons. Dendrites, the parts of a neuron that receive signals from other neurons across synaptic junctions, grow in treelike fashion, earning the colorful name *dendritic arborization*. Different brain areas follow different timetables. For example, differentiation of the visual cortex occurs between 25 and 32 weeks of gestation (Purpura, 1975), whereas differentiation of the cerebellum, a structure that controls movement, begins much later and continues to almost 3 years of age (Casaer, 1993).

Synaptic Development

Neuronal interactions occur primarily by chemical activity across synapses. Across these gaps, branches from a neuron's axon may trigger the electrical discharge of another neuron. Synapse formation in the human cerebral cortex increases greatly after neuronal migration is nearly complete in the second trimester of pregnancy (Huttenlocher, 1994). Most occurs after birth, however, especially in a burst of activity between 2 and 6 months of age. During this time, the number of synaptic contacts increases by a factor of 10, reaching a total number that is approximately double that typically found in young adults (Figure 2.1). The overproduction of synapses is corrected by a synapse elimination process that begins at approximately 1 year of age and is completed by 10 years (Huttenlocher, 1994).

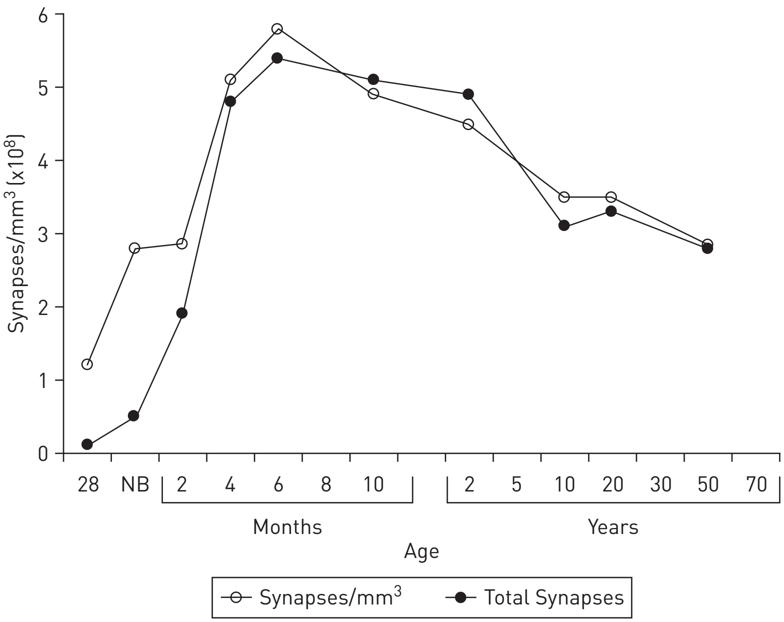

FIGURE 2.1
Changes in synaptic density across the life span. "28" indicates density estimates at 28 weeks of gestation, and "NB" indicates density in newborn infants. Source: Redrawn with permission of Elsevier from Huttenlocher, P. R. (1990). Morphometric study of human cerebral cortex development. *Neuropsychologia*, *28*, 517–527; permission conveyed through Copyright Clearance Center, Inc.