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Theories of Perception and Research in Perceptual Development

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Understanding the development of perception involves issues at multiple levels of analysis. A casual observer might wonder what scientific topic could unite, in a single symposium, discussions of human infants' intermodal perception of speech, microelectrode recording from single cells in cat cortex, and computer programs that simulate the detection of optical information by moving observers. These investigations, as well as others in the symposium on which this volume is based, have illustrated the various levels of approach to perceptual development, and have provided some clues about how the levels fit together.

My comments are of two kinds. First, I try to unify the various presentations somewhat by making explicit the different levels of investigation in research on perceptual development and their relations to each other and to theories of perception. Second, I take up some issues in object perception, as an example of research driving and being driven by perceptual theory.

MARR'S FRAMEWORK

The realization that distinct levels are involved in explaining perceptual phenomena was made most explicitly by Marr (1982), who argued for three levels of inquiry. The first, and most important according to Marr, is the level of computational theory. The computational level is concerned with the *task* in perception. What is it that organisms need to perceive? What information is available in the environment? What physical laws or constraints apply that may make the task feasible, or simpler? Marr appropriately credits J. J.

Gibson (1950, 1966, 1979) for pioneering analyses of the task and the environment ("ecological optics") in visual perception. Computational explanation sets the agenda for the other levels. Neurophysiological investigation, for example, depends on a clear understanding of the task because, on one hand, not all properties of neural systems that might be catalogued are functionally relevant, and, on the other hand, a detailed functional understanding constrains hypotheses about underlying mechanisms. The realization that investigation of psychological processes presupposes a highly developed, abstract analysis of the task and available constraints has perhaps been the major advance in psychology in the last several decades. It has assumed a central place in the study of perception and perceptual development, via ecological and computational approaches (J. J. Gibson, 1979; Marr, 1982), and can also be seen in other domains of cognition, including language and its acquisition (Chomsky, 1975) and conceptual development (Keil, 1981).

The second level of inquiry suggested by Marr is the level of the representation(s) and algorithm(s). As Marr puts it, "What is the representation for the input and the output, and what is the algorithm of its transformation?" This level is separate from the first because, even with a clear computational account of an ability, many different information-processing procedures might be possible. Marr's second level is the most controversial of the three. J. J. Gibson (1966, 1979) in particular argued that perception occurs without the need for intermediate representations or "information-processing" descriptions. We return to this issue later.

The third level is the level of hardware implementation. What neurophysiological mechanisms carry out the algorithms (or direct detection) in perception? The separability of this level from the others rests on one of the most basic insights of cognitive science, that an information-processing system may be realized in different physical contexts. An essential part of an account of human perception is understanding the particular mechanisms that pick up information about the environment. Moreover, knowledge at this level is primary in understanding defects or aberrations of perception and their treatment.

THE LEVEL OF COMPUTATIONAL THEORY: TASKS AND CONSTRAINTS IN PERCEPTUAL DEVELOPMENT

Advances in the computational understanding of perceptual development share much with advances in the study of mature perception. Two of the most significant contributions in the last several decades have come from J. J. Gibson's work (1966, 1979). The first is a detailed description of the goals of perception. Put very generally, mobile organisms need to perceive the layout of surfaces in three-dimensional space, the objects arrayed on these surfaces, and the events or changes taking place. The second contribution concerns the description of information available to perceivers, especially in visual perception. Changing stimulation given by events contains information about both the persisting properties of the environment and changes occurring within it. Especially important is the pervasive event of observer motion. Along with those of others (e.g., Johansson, 1970, 1975; Michotte, 1963; Shepard, 1984), Gibson's ideas have shifted emphasis from the study of information available in momentary samples of energy incident upon sensory receptors, to abstract relations given in energy patterns over space and time. At the root of these advances is a deeper understanding of the basic physical constraints governing the relations between the geometry of natural environments and the information available to perceivers (J. J. Gibson, 1979; Johansson, 1970; Shepard, 1984). Despite the fact that many aspects of Gibson's approach remain controversial, it is fair to say that the joint emphases on the task of ordinary perception and of information given over time to mobile observers have influenced most workers in the field.

Both of these concerns are also central to the study of perception in early infancy. A computational account of the origins of human perception requires a clear description of perceptual abilities at the earliest ages and a determination of what specific information underlies them. Our symposium presentations reveal many examples of progress that has been made on these questions.

Spelke reviews advances in understanding the origins of object perception. The earliest visual perception of object unity seems to be based on information in optical change given by events (Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986). Early perception of objects' three-dimensional forms also depends on optical transformations (Kellman, 1984; Kellman & Short, in press; Owsley, 1983). Haptic perception of the unity of spatially separated object parts also seems to depend on motion relationships (Streri & Spelke, in press).

Infants' sensitivity to other properties of objects and surfaces, such as substance and rigidity, has been documented by E. J. Gibson and colleagues (E. J. Gibson, Owsley, & Johnston, 1978; E. J. Gibson, Owsley, Walker, & Megaw-Nyce, 1979). Yonas and his colleagues (e.g., Yonas & Granrud, 1985) have systematically investigated many sources of depth and distance information in human perception, finding sensitivity to kinetic information as early as infants have been tested and sensitivity to pictorial depth only later. A particularly important source of depth information, stereoscopic depth perception, has been found to emerge between 3 and 5 months of age, probably as a result of maturation (Braddick & Atkinson, this volume; Fox, Aslin, Shea, & Dumais, 1980; Held, Birch, & Gwiazda, 1980).

Early competence in perceiving certain events in three-dimensional space, such as the approach of objects, is well established (Carroll & Gibson, 1981; Yonas, Pettersen, & Lockman, 1979), and in some cases the particular informational bases have been specified (Yonas et al., 1979; Kellman, von Hofsten, & Soares, 1987). There are some early indications that infants accurately perceive environmental motion and stability during their own motion (Kellman, Gleitman, & Spelke, in press), a fundamental problem discussed by Banks.

Kuhl reveals infants' use of intermodal relationships in the perception of speech. These results complement an impressive array of earlier ones showing that infants perceive and represent event information from multiple sensory channels in a unitary and abstract manner (Meltzoff & Moore, 1977; Moore, Borton, & Darby, 1978; Spelke, 1976; Wertheimer, 1961).

These research findings, most obtained within the last decade, share a number of implications. The most general is that at least some meaningful perception of the environment seems to exist from the beginning of life or as early as tests have been conducted. Almost no evidence supports the traditional empiricist picture of an initially meaningless sensory array as the starting point for perceptual development. A more plausible current view is that the evolution of perceptual systems has furnished abilities that allow perceivers to detect aspects of objects, the spatial layout and events from the start.

A second implication of research at the level of computational theory concerns the specification of the information underlying early abilities. Research efforts in infant perception are not well summarized by saying that infants do "neat tricks," or that, aside from a little maturation, "everything is built in." In fact, infants' competence in virtually every perceptual domain looks quite different from that of adults. It is the nature of these differences that is important for understanding the neurophysiological substrate of perception and for theorizing about development.

One generalization about the differences between infants' and adults' perceptual competence is striking. In virtually every domain, the earliest abilities seem to be based on temporally extended information. Adults can perceive much of the structure of the world, including ongoing events, either from temporally extended information or from momentary arrays of energy. For young infants, information in stationary arrays, even those that attract very high levels of attention, does not specify much about the three-dimensional structure of the world. It is perhaps less surprising that information in changing stimulation dominates perception of events. Events by their nature unfold over time. Even when static information sources about events are available, however, they are overshadowed by transformational information. One example comes from studies of intermodal perception of events specified auditorily and visually (Spelke, Born, & Chu, 1983). When one of two objects moving up and down was synchronized with an impact sound, infants detected the correspondence. Interestingly, their behavior was not controlled by the visual information for surface tangency at the moment of the sound, a key variable in adult perception of such an event; the time-extended information of change in direction of movement, whether or not this occurred tangent to another surface, was the invariant underlying perception of correspondence.

A third implication concerns the linkage of event-based competence with underlying mechanisms. As Marr suggested in general, descriptions of early competence and the stimulus information on which it is based help to set the agenda for the exploration of neural mechanisms. It is becoming clear, both in infant and adult perception, that mechanisms tuned to changing stimulation must exist and may even require some revision of existing concepts about the functions of single cells (Allman, Miezin, & McGuiness, 1985). As discussed below, the presentations by Atkinson and Braddick and Aslin and Banks suggest that some of these mechanisms are already being uncovered (cf. Allman et al., 1985).

THE LEVEL OF REPRESENTATION AND ALGORITHM: THEORETICAL CONTRASTS

Research in perceptual development has so far had the least to say about the level of representation and algorithm. By contrast, it is at this level that some of the major theoretical controversies in perception are defined.

Although the terms are new, algorithmic explanations of perceptual phenomena have a long history. All inferential views of perception (Berkeley, 1709/1963; Epstein, 1982; Helmholtz, 1866/1925; Hochberg, 1974; Rock, 1983) posit that intermediate representations and algorithms relate inputs and outputs in perception. The general view that incoming sensory arrays evoke associations with previously stored information has this character, as do more explicit formulations of perceptual abilities, e.g., the claim that perceived size is derived from a calculation involving registered distance and retinal size (Holway & Boring, 1941).

Claims of a central role of *learning* in perception have usually been closely allied with inferential views, although Rock (1983) has argued persuasively that there are two separable issues here. For example, the formal character of perception may be inferential, even though the "premises" (other than incoming sensory information) are innate. This latter possibility may not be far from Spelke's proposal that objects are known rather than perceived.

Theoretical controversy involving representations and algorithms in perception may be expected to intensify as more data about early perceptual abilities become available. Do most or all developing perceptual abilities require explanation in terms of intermediate representations and computations relating the input information and the percept? J. J. Gibson (1966, 1979) was the most emphatic critic of this sort of explanation. As an alternative, he suggested that perceptual mechanisms "resonate" to information given in energy from the environment, giving a direct connection between input and output. The resonance metaphor is a starkly promissory suggestion, no such (neurophysiological) mechanisms have yet been identified. However, there are two reasons why alternatives to algorithmic models, such as resonance, should be explored. First, although resonance is a somewhat vague notion at this point, so are the notions of representation and algorithm in many perceptual explanations. Criteria are needed for distinguishing when something is to be considered merely a neurophysiological process as opposed to a neurophysiological process that is representational or that instantiates an algorithm. For example, inferential views of size perception usually claim that real or perceived size is "computed" but retinal size is "detected." A second observation is that resonance notions are being taken more seriously as new and different kinds of computer systems, such as massively parallel networks (e.g., Grossberg, 1981), are developed. Here, as the past amply illustrates, it may be prudent not to limit our imagination about mechanisms in the neurosciences to the class of currently familiar devices, such as ordinary serial, digital computers.

Advances in understanding early perception at the computational level will increasingly demand some account of the role of representations and algorithms. In these respects, the study of perceptual development occupies a central place in the study of perception generally. It appears to be the most promising approach toward understanding the role of learning in perception. Moreover, it may help in identifying the most fruitful lines of inquiry in the study of underlying mechanisms. Isolating neurophysiological mechanisms will likely prove more feasible for relatively autonomous perceptual systems that function from early in life (cf. Fodor, 1983) than for aspects of mature perception that result from extensive experience or involve general cognitive processes (Rock, 1983; Wallach, 1985).

THE LEVEL OF HARDWARE IMPLEMENTATION: PERCEPTUAL MECHANISMS

Much of the research presented in this symposium has illustrated impressive techniques and results in the study of the neurophysiological mechanisms underlying perception.

Aslin's research deals with anatomical variables that have fundamental implications for visual perception. For example, the mapping between points in the environment and retinal points is subject to maturational changes of various types. Maturational migration of receptors potentially alters the metric of retinal space; growth also affects the changes in visual direction resulting from saccades and the vergence movements necessary to bifoveally fixate a given point. All of these alterations have implications for accurate or even consistent perception of the spatial layout. Although much recent research emphasizes the possibility of unlearned capacities in perception, these effects of growth suggest a large set of issues in which calibration based on perceptual and motor experience must play the central role.

One hint about the calibration process mentioned by Aslin is that temporal resolution, unlike spatial resolution, seems to be quite mature in newborns. Given the emerging evidence that early visual competence often depends on optic flow information, it is natural to speculate that mechanisms sensitive to change might also play a key role in calibrating other sources of information. One caution here, noted by Banks, is that detection of optic flow information may have its own calibration problems related to growth.

Mitchell describes plasticity in the neural mechanisms underlying vision. It is interesting to ask whether plasticity has a function in perceptual development or whether it is an incidental consequence of facts at another level, e.g., embryology. Does plasticity when confronted by a range of normal environments, result in a range of adaptive outcomes, that is, visual function somehow specially attuned to slightly differing circumstances? Such circumstances might include the challenges, such as those identified by Aslin, posed by routine growth. Whether plasticity is functional may well differ for different domains. For example, plasticity in the orientational selectivity of neurons may have functional value if an animal lives primarily on particular sorts of textured surfaces. In contrast, the plasticity that makes it possible to lose binocular driving of cortical neurons may have no possible adaptive consequences, but may be a vulnerability present for other reasons.

This issue reminds us that the reasons to study the neurophysiology of perception are diverse. Several of our contributors (Atkinson and Braddick, Aslin and Mitchell) describe work with current or potential clinical applications. The study of basic visual mechanism is yielding tools for both the assessment and treatment of early visual problems as well as the prediction and treatment of later ones.

LINKING LEVELS

Banks's investigation of optical information given by motion is one of the best examples we have heard of research that might link all three levels in the study of perceptual development. Work at the computational level, in the form of mathematical analyses of optic flow information, forms the starting point. Banks refines these accounts somewhat by noting the differences in available information in different kinds of environments, and most important, noting that the information extraction task must differ at different points in development. This latter claim is based on information already in hand about some aspects of retinal growth and development. An ingenious step, in my opinion, is the use of constraints determined at the computational level along with constraints given by anatomical development to begin to define the class of plausible algorithms for performing the computations. In Banks' recalibration algorithm, distortion across the visual field is determined from a situation in which only rotation and distortion contribute to optic flow (no translation). Since rotation has predictable (i.e., non-distance dependent) effects across the field distortion can be computed. One of the nicest features of Banks's approach is his linking of perceptual adaptation research with adults to the calibration problem in infant development. Interestingly one such study with adults may provide some empirical support for an algorithm like the one he proposes. Wallach, Moore, and Davidson (1963) found that subjects looking through a telestereoscope recalibrated retinal disparities by viewing a rotating cube. The telestereoscope, which increased all disparities, causes subjects at first to see the cube deforming, with each side elongating as it rotated away. After a short viewing period, however, the cube was seen as rigid, and other tests showed that disparities had been recalibrated appropriately. Rotation of the object was well specified by the information given to each eye. The parallel is that the predictable effects of rotation of the object in Wallach et al. (1963), analogous to rotation of the observer in Banks's situation, allowed distortions to be identified and enabled recalibration to occur.

Linkages across levels are also a primary concern of Braddick and Atkinson. Several of their studies involve both behavioral and neurophysiological measures of sensory function. Caution is required, of course, in inferring perceptual limits from measures, e.g., visual evoked responses, whose functional status remains uncertain. Moreover, displays that are elementary from the perspective of some stimulus descriptions (e.g., static sinusoidal luminance gratings) may not be building blocks of ordinary perception, nor even diagnostic of ordinary processes. Despite such uncertainties, the convergence of physiological and behavioral measures helps to confer validity on both the stimulus descriptions and dependent measures. Atkinson and Braddick's work provides some of the most impressive evidence of progress using this strategy.

One example is the relating of visual evoked potentials triggered by binocular correspondences to the emergence of behavioral evidence for binocular function. The understanding of binocular function as emerging by cortical maturation at 3–5 months of age is one of the noteworthy achievements in research in perceptual development in the last decade (Braddick & Atkinson, 1983; Fox et al., 1980; Held et al., 1980). The convergence of behavioral and neurophysiological data places the argument for maturational origins on a much stronger footing than would be possible from either kind of data alone.

Other results reported by Braddick and Atkinson may indicate other maturational constraints on the emergence of perceptual knowledge, such as 1-month-olds apparent lack of orientational selectivity and also their failure to discriminate patterns composed of the same spatial frequency components on the basis of phase differences. Braddick and Atkinson distinguish between spatial frequency analysis as a stimulus description and as a description of processing. As they point out, however, even if spatial frequency components are not the units of early visual processing, the results point to early difficulties in detecting certain local properties of patterns.

It is interesting to try to reconcile these findings with certain reports of neonatal perceptual competence, for example, shape constancy for planar figures in different orientations (Slater & Morison, 1985). Moreover, one wonders whether sensory limits in the earliest weeks apply equally well to sensitivity to information in moving displays, upon which much of early object perception appears to be based (Kellman, 1984; Kellman & Spelke, 1983).

OBJECTS: PERCEIVED OR KNOWN?

In the remainder of my comments, I take up object perception as an example of an ability that has been illuminated by recent research, but that still poses major questions within and between the various levels of study in perception. The most open-ended question is, not surprisingly, the level of representation and algorithm.

Empirical work of recent years has sharply constrained the class of plausible theories of the origins of object perception. As Spelke points out, it is no longer plausible to think of the visual perception of objects as deriving from active manipulation of objects, as in Piaget's or Helmholtz's view. It is furthermore clear that transforming optical stimulation plays a special role in infants' perception of object unity and form. Our increasingly specific knowledge about the conditions under which young infants perceive objects allows us to frame hypotheses about the processes involved. Spelke goes so far as to suggest that the apprehension of objects is not a process of perception at all, but one of cognition. The outputs of perceptual processes – representations of surfaces and of motion, for example – are used in knowing objects, but perceptual outputs are not sufficient. Instead, inborn concepts guide the segmenting of the world into units. This position might be called a Chomskian view of object perception. In *Rules and Representations* (1980, see especially pp. 94–100), Chomsky suggests that, like language, object knowledge might be a richly structured cognitive domain, triggered or engaged by, but not determined by, input from the environment.

Thinking about this view, it is hard for me to resist a personal note. When I first began to study perception almost a decade ago, my intuitive outlook was that perception of the world depended heavily on other cognitive processes. Now, I believe that the major determinants of perception are twofold. One is the information given by the physical environment. The other is perceptual machinery that by its design constrains perceptual outcomes in accordance with the most basic physical properties of the environment (e.g., space has three dimensions). The design constraints are also products of the environment, fashioned over evolutionary time. The key instigator in leading me to view perception as determined more by the world than by the mind was Liz Spelke, who introduced me to J. J. Gibson's work. It is possible that Liz and I have switched places, at least regarding objects.

Perhaps our positions are not really so far apart. The need for innate constraints related to the basic structure of the physical world seems clear. The main difference is that I believe such constraints are not based on explicit beliefs but are incorporated in the design of systems that are truly perceptual. The claim that surfaces and motion are perceived but objects are not seems especially unwarranted, since in all of these cases the outputs are rich descriptions of the world obtained by means of incoming information along with built-in constraints.

In my opinion, Spelke's arguments are important more for considering what kinds of perceptual theories are workable, rather than for distinguishing perception and cognition. She argues against J. J. Gibson's idea that object perception is based on invariants, raising two aspects of that approach that have proved problematic. One is the idea that a one-to-one correspondence exists between invariants and properties of the environment. Certain interactions of spatial and kinetic properties in object perception seem incompatible with a simple mapping of information onto percepts. For example, when a gap is visible between two objects sharing a common motion, they are not perceived as a unit, as they are when the gap is occluded. It is not clear to me that the information for unity could not be formulated in a general fashion unifying both spatial and kinetic factors. More generally, however, the one-to-one correspondence idea is not as plausible as the alternative idea that certain properties are specifiable by multiple invariants (Cutting, 1986). This modification in object perception need not make it nonperceptual, however. A second argument concerns specification. Spelke claims that object perception must be inferential because "the object properties of cohesion and boundedness, unlike the surface properties of spatial contiguity and common movement, do not appear to be specified by optical invariants." If information available is insufficient to "univocally specify" the layout (J. J. Gibson, 1966, 1979), the process must be considered inferential, at least formally (cf. Fodor & Pylyshyn, 1981).

Most theorists would accept the claim that constraints of some kind are required to map stimulus information onto perceptual outcomes. The need for constraints does not, however, distinguish motion and surface perception, which Spelke suggests are perceived directly, from object perception. For example, Marr (1982) has argued persuasively that built-in constraints are required to solve the correspondence problem in stereopsis, which is a basic way of perceiving the surface layout. In my view, the crucial and "live" issue dividing direct and inferential theories of perception is whether constraints are incorporated in the design of "detectors" of environmental properties (Braunstein, 1976; Johansson, 1970) or whether intermediate representations and algorithms mediate between incoming information and percepts (Epstein, 1982; Marr, 1982; Rock, 1983).

Framed in this way, Spelke is arguing that surfaces and motion are directly perceivable, but that objects are not; detecting objects requires computation based on the outputs of surface and motion detection systems. The specific step that cannot be performed directly is the imposition of *boundaries* in space and time.

The argument seems unworkable to me. Some kinds of optical information for boundedness, such as the accretion and deletion of texture elements during object or observer movement (J. J. Gibson, Kaplan, Reynolds, & Wheeler, 1969), are among the very best examples of perception tied directly to specific stimulus variables. Some additional reflection on the notions of surface and object also casts doubt on the distinction: to perceive a surface *is* to perceive a bounded entity, but one that, unlike an object, is not bounded in all dimensions of space. It is hard to imagine a principled reason why partial boundedness can be specified optically but complete boundedness cannot.

It seems more likely that *some* aspects of objects *some* of the time are perceived through algorithmic processes. The best available candidate is early perception of the unity of partly occluded objects, which depends on relationships in perceived motion, no matter how the motion is specified (Kellman, Gleitman, & Spelke, in press; Kellman, Spelke, & Short, 1986). Even here, caution is in order. Arguing that perceived unity depends on perceived motion is motivated by parsimony: Unity depends on a single dependent variable, perceived motion, rather than on a list of multiple stimulus variables that can specify motion. However, motion, which we take to be directly detected, already requires explanation in terms of multiple variables. Is it really less parsimonious to explain unity in terms of the multiple variables already required to explain motion? In both domains, it also remains possible that some higher order description of the available information could unify what currently seem to be separate stimulus variables.

Despite this caution, it still seems plausible that perceived object unity in occlusion cases involves algorithmic processes. Other aspects of object perception may not, however, As mentioned above, some sources of information for boundaries seem direct, such as the accretion and deletion of texture.

Moreover, object properties such as three-dimensional form may be tied to specific projective geometric information in transforming optic arrays (Kellman, 1984).

Spelke discounts the idea that objects may be *perceived* according to either direct or computational theories on the basis of another argument. Early object perception in different modalities, specifically visual and haptic, seems to rest on the same kinetic relationships. If different perceptual systems were responsible, we would not expect them to follow similar principles, since each "operates on one kind of physical stimulation . . . in accord with constraints on the way the layout is projected in that sensory mode." Similarities in the rules of object perception across modalities suggest "systems of thought," rather than "modality-specific modules."

In my opinion, this view neglects the most important contributions of both ecological and computational approaches to perception. What these different perspectives agree upon is that much of the important information in perception consists of abstract spatiotemporal relationships; the sensory medium in which these relationships appear is more incidental than previous, sensation-based theories implied. This does not mean that information is not acquired by modular systems specialized to certain kinds of energy; it does mean that the *same* constraints based on the material, spatial, and temporal structure of the unitary world *should* arise in different modalities. The relationships between the movements of parts of a unitary, rigid object are abstract, e.g., not visual, and they are specifiable in reflected light, tactile information, echoes given to bats, and so on. Some of the most persuasive examples in infant perception of informational identities across different senses have in fact been furnished by Spelke's research (e.g., 1976) on the intermodal perception of unfamiliar events based on temporal information.

My arguments so far have suggested that the phenomena of early object perception do not differ in principled ways from other perceptual phenomena and may be subsumed by perceptual theories without undue strain. There may be an additional problem in considering the apprehension of objects to derive from beliefs rather than from perceptual rules. Spelke suggests that infants are born with beliefs about objects, e.g., that visible parts belonging to the same object can move in certain ways, but what the data seem to demand (Kellman & Spelke, 1983) is the belief that visible parts moving in certain ways belong to the same object. It is the direction of the conditional that differs in these two formulations. The latter conditional—if the movements of things relate in certain ways, then they belong to a single object—is not deducible from its converse. Moreover, it does not make a very appealing belief about the physical world. A hand and an object it carries are spatially contiguous and share a common movement, yet they do not make up a unitary object. It seems clear from available data that in such an instance infants might well perceived (or apprehend) unity. The issue is how we should interpret such a mistake. One interpretation is that perceptual mechanisms, following usually accurate but not infallible perceptual rules, can deliver an inaccurate result. Misperception of this sort is compatible with, in fact expected by, most perceptual theories, especially inferential theories but also certain approaches to direct perception (Braunstein, 1976; Johansson, 1970). From a concept-based perspective, this mistake might reflect an erroneous core belief about physical reality. To me, this possibility seems more problematic. Erroneous perceptions can be corrected by inborn or developed concepts of physical reality, but how could erroneous innate ideas—that define what an object is—be corrected? One way to avoid the difficulty would be to impute to infants a belief that certain spatial and kinetic relations pick out unitary objects with high probability. This proposition, however, does not really follow from beliefs about what objects are and how they cohere and move; it also requires some belief about how common it is for separate objects to move in related ways. If such beliefs are necessary for the theory to work, its appeal is lessened, because these beliefs are grounded in probable characteristics of the environment, rather than defining properties of objects.

On balance, I prefer to interpret the evidence and arguments marshaled by Spelke as helping to clarify what perceptual explanations are plausible. Basically, I think she is arguing for an explanation of object perception as primarily unlearned, formally inferential in character, algorithmic rather than direct in process, and guided by ecological constraints. As a perceptual account, I find this one plausible, primarily because of the apparent dependence of perceived unity on perceived motion (Kellman, Gleitman, & Spelke, in press).

I want to close this discussion of objects where I began. Our current concerns raise challenges for further research, but they also mark considerable progress. The alternatives we debate now are not the ones that would have been debated at a meeting like this 20 years ago. Object perception, along with many other important perceptual abilities, seems to rest on innate foundations, whether perceptual or conceptual, and in its earliest appearance, utilizes a special class of information.

More generally, this symposium has demonstrated that research at all levels in the study of perceptual development is propelling similar refinement of theoretical perspectives. Improved analyses of the task and the informational bases of perception in combination with advances in the study of perceptual mechanisms are leading toward explanations that are more integrated and comprehensive than have previously been possible.

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