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The Development of Intermodal Perception*

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I. INTRODUCTION

As people make their way around the world, they encounter objects
and events by looking, listening, and touching. Adults perceive a single
layout through these actions. When we look and listen to a singing bird, or
see and feel the surface of a table, we are aware of unitary objects, not
separate streams of sensation. This experience is possible, in part, be-
cause we are able to detect relationships among the sight, sound, and feel
of an object. If a person can detect such relationships and thereby per-
ceive a world of unitary objects and events, she will be said to be capable
of "intermodal perception."

This chapter is concerned with the origins and development of the
capacity for intermodal perception. It will discuss the primitive structures
which might serve as the foundation for this ability, and the mechanisms
of learning and development that might guide its growth. The discussion is
organized around three theoretical perspectives on perceptual develop-
ment, which I will call the "sensation-centered," the "action-centered,"
and the "perception-centered" perspectives. These perspectives were

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* This chapter was originally conceived in 1979. To the author's regret, it treats only
briefly the work of newer investigators of infant perception.

chosen because each roots the capacity for intermodal perception in a different kind of primitive structure, and each postulates different principles and mechanisms of development. After these perspectives have been described, the chapter turns to selected research on intermodal perception in human infancy. It closes with an evaluation of the perspectives and with some suggestions about further research.

II. THREE PERSPECTIVES ON THE DEVELOPMENT OF INTERMODAL PERCEPTION

All theories of the development of intermodal perception agree on two points. First, the capacity for intermodal perception is influenced by learning. Relationships between sounds, feelings, and visible objects can be quite arbitrary: the sound of a certain kind of siren signals the approach of a fire engine, for example, only because of the conventions of our culture. As adults, we increase our ability to detect intermodal relationships by learning about the arbitrary connections between visible, audible, and tangible events. To account for this and other kinds of learning, each theory provides means by which the capacity for intermodal perception can grow as perceivers gain experience.

The second point of agreement is more subtle. All theories of intermodal perception acknowledge that humans have some unlearned ability to detect relationships among that which they see, hear, and feel. Logic demands that perceivers be sensitive innately to some intermodal relationships: if the eye, ear, and hand gave rise to fully separate streams of sensation on no common base, children could never have experiences through which to learn, on their own, that certain visible episodes belong with certain auditory or tactile episodes. In order to learn that fire engines make siren sounds, for example, children must experience some relation between the visible engine and its siren on some occasion, inducing that the sound and the object go together. If children can perceive the siren and engine as related, however, then obviously they already have some capacity to detect intermodal relationships. According to every theory, therefore, humans are able to detect certain intermodal relationships innately, and we use this ability in order to learn spontaneously about further intermodal relationships.

Although the existence of innate and learned capacities to detect intermodal relationships is not in dispute, the nature of these capacities has been debated greatly. Different theories offer very different accounts of the child's initial capacities for detecting intermodal relationships, and of the principles and mechanisms by which the child learns to detect further intermodal relationships.

A. The Sensation-Centered Perspective

According to the first perspective, sensations and a capacity to detect temporal relationships among sensations constitute the primitive basis of intermodal perception, and associative learning processes provide the mechanism for development. The sensation-centered perspective, inherited from empiricist and associationist philosophers, is probably the dominant contemporary view of the development of intermodal perception. This chapter will focus on one of its many variants, derived from the perceptual theory of Hermann von Helmholtz (1885/1962).

To Helmholtz, any meaningful perception depends on the evocation of a set of unconscious sensations and the interpretation of those sensations by an unconscious process akin to inference. Perceivers infer that they are seeing, hearing, or feeling those objects that are the most likely causes of a given pattern of sensation. The sensations themselves are evoked by stimulation directly and innately. The capacity to discover predictable patterns within a stream of sensation is also innately given: children are naturally predisposed to seek and discover contingencies among sensations. Finally, there is an innate tendency to hypothesize that certain predictable patterns of sensation are caused by external objects. All else is learned. Children learn about the predictable patterns of sensation they are likely to encounter. Like experimental scientists, they generate hypotheses about the external objects that are the most likely causes of each pattern, and they test these hypotheses by exploring the world actively and systematically:

> Just how such cognizance of the significance of visual images is first assembled by young children becomes readily apparent when we watch them while they are busy with objects offered to them as toys, how they handle them, look at them from all sides by the hour, turn them around, put them in their mouths, etc., finally throw them down or try to break them, and repeat this each day. One cannot doubt that this is the school where they learn the natural condition of the objects around them . . .
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> (Reprinted by permission from von Helmholtz, 1894/1970, pp. 252–253.
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This theory can be applied to the problem of intermodal perception. Sensations, for Helmholtz, are modality-specific. When an object is simultaneously seen, heard, and felt, however, sensations in one mode are contingently related to sensations in the other modes. Since children are innately capable of analyzing certain contingencies between sensations, they will come to discover the predictable relations among these visual, auditory, and haptic experiences.

Helmholtz did not describe specifically the kinds of contingencies that children detect or the processes of contingency analysis that they apply. The processes usually discussed within learning theory (see Schwartz,

1978) would *not* seem to be suitable to the task of perceiving a unitary object. Those processes respond not only to relationships among sensations that are produced by one object, but also to relationships among sensations that are produced by several distinct objects. For example, the sound of a doorbell is contingently related to the visual sensation of someone appearing at the door. It would not be desirable, however, for children to treat a person and a doorbell as parts of a single object: children might well learn that the sound of a doorbell predicts the appearance of someone at the door, but they should continue to perceive these events as separate. A major task for any sensation-centered theory of intermodal perception, therefore, is to describe the kinds of contingent relationships that could underlie the perception of unitary objects. No account of contingency analysis within learning theory, to my knowledge, provides a solution to this problem.

Let us suppose, nevertheless, that there are types of contingent relationships among sensations that occur when, and only when, a single object is both seen and heard or seen and felt. If children can detect these relationships through a process of contingency analysis, then they might learn to perceive unitary audible, visible, and tangible objects.

B.   The Action-Centered Perspective

According to the second perspective, actions and their structural relationships provide the innate basis for intermodal perception, and development occurs as these actions become appropriately structured. This perspective derives primarily from the developmental theory of Jean Piaget (1952). Piaget proposed that children are born with ''reflexes'': simple actions that are set in motion by uninterpreted sensory configurations. These actions are independent of one another initially but become coordinated with development because children are also born with tendencies to exercise, extend, and organize their actions into stable structures. Children act spontaneously on the objects that the environment provides, assimilating objects to familiar actions and adjusting these actions to new objects. Thus, a child's activities become articulated and organized. To Piaget, the structuring of action underlies the development of all knowledge. Children come to represent the world of objects in progressively more stable and balanced ways as their actions gain structure and generality.

Piaget's approach to intermodal perception follows from this framework. A reflex action may center on the eyes, hands, mouth, or any other sensitive organ, but there are no reflexes that span separate perceptual systems, and hence no initial capacity for intermodal perception. With

development, the senses become coordinated through a process of "reciprocal assimilation": one action (such as looking) is directed to another action (such as moving the fingers), and each is adjusted to the other. When this assimilatory activity has reached equilibrium, sights will evoke reaching and tactile feelings will evoke looking. The diverse actions that can be directed to one object will be fully coordinated eventually, and the child will be able to represent the object as a unitary entity, perceivable through each act and conceptually distinct from them all.[1]

Piaget has described the developing coordinations among actions at a highly abstract level; his description does not clarify *how* the development of structural relationships among actions leads to the apprehension of unitary objects and events. As infants direct different actions to the same object, similar structures are said to develop in the different action systems. Presumably infants perceive unitary objects by detecting these structural relationships. Structural relationships develop among many actions, however, including actions that are *not* directed to the same object. For example, children come to coordinate the act of following a pitched ball with the act of swinging a bat, and the act of beating a drum with the act of marching in a parade. How do children determine whether two coordinated actions are, or are not, directed to the same object? An action-centered theory evidently must propose that there is a special kind of coordination that develops between different actions when, and only when, the actions are directed to a single object. It must propose, moreover, that children have a capacity to detect this special relationship and to recognize it as an indication of a unitary object. Children may perceive unitary objects by looking, listening, and feeling because they can detect a special kind of structure that unites actions that are directed to the same things.

In brief, the action-centered perspective discussed in these pages posits that the reflex actions of newborn infants share no detectable structural relationship, and that actions directed to a single object became structurally related, in a special way, with development. Children are innately

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[1] In some of his writings (e.g., Piaget, 1969), Piaget states that children and adults have perceptual structures that are only loosely related to action structures. Since he does not directly discuss the perceptual capacities of infants in his principal writings on infancy (Piaget, 1951, 1952, 1954), it is not clear whether he would endow the infant with any innate perceptual structures. Nevertheless, Piaget explicitly states, both in his writings on infancy and in his writings on perceptual development (Piaget, 1969), that knowledge of objects, including knowledge of their multimodal properties, arises from the structuring of action, not from perceptual capacities. In discussing the action-centered approach, accordingly, I will not consider the possibility that purely perceptual structures play a role in intermodal development.

sensitive to these special structural relationships: once the relationships develop, they detect them and perceive unitary objects. Inexperienced infants cannot perceive unitary objects or events, therefore, but they possess some of the central underpinnings of that ability.

C. The Perception-Centered Perspective

According to the third perspective, intermodal perception is rooted in innate mechanisms for perceiving properties of objects, and development occurs as children become able to perceive new object properties. We will focus on the most comprehensive statement of this position, by James J. and Eleanor J. Gibson (E. J. Gibson, 1969, 1982; J. J. Gibson, 1966, 1979).

To the Gibsons, any animal perceives objects, events, and their properties by exploring the environment and detecting invariant relationships in the stimulation it receives. As a person moves her hand around an object, for example, she produces an ever-changing pattern of stimulation on her fingers, but there are relationships in this pattern that are constant. Some of these relationships specify properties of the object, such as its shape and its rigidity. Invariants in stimulation specify properties of events as well. As a person follows an event by looking or listening, her perceptual systems register invariant relationships in light or sound that specify the nature of the event and the things that participate in it. By detecting these relationships, perceivers apprehend properties of the world.

According to the Gibsons, humans and other animals are initially sensitive to certain invariants, and they can perceive the properties of objects and events specified by these invariants. With experience, children become sensitive to new invariant relationships, and thus they come to perceive new aspects of the environment. Learning comes about largely through changes in perceptual selection. Perceivers learn to search for the invariant information that specifies significant properties of the environment. Such learning leads to a progressive differentiation of the perceptual world.

Intermodal perception is possible, according to the Gibsons' theory, because some properties of objects are "amodal": they are specified to more than one perceptual system.

> Unity is the natural effect of multiple specification of invariant properties of things, places, and events.
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> (E. J. Gibson, 1983, p. 23)

For example, a rough, irregular texture is specified both by invariant relationships in arrays of light at the eye and by invariant relationships in

patterns of pressure on the skin. When a perceiver of any age detects an object in two different modes at once, and when the same object properties are perceived in the two modes, she will perceive a unitary object.[2]

Like the sensation-centered and the action-centered perspectives, the perception-centered perspective faces a problem accounting for the development of intermodal perception. Humans perceive the same amodal properties not only when we look at, listen to, and feel a single object, but also when we look at one object while listening to or feeling a second object that is distinct from, but related to, the first. The sound of a violin in an orchestra, for example, has properties in common not only with the visible movements of its bow, but also with the visible movements of the conductor's baton. In order to perceive a unitary object, there must be special amodal properties that unite a visible object only with its own sound, and perceivers must be sensitive to the information that specifies these properties. These properties have not been described in detail (but see E. J. Gibson, 1983, and Spelke, 1983, for further discussion). In the perception-centered perspective discussed in this chapter, it will be assumed that such properties exist and that perceivers detect some of them without learning.

To the Gibsons, in short, the capacity for intermodal perception does not depend on any learned coordination between perceptual modes: humans begin life with capacities to perceive unitary objects by detecting some of their amodal properties. The capacity for intermodal perception does grow, however, as perceivers come to detect further amodal properties. As children explore the environment, they became sensitive to finer and finer distinctions among the properties of events. Furthermore, children come to distinguish among the modalities themselves (Bower, 1979;

[2] The perception-centered approach discussed in this chapter roots intermodal coordination in the perception of "distal," amodal properties of objects, not in the detection of amodal invariants in the flow of "proximal" stimulation. According to this approach, one will experience an intermodal relationship whenever the same object property is detected in two modes, whether or not that property is specified by the same invariant stimulus relationship in each of the modes. For example, a child could perceive a relationship between the face and the voice of her father even if she perceives the father's face by detecting its coloring and its spatial structure and perceives his voice by detecting its fundamental frequency and its temporal structure.

The reader should note that both James and Eleanor Gibson have consistently emphasized the amodal character of most stimulus invariants, as well as the amodal character of most object properties. Intermodal perception, on their view, depends both on the detection of amodal stimulus invariants and on the perception of anodal object properties. Their theory of amodal invariants will not be considered in the present chapter, however, for it is not easily distinguished from certain versions of the sensation-centered theory. For a discussion of amodal invariants and their possible role in intermodal perception, see E. J. Gibson (1983) and Spelke (1983).

E. J. Gibson, 1969). *A young child may not distinguish between seeing an object and hearing or feeling it; she may simply perceive the object itself* and its properties. An older child does distinguish between seeing, hearing, and touching an object, at least in some circumstances.

D. Overview

These are the three perspectives that will guide our inquiry. They offer three contrasting views of the primitive basis of intermodal perception: sensations and mechanisms for detecting temporal contingencies between them, actions and mechanisms for detecting structural relationships among them, and perceptions of amodal properties and mechanisms for detecting stimulus invariants that specify them. The perspectives also propose three kinds of learning process: the analysis of contingencies among sensations and the formation of hypotheses about the likely external causes of these contingencies, the reciprocal assimilation of actions leading to the development of stable action structures and ultimately to the representation of the things that are acted upon; and the abstraction of invariant stimulus relationships leading to the differentiation of the perceptual world.

The rest of this chapter will be concerned with experimental attempts to evaluate these perspectives. This review of research will be selective, for not all research on intermodal functioning in infancy has been undertaken to investigate the child's developing ability to detect relationships among the sight, sound, and feel of an object. Some investigators have focused on the development of levels of coordination between different sensory systems, in order to shed light on the hierarchical development of the nervous system (e.g., Mendelson & Haith, 1976). Some investigators have focused on the development of skills of intermodal exploration, such as the skill of reaching for a visible object, with the goal of understanding skills in general, their acquisition, and their role in cognitive development (e.g., Bruner, 1974). Some investigators have focused on the emergence of abilities to represent an object perceived in one mode and to recognize the object in a second mode, with the ultimate goal of understanding the development of memory, learning, and transfer (e.g., Gottfried, Rose, & Bridger, 1977). The present chapter will not do justice to these efforts. Studies of intermodal development will be discussed only insofar as they shed light on our central concern: the development of knowledge of relationships between auditory, visual, and haptic information about an object or event.

A second caution is in order. Even when an investigation is motivated by the theoretical issues discussed in this chapter, its results are seldom

decisive. It is difficult to evaluate these three perspectives experimentally: one cannot simply show, for example, that a relationship between the modalities is, or is not, detected at some particular age in infancy. The primary difference between the three perspectives concerns the *basis* on which intermodal relationships are detected, not the *time* at which the ability to detect such relationships first appears. It is necessary to determine whether the first intersensory coordinations depend on detecting the contingencies of sensations, the structure of actions, or the properties of objects. Similarly, an investigator cannot simply demonstrate that infants learn, or fail to learn, about intermodal relationships at some age. To distinguish among these theoretical perspectives, he or she must investigate the conditions under which learning occurs and the nature of what is learned: whether sensations become associated, actions become structured, or new object properties come to be perceived. It is not surprising, therefore, that psychologists still cannot pass conclusive judgment on any theory of intermodal development.

III. THE FOUNDATIONS OF INTERMODAL PERCEPTION

This section focuses on investigations of the infant's initial capacities to explore objects and events intermodally, to perceive unitary events by looking and listening, and to perceive unitary objects by looking and touching. These investigations should help to reveal whether children begin with abilities to detect temporally related sensations, structured actions, or amodal properties of objects.

A. Intermodal Exploration

Adults tend to look in the direction of a sound and to reach for things they see, especially when these things are unfamiliar and unexpected. In these ways, adults maximize the pickup of information about objects and events. Psychologists have asked whether infants act in these ways as well, and if so, what capacities underlie their actions.

Many observers now agree that newborn infants look reliably toward or away from laterally presented sounds. Newborns have been shown to turn their eyes quickly and briefly toward soft sounds and away from loud sounds (Butterworth & Castillo, 1976; Crassini & Broerse, 1980; Hammer & Turkewitz, 1975; Mendelson & Haith, 1976; Turkewitz, Birch, & Cooper, 1972; Turkewitz, Birch, Moreau, Levy, & Cornwell, 1966; Wertheimer, 1961). Newborn infants have been found to look in the direction of a centrally presented sound—a human voice—as well (Mendelson

& Haith, 1976). Finally, newborn infants turn their heads as well as their eyes toward a sound if it is of long duration and if the infants are properly supported. In several studies, infants were presented with the sound of a rattle, 90° to one side of the head, for 20 sec. After the sound was played for 2 to 3 sec, infants began to turn their heads slowly until they faced the sound directly (Clifton, Morrongiello, Kulig, & Dowd, 1981; Muir & Field, 1979). The same pattern was observed with sounds that were presented very briefly (Clarkson, Clifton, & Morrongiello, 1983). Head turning toward a sound disappears at about 2 months of age and then returns a month later (J. Field, Muir, Pilon, Sinclair & Dodwell, 1980; Muir, Abraham, Forbes, & Harris, 1979).

These observation show newborn infants at their best. In other situations, young infants do not appear to coordinate their looking and listening. For example, visual scanning is not affected by sounds moving continuously across the field of view, either in the presence or in the absence of a visible object (McGurk, Turnure, & Creighton, 1977). Moreover, the tendency to look to a peripherally presented visual display is unaffected by the introduction of an unrelated sound on the same or the opposite side of the visual display (Castillo & Butterworth, in Butterworth, 1981; J. Field, diFranco, Dodwell, & Muir, 1979; McGurk et al., 1977). In these situations, looking is influenced only by the characteristics of the visual display. It appears that the presence of the visual display either distracts attention from the sound or causes infants to localize the sound incorrectly. Both effects are sometimes observed with adults (e.g., Klein, 1977; Radeau & Bertelson, 1977).

Further studies of looking toward a sound reveal that these turns are very inaccurate. In one experiment, for example, infants were presented with a visual or auditory display 10°, 20°, or 40° to the left or right, and their lateral eye movements were observed. With visual displays, the infants looked rapidly in the appropriate direction, turning their eyes further for a more distant stimulus. With auditory displays, infants again looked in the correct direction, but they looked with longer latencies, and the size of their eye movements was unrelated to the distance of the display (Bechtold, Bushnell, & Salapatek, 1979). The failure of infants to scale their looking to the radial distance of a sound may stem from inaccuracies in sound localization. Alternatively, young infants may localize sounds with some accuracy but may fail to calibrate their eye movements to a sound's perceived direction. Bechtold and his collaborators favored the second possibility, and they suggested that infants may need to learn to calibrate visual and auditory systems for localizing objects.

In brief, there is some coordination at birth between auditory localization and systems controlling head and eye movements, but this coordina-

tion is far from perfect. The basis for this coordination is not clear. It has been suggested that newborn infants perceive a lateral sound to specify a potentially visible object in the sound's direction: infants turn toward the sound because they expect to see something (Bower, 1979). Failures to look toward a sounding object, on this view, are caused by limits on infant's abilities to deploy attention and to coordinate actions.

Other investigators, in contrast, have concluded that sound-guided head and eye movements are controlled by simple motor programs triggered by uninterpreted sensory patterns (Butterworth, 1981; McGurk et al., 1977). For example, lateral eye movements and head movements might be elicited reflexively by a difference in the intensity or in the time of arrival of a sound at the two ears. Gradual head movements toward an enduring sound may reflect a tropistic tendency to eliminate such interaural differences (J. J. Gibson, 1966, 1976; Muir & Field, 1979). In either case, infants would be able to look systematically toward events without anticipating that they will see an object in any definite spatial position. In support of the second view, it should be noted that infants turn their eyes and heads towards sounds in dark rooms as well as lighted ones (Mendelson & Haith, 1976; Muir et al., 1979), when their eyes are closed as well as when they are open (Turkewitz et al., 1966). These findings cast doubt on the view that infants are "looking for" an event, although they do not rule out that possibility.

If the first interpretation of sound-guided looking could be confirmed, it would support the perception-centered perspective on intermodal development, since auditory–visual exploration would depend on the perception of an amodal property of an object: its position in space. The second interpretation, however, is consistent with all three perspectives. Helmholtz's and Piaget's theories deny that infants innately perceive objects in space by looking and listening, whereas Gibson's theory may be noncommittal as to whether such a perceptual ability guides the earliest acts of orienting. In short, research on auditory–visual localization has not distinguished among theories that offer sensations, actions, and perceptions as the primitive basis of intermodal perception. Future research might be more decisive, as investigators focus on the mechanisms that underlie sound-guided looking (for example, see Morrongiello & Clifton, 1984).

Visual–haptic exploration changes dramatically with development (see Hatwell, in press, for a lucid review). Only at 4 or 5 months of age do infants begin to reach effectively for the things they see (see White, Castle, & Held, 1964). Visually elicited reaching could develop in the manner that Helmholtz described: perhaps infants thrash out at random in the presence of certain visible sensations, observe the consequences of these

thrashings, and predict and test these consequences. Alternatively, reach-

ing could develop in the manner described by Piaget, through the recipro-
cal assimilation and coordination of visual and manual actions. Finally,
infants could begin with an ability to perceive some spatial properties of
objects by looking and touching, as the Gibsons suggest, but only gradu-
ally develop the motor skill that allows them to reach for objects success-
fully. Studies of the development of effective reaching have investigated
these possibilities.

Over the last decade, a number of investigators have focused on the
manual activity of newborn infants. Several observers have reported that
certain movements of the hands occur when infants are first presented
with a visible object, and that the patterning of these movements is similar
in some respects to the patterning of movements by older infants who
reach for objects. These manual activities have been termed "prerea-
ching" (Trevarthen, 1974).

The nature of prereaching activities has been a subject of controversy.
Some investigators have reported that newborn infants' hand and arm
movements are adapted to spatial characteristics of an object such as its
distance, direction, and solidity (Bower, 1972; Bower, Broughton, &
Moore, 1970a; Bower, Dunkeld, & Wishart, 1979; Trevarthen, 1974; see
also Butterworth, 1978; de Schonen, 1977; Hofsten, 1982). These investi-
gators have concluded that infants perceive unitary objects by looking
and feeling and move so as to apprehend the objects. Other investigations
have provided no evidence that the earliest manual activity is guided by
visual information for the position and the properties of an object (di-
Franco, Muir, & Dodwell, 1978; Dodwell, Muir, & DiFranco, 1976, 1979;
Rader & Stern, 1982; Ruff & Halton, 1978). These investigations have led
to the suggestion that neonatal arm movements do not reflect a capacity to
perceive objects but rather a state of excitement or orienting (Bushnell,
1981).

Turning to observations of somewhat older infants, a number of investi-
gators have studied the precursors to reaching, asking if infants learn to
reach by trial and error, if they come to reach as they engage in reciprocal
assimilatory activity, or if they already perceive the potentially tangible
properties of an object by looking and need only learn to control their
arms. Most of the evidence supports the last alternative: the manual
activity of prereaching infants appears to be guided by visual perception
of some of an object's spatial properties. Prereaching infants swipe their
arms more frequently when they view an object than when they do not
(Twitchell, 1965; White et al., 1964), and they engage in this activity more
frequently when viewing an object within reaching distance than when
viewing a more distant object (J. Field, 1976a; see also Bower, 1972).
Infants tend to swipe in the visible direction of the object (McDonnell,

1979; White et al., 1964), although their swiping may not be affected by the object's three-dimensionality (J. Field, 1976b). Finally, infants engage in activities precursory to reaching more frequently in the presence of an object of graspable size than in the presence of an object too large to grasp (Bruner & Koslowski, 1972). Before infants can reach effectively, they may perceive visually the size and distance of an object, and they may use this information to guide their attempts to manipulate the object.

Once infants begin to reach reliably, their reaching continues to be guided by the visible direction of an object (McDonnell, 1975), its distance as specified by convergence and certain other depth information (Hofsten, 1977; Yonas & Granrud, 1985), its size (Bruner & Koslowski, 1972), and its orientation (Hofsten & Fazel-Zandy, 1984; see also Lockman, Ashmead, & Bushnell, 1984). Most impressively, infants reach appropriately for moving objects. When infants reach for an object that moves across the field of view, they do not aim for the location of the object at the time the arm extension begins but rather for the location that the object will attain once the extension is complete (Hofsten, 1979, 1980; Hofsten & Lindhagen, 1979). These reaches become more successful as infants grow, and they have not been observed at all in infants younger than 4 months. Careful developmental research suggests, however, that the gradual improvement in reaching reflects the growth of the motor system and not the perceptual systems. Infants of all ages aim their reaches for the future position of a moving object, although older infants are better able to execute the intended motor sequence (Hofsten, 1980).

Mature reaching is visually guided in two senses: it is guided by the seen position of the desired object and by the seen position of the hand. By 5 months of age, an infant's reaching is influenced by both kinds of information. Infants of 5 to 8 months adjust their arm movements to accord with the seen position of the hand when the hand is visually displaced by prisms (McDonnell, 1975). The development of this guidance, however, may depend on experience. Lasky (1977) examined reaching to a visual object under circumstances in which infants either could or could not see their hands. When the hands were not visible, reaching was disrupted at $5\frac{1}{2}$ months, but not at earlier ages. In general, however, the younger children showed little reaching, so it is difficult to assess the effect of seeing the hand at that age.

In brief, young infants seem to perceive visually some of the haptically relevant spatial properties of an object: the object's size, distance, and direction. These findings suggest that infants perceive the same spatial properties of objects by looking and by touching, and that suggestion in turn supports the perception-centered perspective on intermodal development.

Strong conclusions cannot be drawn from this research, however, for

two reasons. First, the infants in all the noncontroversial studies were at least several months old. Visual–manual coordination could, conceivably, have resulted from earlier visual and manual experience. This possibility seems remote, because the manual exploration of a young infant is very limited (see E. J. Gibson & Spelke, 1983), but it cannot be dismissed.

The second reason for caution in interpreting these studies is that the perceptual basis for visually elicited reaching is not clear, especially at the younger ages. Infants' manual activities toward a visible object may not be guided by implicit knowledge of the graspability of the object but by reflexlike mechanisms triggered by sensory properties of the visual array. For example, a visible object may have more interesting sensory consequences if it is nearby than if it is far away: its surface texture is clearer and its texture elements undergo greater displacements in the visual field as infants move their heads. Infants may swipe more at nearer objects because they are more aroused by these sensory patterns. Similar factors could account for the effects of the size and the radial direction of the object (Bushnell, 1981). Hofsten's studies of reaching for moving objects cast doubt on this suggestion. There is no obvious reason why a rightward moving object on the infant's left should elicit a reach to the right, unless the infant perceived the moving object and anticipated its future position. To evaluate the sensation-centered, action-centered, and perception-centered perspectives; therefore, it would be desirable to conduct experiments such as Hofsten's with younger infants, presenting the infants with visible objects whose spatial properties vary systematically and observing the effects of these variations on both gross and subtle properties of the infants' actions.

In summary, studies of auditory–visual and visual–haptic exploration, while documenting that patterns of intermodal exploration improve with development, provide evidence that infants begin with capacities to perceive amodal properties of objects and to use these properties to guide their actions. In neither set of studies, however, is this evidence conclusive. More decisive experiments may be forthcoming, for investigators are now focusing on the detailed characteristics of infants' exploratory actions and on the visual displays that elicit those actions.

B. Auditory–Visual Perception of Events

We turn now to more direct studies of infants' sensitivity to auditory–visual relationships. A number of experiments have investigated the ability of infants, usually aged 3 to 6 months, to perceive a relationship between the sound and the visible appearance of an event. These studies present infants with events of many kinds, animate or inanimate, repeti-

tive or varied, familiar or novel. In all cases, infants are presented with an array of objects that is moved or deformed, and these object transformations are specified in some manner both in light and in sound.

Many of these studies are based on an interesting exploratory pattern. Infants, like adults, tend to look at the objects that they hear, even if auditory and visual information about an object do not come from the same position in space. This tendency provides psychologists with a means to study infants' perception of auditory–visual relationships. Two visible events can be presented simultaneously or successively, and a sound specific to one of the events can be played from a neutral spatial location. If infants perceive the sound as related to the appropriate event, they should look longer, more frequently, or more rapidly at that event.

In one experiment (Spelke, 1976), 4-month-old infants were presented with motion pictures of a game of peekaboo and of a simple percussion music sequence involving a baton, a tambourine, and a wooden block. The films appeared side by side, while one synchronized sound tract was presented through a central speaker. Infants looked longer at the event that was appropriate to the sound track: they evidently perceived each sound as related to the corresponding visible event. Subsequent research extended this finding (Bahrick, Walker, & Neisser, 1981). Four-month-old infants were shown pairs of events involving objects that moved in synchrony with their sounds, each pair accompanied by one of the two sounds. In one event, a ''slinky toy'' sprang back and forth between two hands, causing a metallic sound; in a second event, a hand-held baton hit a xylophone, producing a musical sequence; in a third event, two pairs of hands played ''pat-a-cake'' with appropriate clapping sounds. Infants responded to the sound–object relationships in all three events by looking at the event that corresponded to the sound.

Since these events consisted of natural, possibly familiar objects, infants might have learned about each sound–object relationship. Alternatively, infants might have detected the temporal synchrony of the sound of each object with changes in some of its visible properties. Experiments have now provided evidence that infants are sensitive to auditory–visual synchrony (Allen, Walker, Symonds, & Marcell, 1977; Humphrey, Tees, & Werker, 1979; Mendelson & Ferland, 1982; Spelke, 1979).

For example (Spelke, 1979), 4-month-old infants have been presented with films of two unfamiliar stuffed animals, each paired arbitrarily with a different percussion sound. Each animal was lifted into the air by puppet strings and dropped to the ground repeatedly, and its impacts with the ground were accompanied by one of the sounds. When both objects were shown at once and one sound was played briefly, infants tended to look at the sound-appropriate object. They did this when the sounds and objects

were temporally related in several different ways. In one condition, the two objects moved at approximately the same steady tempo but hit the ground at different times. Each sound occurred at the time of one object's impacts and was unrelated to the movements of the other object. In a second condition, the two objects moved at different tempos, and the sound occurred at approximately the same tempo as one object. The sound was not simultaneous with the impacts, or any other consistent spatial position, of either object. Infants detected both temporal relationships; they are sensitive both to the simultaneity and to the similar tempo of sounds and visible movements.

Further experiments provided evidence that infants are sensitive to the synchrony of speech with the visible movements of a face. Infants of 4 to 7 months of age, presented with unfamiliar faces and voices in a preference procedure, looked longer at a voice-synchronized face than at a nonsynchronized face (Spelke and Cortelyou, 1981; Walker, 1982). The same tendency was observed when 3-month-old infants were presented with one face at a time, accompanied by either a synchronized or a non-synchronized voice (Dodd, 1979). Since many facial movements are synchronized with a voice in the natural speech of adults to infants (Stern, Beebe, Jaffe, & Bennett, 1977), infants might have detected any of a variety of temporal relationships in these events.

Infants of 3 and 4 months, therefore, can detect certain temporal relationships between what they see and what they hear. Can infants detect other auditory–visual relationships? Experiments have addressed this question by presenting infants with temporally related sounds and objects that vary in their nontemporal properties.

One investigation focused on infants' perception of events involving impacts (Spelke, Born, & Chu, 1983). Infants could detect the synchrony of inanimate percussive sounds with the visible impacts of surfaces by relating the sounds to any of three types of visible events: the moment of impact, the moment at which the movement of the object changes, or the moment at which the object passes through a particular spatial position. These sound–object relationships were varied in a series of experiments, and infants' sensitivity to the intermodal relationships was assessed with preferential looking procedures. Infants were found to detect the synchrony of sounds with changes in the movement of an object, irrespective of its spatial position or its impacts with other surfaces. Adults, in contrast, perceived the clearest intermodal relationships when sounds were synchronized with impacts. By 4 months, infants already relate sounds to visible movements; their ability to relate percussive sounds specifically to visible impacts appears to develop after this time.

A second investigation focused on $4\frac{1}{2}$-month-old infants' perception of objects of different substances (Bahrick, 1983). Bahrick hypothesized that

infants would detect relationships between the characteristic sounds and visible movements of a rigid versus deformable object. Infants were presented with filmed events involving sponges and wooden blocks. In one film, two wet sponges were squeezed against each other in a manner that would normally produce a "squishing" sound. In the other film, two blocks were made to hit each other so as to produce a "clacking" sound. The squishing sounds were synchronized with the sponges and the clacking sounds with the blocks in one experimental condition; in a second condition, each type of sound was synchronized with the wrong type of object. Infants evidently were sensitive to the relationships between rigid or nonrigid sounds and movements, for they responded to the temporal relationships only when each sound was synchronized with the appropriate visible object. Bahrick proposed that infants perceive the substance of an object by looking and by listening, and that this perception serves as a basis for detecting intermodal relationships. She noted, however, that the infants in her experiment might have responded to further temporal characteristics of the sounds and movements, relating continuous sounds to continuous movements and discrete sounds to discrete movements.

A third experiment investigated infants' perception of expressive behavior by looking and listening (Walker, 1982). Infants of 5 and 7 months were presented with two films of a speaking person, one expressing happiness and one expressing sadness, while tape recordings of the corresponding voices were played. The voices were not synchronized with either of the moving faces. At first, infants showed no preferences between the faces, probably because of the absence of face–voice synchrony. After a few minutes, however, the infants began to look longer at the face that expressed the same mood as the accompanying voice. The infants might have responded to the emotional tenor of each face and voice. Alternatively, they might have responded purely to temporal information, since the happy speech was more rapid and animated than the sad speech. A further experiment supported the first possibility (Walker, 1982). Infants were presented with a happy face and a sad face under conditions in which the faces appeared either right side up or upside down. In both conditions, the faces were accompanied by a voice that was emotionally appropriate to, and synchronized with, one face. The upside-down condition is of interest because it preserves all the temporal relationships present in the right side up condition, yet adults have great difficulty discerning emotional expressions at this orientation. Infants looked at the appropriate face only when it appeared in its canonical orientation. Infants did not respond exclusively to the temporal structure of the visible events, but also to some properties specific to a face, perhaps properties associated with an expression of emotion.

Finally, two series of experiments have focused on intermodal percep-

tion of specific speech sounds (Kuhl & Meltzoff, 1982; MacKain, Stud-
dert-Kennedy, Spieker, & Stern, 1983). Following the preferential look-
ing method, infants were played a series of vowels or simple syllables
while watching two faces. Both faces (on film or videotape) moved in
synchrony with the voice: one face articulated the appropriate speech
sounds, and the other articulated inappropriate speech sounds. The in-
fants looked preferentially to the person whose articulations corre-
sponded to the accompanying speech. By 4 months of age, infants evi-
dently detect relationships between particular speech sounds and
particular facial movements.

In summary, infants are responsive to a variety of auditory–visual rela-
tionships. Does their response depend on detecting contingencies be-
tween sensations, structural relationships between the acts of looking and
listening, or bimodally specified properties of objects? The action-cen-
tered perspective might explain the findings of the face perception and the
speech perception studies. Infants may react emotionally to a happy face
and to a happy voice, and they might respond to similarities between
these two reactions. Moreover, infants may attempt to imitate the speech
gestures they hear and the facial movements they see (see T. Field,
Woodson, Greenberg, & Cohen, 1982; Meltzoff & Moore, 1977), and they
might detect correspondences between these attempts. Similar explana-
tions for the findings of the experiments with inanimate objects are more
difficult to imagine, however, since it is not clear that these events engen-
der any actions. The action-centered perspective seems least promising as
a general account of perception of auditory–visual relationships.

The sensation-centered perspective appears to account well for some of
the experimental findings and less well for other findings. In the experi-
ments in which sounds were temporally synchronized with one of two
moving objects, infants might have detected the intermodal relationships
by analyzing the temporal contingency of certain auditory and visual
sensations. A sensation-based theory cannot account so easily, however,
for infants' detection of relationships between nonsimultaneous sounds
and impacts that occur at the same tempo, between the sounds and the
movements of rigid versus deformable objects, or between auditory and
visual information for specific speech sounds.

Proponents of a sensation-centered theory might propose that infants
learn about the relationship between the sound and movement of a rigid
object, and about the relationship between specific speech sounds and
gestures, over the first 4 months of life: experiments with younger infants
are needed to assess this possibility. To account for infants' perception of
the common tempo of sounds and movements, such theorists might pro-
pose that infants do not only detect contingencies between individual

sensations but also detect contingencies between patterns of sensation. To be testable, this hypothesis must include a specification of the kinds of sensory patterns that infants analyze and the contingent relations among these patterns that they detect. Although considerable effort has been devoted to the study of contingency analysis by humans and other animals (see Schwartz, 1978), the ability to detect such higher-order patterns of contingency has not, to my knowledge, been studied. No existing sensation-centered perspective can account for the findings of all the experiments on auditory–visual perception.

The perception-centered perspective appears to provide the simplest account of research on auditory–visual perception. Infants may perceive auditory–visual relationships by detecting amodal properties of objects. They may detect higher-order relationships in light and sound that specify the movements and the substance of an inanimate object and the actions, emotional expressions, and articulatory gestures of a person. Studies of perception within a single modality suggest that infants do perceive the rigidity or deformability of objects (E. J. Gibson, Owsley, & Johnston, 1978), the translatory movements of surfaces (Hofsten, 1979; Kellman & Spelke, 1983), the expressions of emotion of persons (Walker, 1980), and the distinctive sounds of speech (e.g., Eimas, Siqueland, Jusczyk, & Vigorito, 1971). These studies lend credence to the perception-centered theory.

C. Visual–Haptic Perception of Objects and Surfaces

We turn now to infants' perception of a layout that is both visible and tangible. A number of experiments have investigated visual–haptic perception of the shapes, substances, and textures of objects. Other experiments have investigated visual perception of an extended surface and anticipation of its tactile consequences.

By 6 months of age, infants who explore an object manually can subsequently recognize its shape visually. They may demonstrate their recognition by looking at or reaching for the object they have felt in preference to a novel object. For example, 8-month-old infants were allowed to manipulate a noise-making toy that they could not see, and then they were shown that toy and a different toy side by side. The infants reached for the familiar toy (Bryant, Jones, Claxton, & Perkins, 1972). Similarly, infants of 6 months who were allowed to touch an unseen object later looked longer at that object than at a novel object (Ruff & Kohler, 1978). The same patterns have been observed with nonhuman infant primates (Dolgin, Premack, & Spelke, 1980; Gunderson, 1983).

Infants do not always look at an object they have felt. After tactual

familiarization with an object of one shape, 1-year-old infants may look longer at an object of a different shape (Gottfried, Rose, & Bridger, 1977), whereas infants who were born prematurely and/or who live in less well-educated families may show no reliable visual preferences (Rose, Gottfried, & Bridger, 1981). In a more recent series of experiments (Streri & Pêcheux, in press), 4½-month-old infants who were familiarized with an object visually were found subsequently to engage in greater haptic exploration of an object with a novel shape, although no consistent preferences were obtained in a symmetrical haptic-to-visual transfer task. Conflicting findings may have been obtained in these experiments, because intermodal transfer tasks elicit two conflicting tendencies: a tendency to explore one object both by looking and by touching, and a tendency to explore something new (Spelke, 1985; see also Rolfe & Day, 1981). In any case, the above studies reveal that 6-month-old infants do detect the relationship between visual and haptic information for an object's shape.

Three experiments suggest the capacity for visual–haptic perception is present earlier in life. Meltzoff and Borton (1979) allowed 1-month-old infants to suck either a smooth sphere or a sphere with nubs without seeing the object. Subsequently, the infants were given a visual preference test between two larger objects with these smooth and rough textures. The infants tended to look at the object with the texture they had felt. This experiment provides evidence that infants can perceive the texture of an object both visually and haptically. Unfortunately, one experiment has failed to replicate this effect (Allen, 1982).

Similar research has focused on visual–haptic perception of substances (E. J. Gibson & Walker, 1984). One-month-old infants were allowed to explore either a rigid or a flexible object in the mouth. After mouthing the object for 60 sec without seeing it, the infants were shown two visible objects, side by side. One object was moved rigidly while the other was subjected to an elastic deformation. The infants looked longer at the object that underwent a *novel* pattern of motion. It is not clear why a novelty preference was observed in this study, rather than a preference for the familiar substance (see E. J. Gibson, 1983, and Spelke, 1985, for discussion). Nevertheless, the experiment provides evidence that 1-month-old infants perceive the substance of an appropriately moving object both visually and haptically.

In another study (Streri, 1985), 2½-month-old infants were allowed to explore an object of a simple shape (a ring or a disk) in one hand, out of the visual field. After a period of haptic habituation (following Streri & Pêcheux, 1986), the infants were given a visual preference test with the two forms. Infants looked longer at the novel form. It appears, therefore, that prereaching infants can perceive the textures, substances, and shapes

of certain objects either by touching or by looking, and that they can recognize visually a texture, substance, or shape they have felt.

Visual–haptic perception of extended surfaces has been studied in detail, using techniques that differ considerably from those discussed so far. In all the above studies, infants were presented both with visual and with auditory or haptic information about an object, and their sensitivity to the congruity or incongruity of the two sources of information was assessed. In the studies that follow, infants are presented only with visual information for a surface, but it is a surface with certain affordances (J. J. Gibson, 1979): certain consequences for action. Activity in response to this visual information is observed in order to determine whether infants appreciate, on some level, that the visible surface has certain tactile consequences. The existence of such anticipatory activity is of interest for many reasons: it may shed light on the development of perception, of cognitive processes, and even of emotion (see Campos, Hiatt, Ramsay, Henderson, & Svejda, 1978; E. J. Gibson, 1982). In this chapter, however, infants' anticipatory activity is described only insofar as it sheds light on the capacity for intermodal perception. If an infant, on seeing an object, expects the object to have certain tactile qualities, he or she obviously appreciates the relationship between these visual and tactile qualities.

The most well-known studies of this kind concern infants' behavior on the "visual cliff" (E. J. Gibson & Walk, 1960; Walk & Gibson, 1961). Infants in the second half-year of life often avoid crawling off a support when they face a visually specified drop-off, even when coaxed by a parent: they move forward only in the presence of visual information for a surface of support. Animals of other species such as chickens, goats, and sheep also avoid an optically specified drop-off from birth, as do hooded rats who are reared in darkness and are tested on their first exposure to the light.

Since human infants do not crawl until 6½ months, the development of avoidance of the cliff is not well understood. Investigations of younger infants placed directly on the cliff or placed in walkers that permit independent locomotion suggest that avoidance of the cliff is affected by experience (Campos et al., 1978) and/or maturation (Rader, Bausano, & Richards, 1980). The interactions of these factors are still not clear.

Further evidence for visual–tactual perception of surfaces comes from studies of younger infants. Studies of "looming" have revealed that newborn animals of many species back away from an approaching surface or from a two-dimensional display that simulates the approach of a surface by a pattern of symmetrical expansion (Schiff, 1965). When young human infants are presented with such displays, they have been reported to blink (White et al., 1964; Yonas, 1979), to stiffen (Ball & Tronick, 1971), to

withdraw the head (Ball & Tronick, 1971; Ball & Vurpillot, 1976; Bower,
Broughton, & Moore, 1970b), and to interpose their arms between their
faces and the object (Ball & Tronick, 1971; Bower et al., 1970b; Yonas,
Pettersen, Lockman, & Eisenberg, 1980; see Yonas, 1981, for a review).

Are infants' reactions to an approaching surface guided by visual per-
ception of the surface and its approach? One series of experiments
(Yonas, Bechtold, Frankel, Gordon, McRoberts, Norcia & Sternfels,
1977) suggested that head withdrawal to a looming display depends only
on infants' perception of moving two-dimensional contours: infant with-
draw their heads not in order to defend themselves but to follow visually
the rising upper contour of the display. Two experiments have cast doubt
on this suggestion and provide evidence that a looming display specifies
imminent collision for an infant. Bower (comment on Yonas et al., 1977,
pp. 281–282) presented infants with a shadow pattern specifying an object
about to fall upon them. He reported that infants withdrew their heads
from this display as they do from looming displays, even though the
falling object had a falling rather than a rising upper contour. Carroll and
Gibson (1981) presented 3-month-old infants with two different displays
of expanding contours. In one display, a small surface approached the
infants on a collision course. In the other display, a large surface with an
aperture approached the infants. The aperture occupied the same position
as the object in the first display. Infants withdrew their heads sharply
from the approaching object, but they leaned back only slightly when the
aperture approached them and many infants turned as if to watch this
surface go by. This experiment indicates that infants show defensive head
withdrawal only to certain kinds of expanding contours. Although ap-
proaching obstacles and approaching apertures both have expanding con-
tours, they have different consequences for an infant, and infants appear
to appreciate these consequences. These experiments provide evidence
that infants can perceive visible surfaces and take account of their tactile
consequences.

Finally, experiments reveal that young infants use visible surfaces as
information about their own posture. For adults, visual information for an
upright stable orientation guides postural stability; we can sometimes be
made to lose our balance if the walls of a room move around us (Lishman
& Lee, 1975). One-year-old infants who can stand independently can be
similarly fooled: they are likely to fall backward, for example, if the walls
of the room swing toward them. These infants evidently take the move-
ment of the walls as information that they are falling forward, and they
compensate by moving in the opposite direction (Lee & Aronson, 1974).
Although 1-year-olds might have learned to use vision as a source of
postural information when they learned to stand, recent studies indicate
that analogous adjustments are made by infants too young to stand, to sit,

or even to reach for objects (Butterworth, 1983; Butterworth & Hicks, 1977; Schonen, personal communication). Once again, a linkage between different perceptual systems is indicated. It is not clear if this linkage results from infants' perception of amodal properties of surfaces and their orientations, or if the response is evoked directly by certain sensory patterns.

In summary, infants of 1 and 2 months can coordinate visual and tactile information about the texture, the substance, and the shape of an object and about the movements of extended surfaces. As infants grow, their active manipulation becomes more effective and new actions come to be guided by visual information. Most infants of 7 months take account of the visually specified distances of surfaces and use this information to guide their locomotion. Younger infants, however, are already sensitive to relationships between how a surface looks and how it feels.

The sensation-centered and action–centered perspectives provide natural accounts for the slow development of haptic exploration and of certain visually-guided actions. These perspectives have more difficulty accounting for the results of experiments showing visual–haptic coordination in young infants. Proponents of these perspectives could propose that the early intermodal coordinations depend on specific linkages between motor patterns and uninterpreted visual sensations. Such explanations are attractive as long as the coordination exhibited by infants is limited and the stimulus displays that evoke a reaction can be simply described. Blinking to a looming object at 3 weeks of age, for example, might well depend on a reflex linkage. Later in infancy, when a looming object evokes a wide range of different adaptive activities, and when these responses occur only when an object (not an aperture) approaches, sensory–motor linkage hypotheses are strained, but then one could propose that the later coordinations develop through experience. Defensive reactions to an approaching object, for example, may result from associative learning or from a process of reciprocal assimilation between acts of visual perception, arm raising, and head withdrawal. If learning does underlie defensive reactions, the speed of this learning is quite remarkable. Three-month-old infants cannot begin to reach for an object, yet they respond appropriately when an object approaches on a collision course.

The sensation-centered and action-centered perspectives would seem to have the greatest difficulty explaining the finding that 1- and 2-month-old infants can perceive an object's texture, substance, and shape intermodally. One might amend a sensation-centered theory by proposing that infants detect contingencies among spatial patterns of sensations, and that the visual and haptic patterns of sensations evoked by an object of a certain texture, shape, or form have something in common. Similarly, one

might develop an action-centered theory that postulates innate structural relationships between the actions of looking at and feeling an object of a certain texture, substance, or shape. These amended theories would be very different from Helmholtz's and Piaget's original proposals, however, and they currently have little independent motivation. The sensation-centered and action-centered perspectives offer no straightforward explanation of experiments on visual-haptic perception.

In contrast, the perception-centered perspective could account for all the abilities demonstrated by young infants by proposing that infants perceive certain properties of objects and surfaces both visually and tactually. Adherents to this perspective must offer a separate explanation for developmental changes in responses to a visually specified drop-off, perhaps in terms of the maturation of a visuomotor program controlling crawling (see Rader et al., 1980; Richards & Rader, 1981). Aside from this complication, the perception-centered perspective seems to offer a reasonably simple account of all the studies of visual–haptic perception.

D. Overview

In this author's opinion, studies of the early capacity for intermodal perception lend greatest plausibility to a perception-centered theory of development. Experiments on intermodal exploration, auditory–visual perception, and visual–haptic perception all provide evidence that infants perceive some of the distal properties of objects when they look at, listen to, and manipulate those objects. When infants detect the same object property through two perceptual systems, they appear to perceive an intermodal relationship. No conclusive choice among the three perspectives can be made, however, for no experimental findings directly refute any of the theories. The sensation-centered and action-centered perspectives remain tenable, and each position has contemporary adherents (for example, see Bushnell, 1981; McGurk & MacDonald, 1978). The innate basis of intersensory coordination is still not known.

IV. DEVELOPMENTAL CHANGES IN INTERMODAL PERCEPTION

This discussion will focus first on studies of infants' learning about relationships between the audible and visible properties of objects, and then on studies of developmental changes in infants' reactions to conflicting visual and haptic information. We will consider whether the development of intermodal perception can be explained by processes of hypothe-

sis testing and associative learning, by the structuring of actions, or by the differentiation of perception of object properties.

A. Learning about Auditory–Visual Relationships

Adults perceive many auditory–visual relationships that are quite arbitrary. They relate thunder to lightning, chimes to a grandfather clock, and a friend's voice to her face. These abilities surely depend on acquired knowledge about visible, sound-producing objects. Recent research suggests that the acquisition of such knowledge begins early in life.

The most familiar audible and visible objects in the infant's world are probably his parents. Young infants have been shown to know about the relationship between each parent's face and voice and to use knowledge of this relationship when they explore. In one study (Spelke & Owsley, 1979), infants of $3\frac{1}{2}$, $5\frac{1}{2}$, and $7\frac{1}{2}$ months sat facing between the mother and father and heard the nonsynchronized voice of one parent spatially centered between the parents. Infants of all ages tended to look to the parent whose voice was played. Knowledge of the face–voice relations evidently guided their looking. In a similar study (Cohen, 1974), infants of 8 months were found to look longer to the mother when her own voice was played from her direction than when a female stranger's voice was played from the mother's direction. Infants as young as 2 weeks may exhibit the same pattern, though the results of studies at this age are not fully clear (Carpenter, cited in Bower, 1979, and in Mendelson, 1979; Bigelow, 1977; Spelke & Owsley, 1979). Knowledge of the relationship between each parent's voice and face appears to develop in the first year of life, perhaps quite early in that year.

By 6 months of age, infants have also learned that male faces go with male voices and female faces go with female voices (Francis & McCroy, 1983; see also Miller & Horowitz, 1980). When presented with an unfamiliar voice played between a male and a female face, 6-month-old infants look longer at the face of the same sex. Three-month-old infants show no such tendency. Infants may learn about these intermodal relationships during the first months of life.

Infants also learn about relationships between the sounds and the visible appearance of inanimate objects. Learning can take place over one brief laboratory session in which infants are presented with an unfamiliar, sounding object. For example, Lyons-Ruth (1977) presented 4-month-old infants with a visibly moving toy and a sound that came from the same direction. The toy moved laterally, back and forth, in repeated 10-sec turns, and the sound occurred at the end of each movement. Lyons-Ruth tested whether infants learned about the sound–object relationship by

determining if familiarization with the sounding object affected infants'
subsequent patterns of looking. In the test, the sound was presented to
the baby's right, accompanied by the same object or by a different object.
Sounds and objects were not synchronized. Infants looked in the sound's
direction for a longer time if they encountered the appropriate visible
object.

Lyons-Ruth's study revealed that infants can learn rapidly about audi-
tory–visual relationships. During the familiarization period, the sound
and object were related in several ways: they were spatially coincident,
the sound was temporally synchronized with the object's movement, and
the object was the only thing that moved in the infant's field of view while
the sound was played. Subsequent research by Lawson (1980) and Spelke
(1981) has attempted to determine which of these conditions of familiar-
ization were critical for learning.

Lawson investigated the effects of spatial and temporal information on
infants' learning about sound–object relationships. Six-month-old infants
were familiarized with a single inanimate object and an inanimate sound
that were spatially coincident, temporally synchronized, or both. After
the period of familiarization, the infants received a test in which the
familiar object and a novel object were presented side by side, accompa-
nied by the familiar sound or a novel sound. If infants had learned about
the sound–object relationship during the familiarization period, they were
expected to look at the familiar object when its sound was played.

Lawson's experiments provide evidence that both temporal and spatial
information affect infants' learning. The effects of temporal information
can be discerned by considering patterns of searching after familiarization
with a spatially coincident sound and object that either were or were not
temporally synchronized. Infants learned about the auditory–visual rela-
tionship when a spatially coincident sound and object were temporally
synchronized (Experiment 1). When the object moved together with a
continuous, nonsynchronized sound (Experiment 4), significantly less
searching occurred: the disruption of this temporal relationship affected
infants' learning. Not all disruptions of temporal synchrony disrupted
learning, however: when an object moved continuously with the discon-
tinuous sound (Experiment 3), patterns of searching were the same as in
the first condition.

The effects of spatial information in Lawson's experiments can be dis-
cerned by considering patterns of searching after familiarization with a
temporally synchronized sound and object that were, or were not, spa-
tially coincident. As noted, appropriate search occurred when infants
were familiarized with a synchronized sound and object that were spa-
tially coincident (Experiment 1). When the synchronized sound and ob-

ject were widely separated in space (Experiment 2), a nonsignificant drop in appropriate search occurred. This drop suggested that the spatial relationship between the sound and object affected learning about the auditory–visual relationship. Learning may be affected in complex ways both by temporal and by spatial information for a sound–object relationship.

Other experiments indicate that infants learn about the relationship between a sound and a synchronized moving object when the sound and object are spatially separated to a smaller extent (Spelke, 1981). Infants of 4 months were presented with two stuffed animals, side by side, that bounced against a surface at approximately the same steady rate, out of phase with each other. While the animals moved, two percussion sounds were played in succession through a speaker that was centered between the objects. Each sound was synchronized with the bounces of one object.

Learning was tested in two ways. One procedure was similar to the methods of Lyons-Ruth and Lawson. When infants were looking between the two objects, one of the sounds—now out of synchrony with both objects—was played. Infants evidently learned about the sound–object relationship, for they tended to look at whichever object had been formerly synchronized with the sound. Learning was also tested through a habituation and transfer test. One of the sounds was played with no visual accompaniment for an extended period, and it was followed by a silent preference test between the objects. Infants showed a novelty preference for the object not specified by the preceding sound; this effect provides further evidence that they had learned about the intermodal relationship. Appropriate search and novelty preferences were observed in two further experiments in which the lateral positions of the objects were reversed during the test. Infants evidently learned to relate sounds to objects with particular visible characteristics, not to objects in particular spatial positions. These studies provide evidence that infants can learn about an auditory–visual relationship when a sound and a moving object are united only by their temporal synchrony during a period of familiarization.

In summary, infants can learn about a sound–object relationship after very brief exposure to a sounding object: 1 or 2 min of familiarization is sufficient. Infants are most apt to learn about auditory–visual relationships when sounds and objects share a common temporal and spatial structure. Under some conditions, however, it may be sufficient for the objects and sounds to be spatially related (Lawson, 1980) or temporally related (Spelke, 1981). Finally, infants can learn to relate a sound to a synchronized object even if a second, nonsynchronized object is present, and even if the infants spend much of their time looking at the nonsynchronized object while the sound is played. Infants in Spelke's (1981)

studies, for example, observed two visible objects at once during the familiarization period, and looking times to the two objects were roughly equal. In some studies, infants actually looked longer at the object that was not synchronized with a sound than at the synchronized object. They learned, however, to relate the sound to the synchronized object. Infants do not come to associate all sounds and objects that they perceive at the same time.

None of the three theoretical perspectives accounts fully for infants' learning in these experiments. In all the studies, infants were familiarized with sounds and objects that were temporally and/or spatially related but which were otherwise paired arbitrarily. Because of the arbitrary nature of these pairings, there would not seem to be any special structural relationship between the acts of looking at a toy and listening to a percussion sound, and it is unlikely that the infant changed his actions so as to construct such a relationship. Similarly, there would not seem to be any amodal object property that unites each animal with each percussion sound. It is unlikely that infants searched for and detected new stimulus invariants that specified such a property. Neither the action-centered nor the perception-centered perspective, therefore, can account easily for learning about these arbitrary intermodal relationships.

The sensation-centered perspective would seem to offer a more natural description of infants' learning about arbitrary sound–object relationships. Infants may have learned to associate each sound to a particular visual object by analyzing the contingent relations between the occurrence of the sound and the movements of the object. It is not clear, however, why learning is affected by the spatial relationship between the sound and object, or why learning is so little affected by the amount of simultaneous exposure to a sound and object. Furthermore, the above experiments indicate only that infants can learn about *certain* arbitrary sound–object relationships; they do not indicate whether infants will learn to connect *any* sound and visible object with equal ease. According to the sensation-centered perspective, a child should apply the same principles of contingency analysis to any patterns of sensation. It is possible, however, that children are more selective. Even newborn infants might resist learning that a visible person produces the sound of a buzzer, however contingent one stimulus is upon the other. This possibility remains untested.

B. Reacting to Discrepant Visual and Haptic Information

The studies reviewed in previous sections provide evidence that infants' manual activity is guided by visual information for the distance, the

direction, and some aspects of the size, shape, and texture of an object. These studies appeared to provide evidence that infants are sensitive to certain visual–haptic relationships. Further experiments, however, call that conclusion into question. Young infants have been shown to respond differently than older children when reaching for certain objects that they see or hear. In particular, there are developmental changes in infants' reactions to situations in which visual and haptic information are placed in conflict.

In some studies, infants have been presented with stereoscopic information specifying an object in front of them, under conditions in which no object is actually present. This illusion can be produced with various devices (see Bower, Broughton, & Moore, 1971; J. Field, 1977). From $5\frac{1}{2}$ months of age—and perhaps younger—infants reach for the visible object, and their reaching is adapted, at least grossly, to the object's visually given distance (Gordon & Yonas, 1976). When the infant's hand reaches the empty space where the object is seen, she feels nothing, and her hand is seen to pass through the object. Older children express considerable surprise in these circumstances, and they may test their hands for numbness or search haptically for the object with extensive movements of the fingers, hands, and arms. In most studies (see Bower et al., 1971, for an exception), infants as old as $9\frac{1}{2}$ months show neither of these reactions (J. Field, 1977; Gordon, Lamson, & Yonas, 1978, cited in Yonas, 1979; Gordon & Yonas, 1976).

Similar findings emerge from studies by Bushnell (for a review, see Bushnell, 1981). She presented infants of 8 to 15 months with a solid object that was visible in a definite location within a box. The seen location of the object was displaced from its true location by a mirror arrangement, and a different unseen object was placed where the first object appeared to be. Thus, when infants reached for the visible object, they encountered an object of a different size, shape, and/or texture. They also could not see their hand touch the object. One might expect a person in this situation to be surprised, to explore the object intensely, or to search for the source of the discrepancy. Infants above 9 months of age tended to act in these ways, but 8-month-old infants did not.

How is one to account for these findings? The infant's problem evidently does not stem from an inability to detect a correspondence between the seen and felt shape or texture of an object, for much younger infants can do this in some circumstances (Meltzoff & Borton, 1979; Streri, 1985). It is possible that infants do not react to discrepant visual and haptic information because of an attention limit of some kind: they may be unable to perceive two different shapes or substances at the same moment. Alternatively, it is possible that infants cannot detect discrepant

visual and haptic information when they see and feel an object simultaneously because of a "visual capture" effect: the presence of visual information about the object's shape may distort the child's haptic perception of its shape so as to reduce or even eliminate the discrepancy. Visual capture effects of this kind are obtained with adults (e.g., Rock & Victor, 1964; see Welch & Warren, 1980, for a review). Neither of these explanations, however, offers a plausible account for the infant's behavior when she reaches for an object and encounters nothing at all.

At least one potential explanation remains. Young infants may experience an intermodal conflict, but they may fail to show surprise or systematic search because these reactions cannot be set in motion by the detection of such a conflict. According to the latter explanation, the perceptual knowledge of young infants is less *accessible* to them than is the otherwise similar perceptual knowledge of adults. Adults can use knowledge of intermodal relationships to guide any actions or thoughts. Infants, in contrast, may be able to use knowledge of intermodal relationships only in certain restricted ways. Such knowledge may guide their looking at an object they feel, but it may not lead them to search for the causes of discrepant sensory patterns.

In many cognitive domains, psychological capacities may become progressively more accessible with development (Rozin, 1976). Rozin suggested that the development of intelligence, both phylogenetically and ontogenetically, is characterized by the achievement of progressively greater access to abilities that are innate but are initially functional only in quite restricted contexts. On this view, individuals of different ages differ less in the complexity of the systems that govern their actions than in their ability to harness such systems for new purposes. As children grow, they achieve greater access to their intrinsic capacities, and so they become capable of acting and thinking in new ways.

None of the three perspectives on intermodal perception truly captures this kind of change. The accessibility hypothesis, nevertheless, seems to combine insights from the perception-centered and the action-centered perspectives. To propose that the development of intermodal perception reflects the increasing accessibility of intrinsic perceptual capacities is to grant that such intrinsic capacities exist, in accord with the perception-centered theory. To propose that these perceptual capacities are initially restricted in range and become more broadly useful with growth, however, is to describe a kind of development that is central to Piaget's action-centered theory. The entire period of infancy, according to Piaget, is a time when innate action structures are extended, coordinated, and generalized as they are applied to new objects. In different ways, both Gibsonian and Piagetian theories may help to explain the developmental progression that Rozin describes.

C. Overview

The above research suggests, in brief, that developmental changes in intermodal perception spring from several sources. Like older children and adults, infants may learn to relate certain arbitrarily paired sounds and visible objects by analyzing the structure of the events in which those objects participate. Moreover, infants may come to act on objects in new ways as their initial capacities to detect intermodal relationships become more accessible for new purposes. Each of the three perspectives on intermodal perception seems to shed some light on these phenomena. No general account of perceptual learning yet encompasses them all.

V. CONCLUSION

The research that has been discussed provides ample evidence that looking, touching, and listening are coordinated from a very early age, and that learning and development extend and change that initial coordination. The most interesting questions, however, concern not the existence of an innate coordination between the modalities but its basis, not the existence of learning but the nature of the mechanisms that subserve it. We have seen repeatedly that experiments addressing these questions are difficult to devise. Thus, students of intermodal perception find themselves on a terrain furnished with many experimental findings to use as landmarks, but with few unassailable principles to provide an appropriate frame of reference.

We have considered three hypotheses about the innate basis of intermodal perception: sensations and their contingent relationships, actions and their structural relationships, and perceptions of objects and their amodal properties. The third, perception-centered perspective seemed the best-supported account of the origins of intermodal perception. Infants do perceive properties of objects such as their size and substance from a very early age, and they appear to perceive the same object properties by looking, listening, and feeling. It seems likely that infants perceive unitary objects and events by detecting these amodal properties.

We have also considered three accounts of intermodal learning and development, accounts that center on processes of associative learning about relationships among sensations, processes of reciprocal assimilation leading to the structuring of actions, and processes of invariant detection leading to perceptual differentiation. All three processes seem to provide explanations of certain aspects of intermodal development. Associative and invariant-detection processes may partly account for infants' learning about arbitrary auditory–visual relationships; invariant-detection

processes and processes for structuring actions may describe certain aspects of the development of reactions to intermodal discrepancies.

These conclusions are tentative. Experiments on intermodal perception in infancy permit one to reject certain specific theoretical proposals, and they highlight ways in which each theoretical perspective might be made more specific. These experiments, however, have not resolved the basic controversy between the sensation-centered, the action-centered, and the perception-centered perspectives on development.

Some aspects of this controversy may be settled by further research on intermodal perception in infancy. It is important, for example, to investigate the capacity for intermodal perception in newborn infants, to investigate more closely the process of learning about intermodal relationships, and to assess the contribution of maturation and learning to the development of intermodal functioning. I believe, however, that the greatest advances in our understanding of the development of intermodal perception will not come from research on intermodal perception specifically, but rather from research of broader scope.

None of the three perspectives guiding this chapter proposes that there is anything special about *intermodal* perception, or about human infants. The same sensations, actions, and mechanisms for perceiving objects that are said to underlie intermodal perception are thought to underlie perceptions of all kinds. For all theorists except possibly Piaget, moreover, the same principles that characterize the development of perception in humans are proposed to characterize the development of perception in other animals. According to all three perspectives, therefore, an understanding of intermodal perception in infancy could grow from investigations of other capacities and even other species.

For example, comparative research could be undertaken to test the central claims of the three perspectives. If the specific sensations, actions, and perceptions of very young animals differ somewhat from species to species, then comparative research could investigate whether species differences in the initial capacity for intermodal perception are best predicted by species differences in what animals can sense, in how they can act, or in what they can perceive. Furthermore, controlled-rearing studies of nonhuman species could probe the effects of early experience on intermodal perception, thereby shedding light on the mechanisms of development. Both methods have been used to investigate responses to looming objects (Schiff, 1965) and to the visual cliff (Walk & Gibson, 1961); studies using these methods appear to support a perception-centered theory. More such experiments, focusing on auditory–visual perception of events and on visual–haptic perception of objects, might be illuminating.

Studies of intermodal development could be broadened in a second way, for the three perspectives on intermodal perception can be tested through other kinds of experiments with human infants. Piaget's experiments with his own infants provide one illustration of the benefits of a broad approach to the study of early perceptual and cognitive development (Piaget, 1952, 1954). Piaget examined his infants' reactions to a variety of problems in a variety of domains. His theory of sensory–motor development is highly compelling, in part, because his interpretation of an infant's performance on one cognitive task is constrained by his interpretations of performance on all other tasks. In particular, Piaget's claims about the development of intermodal perception are bolstered by his studies of the development of concepts of objects, causality, space, and time: all converge on a single description of development in infancy.

A second example of a broad approach to development is provided by E. J. Gibson's research on infants' perception of substances. Gibson and her colleagues propose that infants, like adults (Fieandt & Gibson, 1959), are able to perceive the rigidity or flexibility of a moving object by detecting invariant information specifying the object's characteristic motion. To investigate the development of this sensitivity, Gibson has studied infant's perception of the rigidity or flexibility of a single moving object (E. J. Gibson et al., 1978; Walker, Gibson, Owsley, Megaw-Nyce, & Bahrick, 1980), of a set of different moving objects composed of the same substance (E. J. Gibson, Owsley, Walker, & Negaw-Nyce, 1979), of an object both seen and heard (Bahrick, 1983), of an object both seen and felt (E. J. Gibson & Walker, 1982), and of an extended surface (E. J. Gibson, 1984). These studies all provide evidence that infants can perceive the rigidity or flexibility of a substance and that this perceptual ability can underlie perception of intermodal relationships.

Theoretical progress will be made, I believe, if more investigations follow these examples. Instead of exploring the development of intermodal perception *per se*, investigators might focus more directly on the capacities that serve as the basis of *all* perception and on the principles that underlie all perceptual development. Those working from a sensation-centered perspective could investigate the nature of the unconscious, elementary sensations that, they believe, form the building blocks of perception. They might also investigate the processes of contingency analysis that could lead the child to discover just those contingent relationships that unite the visual sensations evoked by an object to the auditory and tactile sensations the object produces. Those working within an action-centered theory could focus on the nature and structure of the child's initial actions, on the infant's sensitivity to structural relationships uniting actions directed to the same object, and on the principles by which

actions become further structured and coordinated. Those working within
a perception-centered theory could study the invariant relationships in
stimulation that infants detect, the properties of objects and events that
infants might thereby perceive, and the principles and mechanisms by
which the infants' perceptions undergo differentiation.

By turning in these directions, investigators of infant perception could
help to overcome the most serious weakness of each perspective: the
central concepts of these theories need to be formulated more precisely.
Research is needed to investigate which, if any, of the potential concepts
of sensation, action, or invariant should figure in an account of the initial
capacity for intermodal perception. Research is also needed to investigate
the nature of the processes by which infants analyze contingencies, coor-
dinate actions, and detect new invariants, to determine the roles these
processes play in the development of intermodal perception.

It may seem unfair to burden the student of infant perception with these
tasks. Physiologists and psychologists have attempted to discover the
properties of elementary sensations for over 100 years, with little success
(see Hochberg, 1979). Attempts to specify the universal processes of
contingency analysis have met with somewhat greater success, but the
nature and the generality of those processes are still disputed (Schwartz,
1978). The tasks of defining an elementary unit of action and of specifying
the principles by which actions are coordinated have also proved difficult
(but see Gallistel, 1980), and the relationship, if any, between the coordi-
nation of action and the perception of objects and events has not fre-
quently been studied. Finally, the task of specifying what invariants per-
ceivers detect, and what properties of objects and events these invariants
specify, has only begun (J. J. Gibson, 1966, 1979; E. J. Gibson, 1982).

Students of infant perception have made little contribution to these
theoretical efforts in the past. They may, however, be especially well
suited to this task. One reason the analysis of perception has been so
difficult in the past, I believe, is that investigators have focused on sub-
jects whose fundamental processes of perception are hidden under layers
of knowledge, skill, and ingenuity. In studies of human adults, any ele-
mentary sensations and actions that might exist will surely be cloaked by
vast collections of perceptual and motor skills. Mechanisms for perceiv-
ing properties of objects and events will also be difficult to discern, amid
the adult's many other means for arriving at judgments in perceptual
tasks. Finally, basic principles of learning and development will be hidden
among the many special learning strategies that adults have discovered
through luck, instruction, or insight.

Consider, in contrast, the newborn infant. Infants surely lack most of
the knowledge and skills that we enjoy as adults. The most basic and

general mechanisms of perception, therefore, are more likely to serve as guides to their actions, and the most basic mechanisms of learning are more likely to provide the means by which they acquire knowledge. Psychologists may glimpse the fundamental basis of perception, and the principles of its development, through studies of human infancy.

ACKNOWLEDGMENTS

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