CHAPTER NINE

Amodal Relations: The Basis for Intermodal Perception and Learning in Infancy

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The Problem of Intermodal Perception

Put yourself in the place of an infant attempting to make sense of the world. Objects and events come and go within your perceptual field. Most are multimodal and evoke a diversity of sights, sounds, and tactile and olfactory impressions simultaneously. The sound of your mother's voice and the sight of her changing face; the feel of being picked up and of movement through space and the experience of a rapidly shifting visual field; the sounds of the radio and the smells of toast and coffee may all co-occur. How does the infant, like the adult, come to perceive a stable world of unitary objects and events from this continuously changing flux of stimulation? How does the infant determine which patterns of stimulation belong together and originate from a single event, and which are unrelated? How does she select stimulation that is relevant to her needs and actions?

Cognitive psychologists agree that perception and learning in the adult are guided by expectations, plans and prior knowledge. They have postulated that plans, goals, expertise, perceptual sets, schemas, scripts, and story grammars direct and constrain what we perceive, learn, and remember (see, e.g., Bartlett, 1932; Bower, 1976; Chase & Simon, 1973; Neisser, 1976; Schank & Ableson, 1977; Soloman, May, & Schwartz, 1981). These constructs describe how prior knowledge enables us to economically select from the vast flux of stimulation, information that is relevant, coherent, and meaningful to us, while ignoring the great majority of stimulation that is not. How, then, can the infant, with relatively little experience in the world, solve this problem? How can she select stimulation originating from unitary multimodal events rather than from unrelated streams of sights, sounds, and tactile impressions? How can she focus on information that is meaningful and relevant to her needs and actions, while ignoring information that is irrelevant?

In this chapter, we present evidence that this process is set in motion and guided by the detection of amodal invariant relations. Amodal invariant information is information that is not specific to a particular sensory modality; rather, it is completely redundant across one or more senses (E. J. Gibson, 1969; J. J. Gibson, 1966). Most audible and visible events occur over time and can thus be characterized by a temporal structure that is invariant across vision and audition. For example, the sights and sounds of a single event typically share a synchrony relation, a common tempo of action and a rhythm. The same rhythm, tempo, and synchrony may be picked up visually, acoustically or haptically. The different senses provide no unique information with respect to these properties. According to E. J. Gibson (1969), infants come into the world equipped to abstract amodal relations. Detection of amodal temporal relations is an ideal way to insure that perceptual differentiation will be veridical. Because the same temporal structure can be detected through two senses, it can specify that the audible and visible stimulation comes from a single event, and separate it from other co-occurring events that do not share the temporal structure. Initial sensitivity to temporal relations can selectively focus infant attention on meaningful, unitary events and serve as a buffer against learning the numerous wrong or meaningless relations one might detect. We believe that there is now sufficient evidence to conclude that young infants are at first selectively tuned to detect certain amodal relations. This initially substitutes for the prior knowledge that adult perceivers find so critical for directing meaningful perception, learning and memory. This chapter addresses this issue by examining and evaluating what we now know about the development of intermodal perception of audible and visual events in infancy. We evaluate the contribution of research from each of five different approaches toward understanding the nature and basis of perceptual development. Our discussion focuses primarily on infants' perception of auditory–visual relations.

Current Theories of Intermodal Perception

There are two essentially opposing schools of thought regarding the manner in which intersensory coordination develops during infancy:

1. *Integration theories*, which consider the senses to be independent at birth and postulate that intersensory coordination emerges gradually through development.

2. *Differentiation theories*, which suggest that the senses are unified early in development, and that perceptual development is characterized by differentiation of increasingly finer aspects of stimulation. Intersensory perception is thus possible from the beginning.

According to the intersensory integration hypothesis (e.g., Birch & Lefford, 1963, 1967; Blank & Bridger, 1964; Bryant, 1974), independent sensory systems are gradually integrated as infants and children learn to associate modality-specific sensations. For example, the visual image of a cube remains unrelated to the feel of the cube until visual and tactile impressions of the cube are associated over time. The senses are viewed as separate and uncoordinated at birth, and as a result cross-modal perception is assumed to be impossible during infancy. As we show, recent studies indicating that young infants are sensitive to intermodal relations appear to weaken some of the central assumptions of the "integration" position.

One of the most detailed accounts of infant sensory development has been offered by Jean Piaget (1952, 1954). Piaget suggested that intersensory perception develops gradually as the child organizes modality-specific actions into a coordinated representation of the world. Actions such as "touching a toy" gradually become coordinated with actions such as "looking at the toy" or "hearing the toy." Thus, "the first stages of development are marked by an absence of coordination between the sensory systems" (Piaget & Inhelder, 1969). Piaget's view is unique in adopting an "action centered" perspective that emphasizes the importance of the child's active experience with the environment for constructing intermodal knowledge. Infants are therefore incapable of intermodal coordination early in the sensorimotor period because motor behavior is not yet well developed. Thus, by assuming that initially independent sensory systems must be gradually coordinated through experience, Piaget's position is an example of an integration view.

In contrast to integration theories, which do not endow young infants with the capacity for intersensory coordination at first, differentiation theories suggest that at least some intermodal perceptual abilities are innate. E. J. Gibson's (1969) "invariant detection" view is the most popular current-day example of a differentiation theory and provides the theoretical context for this chapter. Gibson posits that the senses are unified at birth and that development is characterized as a process of progressive differentiation of increasingly finer levels of stimulation. Young infants have an innate capacity to perceive properties of objects that are *amodal* or invariant across sense modalities. Detection of these amodal relations enables the infant to perceive unified multimodal events from the beginning. According to the invariant detection framework, infants possess some intersensory capabilities very early, and continue to show perceptual learning as they differentiate increasingly finer and more complex multimodal relations. There is no stage where infants must "associate" or "integrate" information across the senses. Rather, amodal information inherently unites multimodal events, and need only be abstracted through a unified perceptual system. A more extreme version of this view (Bower, 1974) is that the sensory systems are totally undifferentiated at birth such that infants cannot distinguish between stimulation arising from the different senses. Through development, the infant must learn to differentiate the sense modalities. Intermodal relations would thus be detected at birth because the infant cannot yet distinguish among the senses.

The intensity hypothesis (Schneirla, 1959, 1965; Turkewitz, Lewkowicz, & Gardner, 1983) also adopts the view that intersensory coordination is possible in infancy, but differs from the invariant detection position with regard to the nature of the information hypothesized as the basis for the perception of intersensory equivalence. The intensity hypothesis suggests that very young organisms respond primarily to quantitative aspects of stimulation: those variables that contribute to the overall amount of stimulation. Thus, several properties of stimulation (size, brightness, loudness, duration, rate of stimulation, etc.) are undifferentiated by young infants. They are thought to respond to the effective intensity of stimulation, which is jointly determined by the physical intensity of external stimulation and the organism's state of arousal. When young infants match across modalities they are thought to do so by detecting equivalent stimulus intensities across modalities (e.g., Gardner, Lewkowicz, Rose, & Karmel, 1986; Lewkowicz & Turkewitz, 1980, 1981). Other stimulus features (such as rhythm, melody, texture or shape) are considered qualitative properties of stimulation, which infants are not predicted to differentiate until after 4 to 6 months of age (Lewkowicz, 1991). This position appears to share some of the assumptions of both the differentiation and integration views. Although multimodal relations are detected early in development and infants discern finer levels of stimulation with experience, detection of these relations progresses from quantitative to qualitative dimensions, and at least one mechanism for this is the integration of sensations from separate input modalities. In contrast, Gibson's (1969) invariant detection view posits that infants respond to both quantitative and qualitative aspects of stimulation from the start and discern meaningful properties of objects through the detection of invariant relations.

EVIDENCE FOR THE PRIMACY OF AMODAL AUDITORY–VISUAL RELATIONS

Young Infants Detect Amodal Relations

We have witnessed an explosion of research on the intermodal capabilities of infants during the past 20 years. As a whole, the research has shown that very young infants possess a surprisingly large and diverse repertoire of intermodal

abilities. Infants' success in intersensory tasks was often found to be based on the detection of amodal relations. It was discovered that infants could match faces and voices on the basis of voice–lip synchrony (Dodd, 1979; Spelke & Cortelyou 1980; Walker, 1982), affective expressions including happy, sad, neutral, and angry (Walker, 1982; Walker-Andrews, 1986), speech sounds such as "a" versus "i" (Kuhl & Meltzoff, 1982, 1984), and gender of speaker (Walker-Andrews, Bahrick, Raglioni, & Diaz, 1991). Infants as young as 4 months of age were found to be sensitive to a number of temporal parameters unifying auditory and visual stimulation from natural events of objects moving through space. They detected the tempo of action uniting the sights and sounds of stuffed animals bouncing (Spelke, 1979), and the synchrony between the visual and acoustic impacts of objects striking against a surface (Bahrick, 1983, Spelke, 1979, 1981; Spelke, Born, & Chu, 1983). Infants were found to be sensitive to the common rhythm and duration uniting flashing lights with tones (Allen, Walker, Symonds, & Marcell, 1977; Lewkowicz, 1986) and the sight of puppets moving with the sounds they made (Mendelson & Ferland, 1982). Infants were found to detect the rigidity versus elasticity of substance for moving objects (Bahrick, 1983) and the composition of moving objects (whether they were composed of a single, unitary element or a cluster of smaller elements, Bahrick, 1987, 1988). Both substance and composition are thought to be properties of objects that are amodally specified across vision and audition through temporal information. By 4 months, selective attention to one of two superimposed films is guided by a synchronous and appropriate soundtrack (Bahrick, Walker, & Neisser, 1981). Finally, infants demonstrated sensitivity to the auditory and visible information of objects changing in depth (Pickens, in press; Walker-Andrews & Lennon, 1985). Thus, infants appear to be adept at perceiving a wide range of amodal invariant relations across a range of different events after only a few months of life.

Evidence of early detection of amodal relations weakens the integration views that suggest that intersensory perception is not possible until infants gradually learn to associate input from separate modalities. This body of research thus lends strength to E. J. Gibson's (1969) differentiation view, which posits that detection of amodal relations is central to the development of intermodal perception. However, to establish that these abilities exist is necessary but not sufficient for concluding that they are fundamental and regulate early perceptual differentiation. They could have come into existence through a number of processes. Converging evidence from several approaches is needed to evaluate the primacy of amodal relations in the development of intersensory perception. No single approach or set of studies can definitively speak to such a broad question. Thus, researchers have continued to explore these newly discovered abilities. They have investigated how these abilities developed, the nature of the intermodal learning process, constraints and boundary conditions for detection of amodal relations, and the developmental sequence in which different intermodal abilities emerged. These efforts are all discussed later in this chapter and evaluated with respect to the question of the basis for perceptual development.

Age-Related Changes in the Detection of Amodal Relations

Few studies have investigated changes in infant intersensory perception abilities across age. Of those that have, all have used cross-sectional approaches. These studies have for the most part found that intermodal abilities either are not evident at an early age and emerge at a later age, or show improvement with age.

The most common approach for assessing intermodal abilities for audible and visible events is some variant of the two-choice intermodal preference and search method (Spelke, 1976). In this method the infant views two films, side by side, along with a soundtrack that matches one of them. Then a soundtrack corresponding to the other film is played on a different trial. The soundtracks always emanate from a speaker centered between the two images so that infants cannot match on the basis of sound localization. Visual fixations are observed to determine whether the infant spends a greater proportion of the time exploring the film that matches the sound. A search procedure sometimes follows where infants again view the two films side by side along with intermittent bursts of sound from each. It is expected that infants will look first more often in the direction of the sound-matched film if they have learned which film goes with the sound.

Using this kind of procedure, Bahrick (1987) found that infants improved with age in their ability to match moving objects and sounds on the basis of two kinds of amodal temporal relations, temporal synchrony and temporal structure specifying object composition for single versus compound objects. (The internal temporal structure of each visual and acoustic impact specifies whether the object is single or compound.) Infants were shown two side-by-side films of rattlelike objects. One was a transparent cylinder with a single large marble, and the other was a transparent cylinder with a number of smaller marbles (see Fig. 9.1). The cylinders were abruptly turned back and forth in a erratic pattern, creating a clear impact sound with each turn. Results indicated that by 6 months, but not at 3 or 4½ months, infants matched films and soundtracks on the basis of object composition. They looked significantly more to the film of the single marble when the single-impact sounds were played, and to the group of smaller marbles when the compound sounds were played, even though the motions of both cylinders were synchronized with each soundtrack. A second study found that making the sounds asynchronous with respect to the films disrupted the infants' detection of composition relations. Further, by 4½ months infants

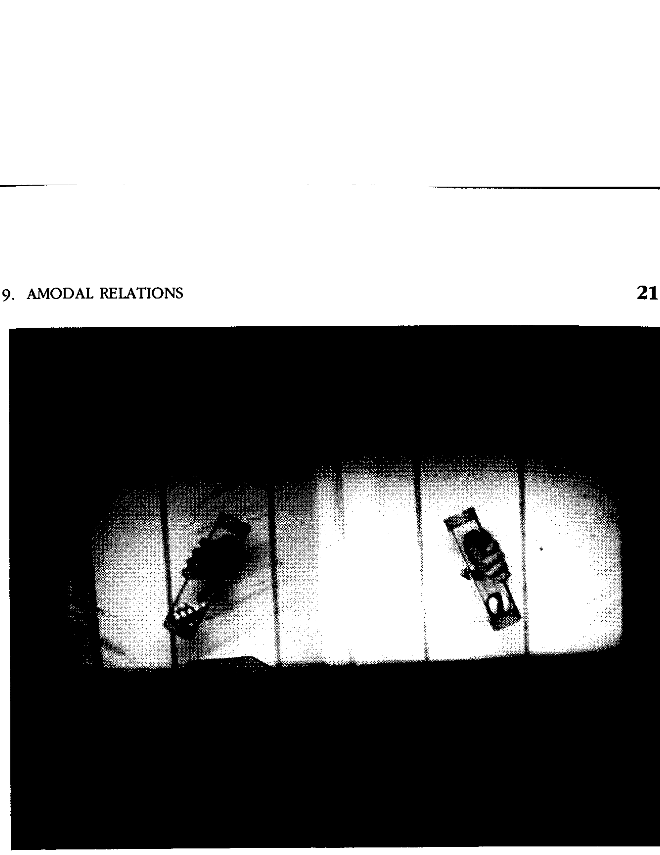

FIG. 9.1. Photograph of the single and compound stimuli used by Bahrick (1987, 1988). Adapted by permission.

showed matching on the basis of motion–sound synchrony alone under some conditions, and by 6 months this matching was more robust. Thus, the ability to match one of two events with a single sound on the basis of amodal temporal relations improves with age. These abilities emerge and develop between the ages of 4½ and 6 months.

The specific age at which different intermodal abilities appear to emerge depends on differences in the stimuli and methods used. However, for any developmental sequences uncovered within a single set of studies (same stimuli and methods), the relative ordering of abilities should be constant and generalizable. For example, in this set of studies there was some evidence that detection of temporal synchrony (4½ months) preceded detection of information specifying object composition (6 months). This finding is consistent with E. J. Gibson's (1969) increasing specificity view of perceptual development, because synchrony relations are characterized as more global whereas temporal structure specifying object composition is an embedded relation (see Bahrick, 1987). It is also consistent with a developmental sequence recently proposed by Lewkowicz (1992a) where detection of intersensory temporal synchrony is thought to emerge prior to the detection of other intersensory temporal relations.

Accordingly, studies in progress in our lab suggest that when an infant-control habituation procedure (Horowitz, Paden, Bhana, & Self, 1972) is used, infants show detection of synchrony and composition relations at a much younger age than findings from the intermodal preference methods would suggest. Infants were habituated to two new events, a single and a compound object, striking a surface erratically and producing natural, synchronous impact sounds. Following habituation, experimental subjects received test trials in which the relation between the visual and acoustic information was changed: Either the synchrony relations were disrupted, or the wrong sounds were synchronized with the visual impacts, disrupting the composition relations. Controls received no change. Bahrick (1992, discussed in more detail in Detection of Amodal Versus Arbitrary Intermodal Relations) found that at 3½ months, infants detected the changes in both synchrony and composition relations. They showed significant visual recovery to both types of test trials when compared with the performance of controls. More recent research from our lab using this method suggests that even infants as young as 6 and 10 weeks also detect these changes. In comparison with results of Bahrick (1987), the habituation method thus reveals sensitivity to these relations at much younger ages than does the intermodal preference method. This is not surprising because habituation is a discrimination task, whereas the intermodal preference procedure is a matching task, assumed to require greater attentional mobility and more sophisticated cognitive skills (Bahrick, 1992).

Intermodal functioning across age has also been investigated for infants' sensitivity to affective information available in both faces and voices (Walker 1982; Walker-Andrews, 1986, 1988). Using the intermodal preference method, Walker (1982) showed 5- and 7-month-old infants two films, side by side, of one woman speaking in a happy manner in one film versus a sad manner in the other. Results indicated that at both ages infants preferentially fixated the film whose matching soundtrack was played. Because voice–lip synchrony and affective information are typically confounded, Walker further investigated the independent contributions of each to infants' ability to match happy, neutral, sad, and angry filmed facial and vocal expressions. Seven-month-olds who were presented with inverted images of happy and angry faces along with a single synchronized soundtrack did not match the faces and voices, whereas those presented upright faces did. Because synchrony information was preserved and affective information is disrupted by showing faces upside down, these results suggest that infants' matching was not based predominately on synchrony information. Rather, infants apparently detected expressive information common to the movements of the face and sound of the voice. Further, when synchrony information was minimized by occluding the mouth area of the faces, 7-month-olds continued to show significant matching whereas 5-month-olds did not. Thus, detection of affective information common to the face and voice improves between 5 and 7 months of age and can be accomplished independent of voice–lip synchrony.

A developmental improvement between 4 and 6 months of age also has been found for infants' detection of intermodal relations specifying gender (Walker-Andrews, Bahrick, Raglioni, & Diaz, 1991). In two independent studies, 6-month-old infants showed matching of faces and voices of males and females speaking a nursery rhyme on the basis of speaker gender while voice–lip synchrony was controlled. Four-month-olds showed only an attenuated matching effect in one study.

A similar improvement in detection of intermodal relations uniting the faces and voices of children versus those of adults was found between 4 and 7 months of age in a recent study in our lab. Infants viewed video films of the faces of an unfamiliar child and adult of the same gender, side by side, speaking a nursery rhyme in synchrony with one another, along with the synchronized voice belonging to one of them. Seven-month-olds were able to match the appropriate faces and voices (Soutullo, Hernandez, & Bahrick, 1992), whereas the 4-month-olds showed only attenuated matching in one of the two trial blocks.

Another set of studies assessing developmental changes in the detection of amodal temporal relations has been conducted by Lewkowicz (1985, 1986, 1992b). With the exception of the most recent set of studies (Lewkowicz, 1992b), infants viewed pairs of spatially static stimuli consisting of flashing checkerboards and listened to a pulsing sound. When the bimodal stimuli were related by both synchrony and duration, 6- and 8-month-old infants performed intersensory matching but 3-month-olds did not (Lewkowicz, 1986). Because asynchrony disrupted the matching effect, synchrony was assumed to be the primary basis for matching. In a study utilizing the same methods and stimuli, where the bimodal stimuli were related by tempo and synchrony, 4-month-olds showed no matching (Lewkowicz, 1985). Similar results were reported by Humphrey and Tees (1980), who found that 3- and 7-month-olds did not match flashing lights with tones on the basis of synchrony and tempo combined, whereas 10-month-olds exhibited marginally significant matching. When infants were presented with spatially dynamic stimuli, both 4- and 8-month-olds were able to match a "bouncing" circle with a synchronous tone under limited conditions (when the sound corresponded with the stimulus that began to move first), but were unable to match on the basis of rate (Lewkowicz, 1992b).

Studies that have compared preterm and full-term infants' intermodal functioning suggest that preterm infants are initially at a disadvantage for detecting and learning about multimodal relations. Rose, Gottfried, and Bridger (1978) contrasted preterm and full-term infants' performance on a tactual–visual cross-modal transfer task. Both preterm and full-term infants exhibited equivalent visual discrimination, but only the full-term 1-year-olds were able to transfer shape information from the tactile to visual modalities. Pickens et al. (in press) investigated auditory–visual matching of faces and voices by preterm versus full-term infants. Side-by-side films of a woman's face were displayed along with a centrally presented soundtrack synchronized with the mouth movements of just one of the two videos. Full-term infants showed a significant looking preference for sound-specified films at 4 months of age, in agreement with prior studies. However, preterm infants did not show evidence of matching until 5 months (corrected for gestation time). One possible interpretation of the above studies is that preterm infants initially demonstrate a deficit in intersensory functioning, but that this deficit is overcome as a result of maturation and/or perceptual experience. New evidence suggests that intermodal perception deficits are more likely to persist for "higher risk" preterm infants with more severe health complications. For example, Lawson, Ruff, McCarton-Daum, Kurtzberg, and Vaughan (1984) showed that both low-risk and high-risk preterms demonstrated no evidence of detecting auditory–visual relations at 3 months of age; however, by 6 months of age, low-risk preterms "caught up" with full-term infants in the ability to associate an object and sound, whereas higher risk preterms continued to perform worse than full-terms. Thus, unlike low-risk infants, the high-risk infants were unable to overcome their initial intersensory perception deficits by 6 months of age. Therefore, further research must determine the extent to which prematurity and other perinatal risk factors, maturation, and perceptual experience all interact to determine infants' intermodal perceptual abilities.

In sum, intermodal matching improves with age. For dynamic, meaningful stimulus events, infants' matching on the basis of synchrony, information specifying object composition, speaker gender, child versus adult faces, and voice–face affect appears to emerge between the ages of 4 and 6 or 7 months of age. The ability to detect some of these amodal relations (e.g., synchrony and composition, tested thus far), however, appears to be present much earlier, as revealed by habituation studies. The apparent delay between the time infants detect amodal temporal relations (in a habituation paradigm) and match a soundtrack with one of two simultaneous films (in the intermodal preference method) may reflect a lag between noticing this information and the ability to use auditory information to guide visual exploration when several events are visible. Results from studies using spatially static and computer-generated stimuli are less clear. Similar improvements with age were found in detection of synchrony relations, although development appeared delayed and effects were more limited.

Although the improvement with age in detection of amodal relations is consistent with both the differentiation and the integration views, the early emergence of these abilities is difficult for integration views to accommodate. Simple association on the basis of co-occurrence seems inadequate to account for such well-developed intermodal abilities at such a young age, and coordination of action schemes is not yet possible due to the immature state of the infants' motor capabilities. Although improvement with age in infants' intermodal abilities would be expected by all theories, improvement characterized by detection of increasingly more specific relations with age would selectively support the differentiation view. The extent to which change across age conforms to this pattern is not yet clear and remains an important topic for future research.

Constraints on Infants' Detection of Amodal Audiovisual Relations

Recently, Rose and Ruff (1987) argued that we do not yet know enough about the specific basis for the infants' responses on various intermodal tasks. More systematic experimental designs were needed to explore the mechanisms underlying infants' intersensory abilities. They described a method developed by Kluver (1933) known as "the method of equivalent and nonequivalent stimuli," which provides a technique for determining the stimulus information that serves as the basis for a subject's response on a given task. A series of different conditions must be systematically presented to establish the range of stimuli to which subjects do or do not respond. Early studies on intermodal perceptual functioning can be criticized in that most have shown (by employing only one or two isolated conditions) that infants detect a given intermodal relation at a given age. This approach cannot reveal the mechanism, boundary conditions, or developmental emergence and progression of intermodal capabilities. Researchers should test infants under a variety of conditions to establish the range of stimulation under which the subjects do or do not respond in a particular way. In this way we may better understand the critical stimulus variables underlying intermodal abilities.

Kluver's method has been applied to the study of infant's intermodal perception of auditory–visual relations. One such study was conducted by Spelke et al. (1983) to determine the basis for detecting sound–motion synchrony relations in 4-month-olds. Using a two-screen intermodal preference paradigm, they found that infants matched discrete sounds with a bouncing stuffed animal when (a) visible impacts were synchronized with the sounds, (b) pauses in midair along with reversals of trajectory were synchronized with the sounds, and (c) reversals in direction of a continuous circular motion were synchronized with the sounds. Thus, infants responded to auditory–visual synchrony when any change in trajectory co-occurred with a sound, regardless of whether it coincided with a visible impact. Spelke et al. (1983) further found that infants did not respond with matching when the discrete sounds were synchronized with objects moving in a continuous circle and arriving at a given spatial position at the time of each sound. Thus, infants do not respond to auditory–visual synchrony for continuously moving objects in the absence of a change in trajectory. In contrast, adults responded more selectively, matching only discrete sounds with visible impacts. By systematically presenting stimulus conditions that were sufficient versus insufficient to promote matching, Spelke et al. (1983) clarified the basis for infants' responding to synchronous sights and sounds.

Kuhl and Meltzoff (1982, 1984) found that 5-month-old infants could match faces and voices on the basis of spectral information in the vowel sounds "a" and "i." When infants viewed two films of two faces side by side along with each vowel sound synchronized with the motions of both, they looked significantly more to the face that produced lip movements appropriate to the sound they heard. However, they no longer showed matching when pure tones were played in precise synchrony with the lip movements. Thus, when spectral information was removed, the temporal information was not sufficient to produce intermodal matching.

Similar constraints on matching synchronous sights and sounds have been documented in our lab. Bahrick (1983) showed that $4\frac{1}{2}$-month-olds matched films and soundtracks on the basis of synchrony and on the basis of elasticity/rigidity of substance. However, they failed to match when sounds of the wrong substance were played in synchrony with the motions of the objects. Similarly, Bahrick (1988) found that infants learned to pair a film and soundtrack after hearing them played in synchrony with the correct sounds, but not when played in synchrony with sounds of the wrong composition. The studies reviewed demonstrate that infants do not respond equivalently to all conditions that present audiovisual synchrony. They show that there are meaningful constraints on the types of sounds that infants will perceive as related to the synchronous motions of objects.

Intermodal matching on the basis of changing distance is another area where Kluver's method has been successfully applied. Walker-Andrews and Lennon (1985) reported that infants were sensitive to auditory–visual relations corresponding to the changing distance of a sounding object. In an intermodal preference procedure, 5-month-old infants preferentially fixated films of an approaching object when the soundtrack of increasing amplitude was presented, and a retreating object when the soundtrack of decreasing amplitude was played. This study promoted further research to delineate what information was necessary versus sufficient for the infants' performance. For example, were the infants responding only to quantitative relations, such as overall auditory and visual intensity, or were they showing veridical perception of meaningful distances? Were some visual cues more important than others for matching?

To answer these questions, Kluver's approach was employed in a recent study of 5-month-olds' perceptions of auditory–visual distance relations (Pickens, in press). Four conditions were presented wherein infants viewed side-by-side films along with a central soundtrack matching one of them. In Condition 1, infants viewed films of a toy train approaching and retreating over a natural landscape (depicted in Fig. 9.2). They were paired with engine sounds whose amplitude was either increasing ("approaching") or decreasing ("retreating"), with sound amplitude varying between 55 and 75 dB. Infants looked significantly longer to the approach film when the sound increased in intensity, and vice versa. Results are depicted in Fig. 9.3 along with those of the other conditions. Three other conditions were presented to assess the specificity of infants' performance. In Condition 2, infants viewed films of the train increasing and decreasing in size alone, along with the sounds that increased or decreased in amplitude. All background textures and landmarks were eliminated. Infants looked significantly more to the expanding film when the sound increased in amplitude, and vice versa. However, matching was significantly less robust than in Condition 1. This suggested that changing size was sufficient to allow matching; however, the availability of multiple depth cues facilitated matching beyond the level observed for changing size alone.

Two further conditions were included to test whether intensity relations alone, or more abstract stimulus relations, were sufficient to promote matching. Condition 3, the test of intensity relations, presented films of the train with no change in size, but with increasing and decreasing brightness, along with soundtracks of increasing or decreasing amplitude. Infants showed no evidence of matching on the basis of intensity alone. It is thus unlikely that auditory–visual intensity shifts played an important role in infants' matching under Conditions 1 or 2. Finally, in Condition 4 we tested infants' response to the image of the train moving up or down against a black background, paired with soundtracks of increasing and decreasing amplitude. Whereas adults consistently "matched" the up motion with the increasing sound amplitude, and vice versa, infants did not. This suggests that infants' matching behavior was specific to distance information and did not generalize to more global, metaphorical relations. Taken together, these results indicate that 5-month-old infants were sensitive to ecological auditory–visual relations specifying approach versus retreat, and that matching was specific to ecological depth information (where one important "cue" was changing size), and did not generalize to intensity relations, or metaphorical auditory–visual relations.

Two other studies examined infants' response to multimodal distance information. Morrongiello and Fenwick (1991) asked whether perception of changing distance relations changed during development. They examined infants' matching of increasing/decreasing amplitude sounds with films of static objects, objects moving laterally, and objects that expanded and contracted in size. Evidence for developmental differences was found: At 5 months of age infants performed audiovisual matching only when a static object was contrasted with a moving one. At 7 months infants matched when a static or

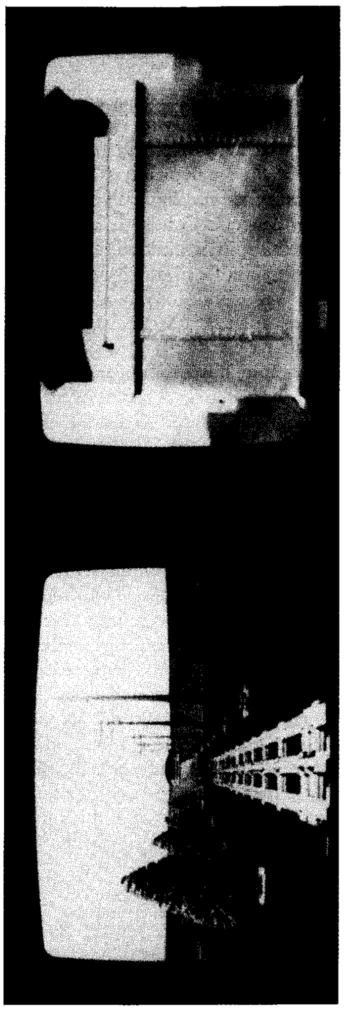

FIG. 9.2. An example of the approaching and retreating events used by Pickens (in press, Condition I).

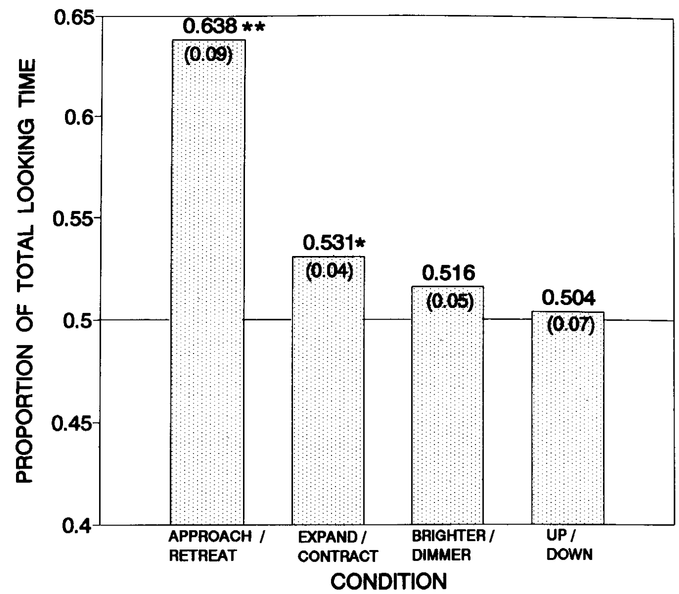

FIG. 9.3. Mean proportions of total looking time and standard deviations to the sound-specified events as a function of four stimulus conditions (Pickens, in press). Significant differences: $*p < .01$; $**p < .001$.

laterally moving object was contrasted with one moving in depth. Finally, at 9 months infants matched when an approaching object was contrasted with a retreating object. Thus, matching became increasingly more specific with age. In contrast with results of the prior studies, infants in this study could not match in the depth condition until the age of 9 months. This may be due to differences in stimulus events. The approach/retreat condition was created by using a zoom lens, and in this respect was not comparable to those of prior studies where objects translating real distances were filmed. The other study that examined perception of multimodal distance information was one by Schiff, Benasich, and Bornstein (1989), which extended the research on perception of changing distance to social stimuli. Schiff et al. found that 5-month-olds responded to coherent audiovisual relations when a speaking person was presented moving back and forth over a distance.

Taken together, the research reviewed in this section demonstrates that there are appropriate constraints on infants' intermodal perception of audiovisual spatial and temporal relations. Infants apparently respond to meaningful properties of objects such as changing distance, object unity, composition, substance, and spectral information. Although sights and sounds co-occurred and were synchronous under a number of conditions, they were perceived as related only under some conditions. These data are most clearly consistent with an invariant detection view of perceptual development. By the age of 4–7 months, infants' intermodal abilities become more specific and have progressed beyond the detection of synchronous relations to detection of more specific amodal relations specifying meaningful properties of objects. Taken together, this research underscores the primacy of amodal relations in directing intermodal perception.

This body of research also provides some direct evidence against the intensity matching view as a basis for intermodal matching after 3–4 months of age. It was shown that infants by 4 months responded to meaningful, qualitative properties of events rather than to simple quantitative aspects of stimulation. Matching on the basis of intensity alone was ruled out by Condition 3 of Pickens' (in press) study where infants failed to match under conditions which maximized intensity relations. It was eliminated as an explanation of matching in the Spelke et al. (1983) study because the sounds and objects were arbitrarily paired and counterbalanced and shared no common intensity relations. Further, although intensity relations were held constant in this study, matching occurred on the basis of synchrony under some conditions but not others. Given that the infants in these studies were 4–7 months of age, however, those supporting a more recent intensity matching view would argue that intensity-based matching occurs at younger ages and may already give way to matching on the basis of qualitative relations by the age of 4–6 months (see Lewkowicz, 1991). Thus, without testing infants of younger ages, one cannot determine how these abilities came into being. However, infants of 1 month and younger have shown cross-modal abilities for visual–tactile and visual–proprioceptive relations. One-month-olds are able to recognize the shape and substance of an object visually after only tactile experience (Gibson & Walker, 1984; Meltzoff & Borton, 1979). Even neonates demonstrate imitation of facial gestures, requiring intermodal visual–proprioceptive abilities (Field, Woodson, Greenberg, & Cohen, 1982; Meltzoff & Moore, 1977). Imitation is clearly an ability that cannot be accounted for on the basis of intensity matching.

Evidence against an integration-association view is also apparent. First, that infants show intermodal matching at such a young age is difficult for a view that posits gradual integration across sense modalities to account for. Second, results of studies using the intermodal preference method suggest that infants do not relate objects and sounds on the basis of mere co-occurrence because even synchronous sounds and sights are not perceived as related under many conditions. Because these studies typically tested infants of 4 months or older, it is still possible that many of these audiovisual relations were "integrated" and associated at younger ages. Infants may have generalized their experience with typically co-occurring sights and sounds to the new events used in the foregoing studies. However, results of studies that employed arbitrarily matched objects and sounds (e.g., Spelke et al., 1983) cannot be accounted for on these grounds. Further, without positing early detection of synchrony, one cannot explain how the infants' attention is focused on the correct object–sound relations in the first place. Thus, on balance, it is difficult for an integration view to accommodate the preceding findings.

Intermodal Learning

Another effective method for assessing the importance of detecting amodal relations in the development of perception is to investigate the process of learning directly. If it can be shown that detection of amodal relations guides intermodal learning, this will provide direct support for our hypothesis regarding the primacy of amodal relations. In the prior studies, the infants tested were already competent perceivers of intermodal relations. Bahrick (1988) examined the learning process directly in younger infants who showed no evidence of spontaneously detecting the amodal relations in question. Three-month-old infants viewed films of the single large marble and the group of smaller marbles, colliding against a surface in an erratic pattern (see Fig. 9.1). The sounds and moving objects shared two kinds of nested amodal temporal structure. Temporal synchrony (macrostructure) united the sights and sounds across impacts, and an embedded temporal structure (microstructure) specified the composition of the object at each impact (single vs. compound). Three-month-old infants were given the opportunity to learn the relationship between the objects and sounds by viewing single film and soundtrack pairings under a variety of familiarization/training conditions where the object motions and sounds were either congruent or incongruent. Specifically, the films were accompanied by sounds that were (a) appropriate to the composition of the object and synchronous with its motions, (b) appropriate and asynchronous, (c) inappropriate and synchronous (the wrong sounds and films were synchronized), or (d) inappropriate and asynchronous. Then all subjects were tested in an intermodal matching test where the two events were presented side-by-side along with one soundtrack to determine under which familiarization conditions intermodal learning had occurred. Control subjects, who had received familiarization with irrelevant events, showed no matching. Thus, any results of the matching test could be attributed to learning during the familiarization phase of the experiment. Results are depicted in Fig. 9.4. They indicated that only subjects who had been familiarized with the appropriate and synchronous film and soundtrack pairs showed evidence of learning. They showed a visual preference for the film that, during training,

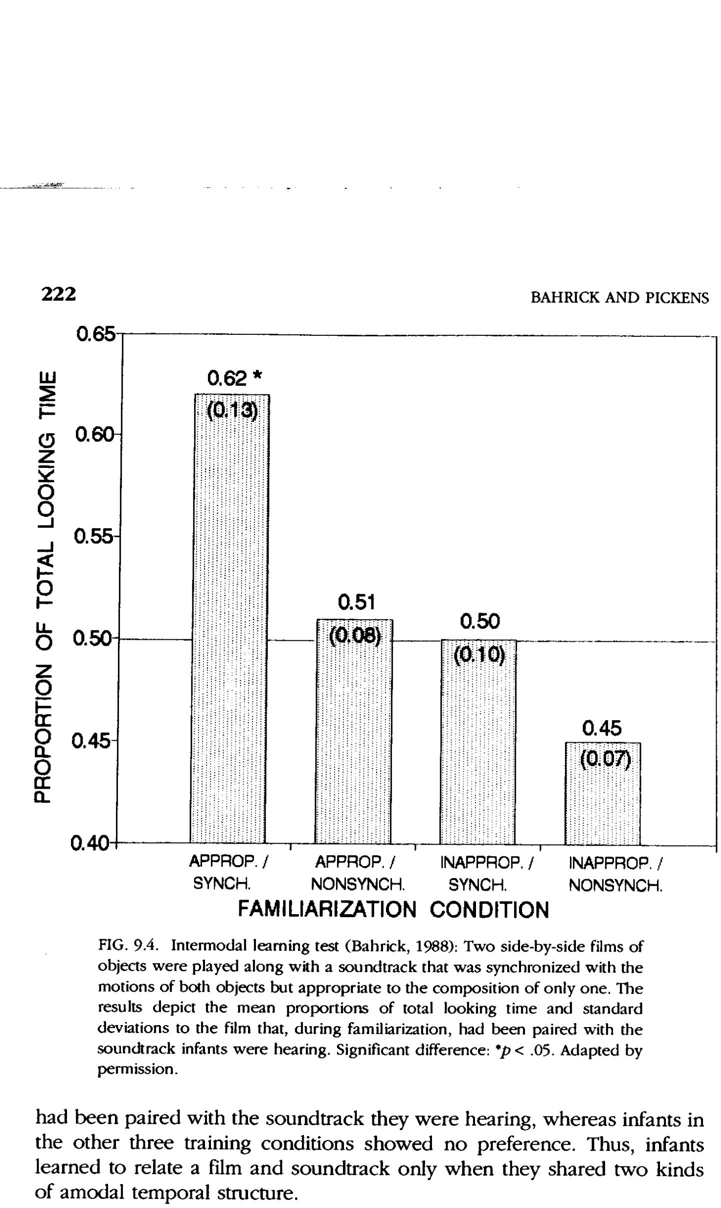

FIG. 9.4. Intermodal learning test (Bahrick, 1988): Two side-by-side films of objects were played along with a soundtrack that was synchronized with the motions of both objects but appropriate to the composition of only one. The results depict the mean proportions of total looking time and standard deviations to the film that, during familiarization, had been paired with the soundtrack infants were hearing. Significant difference: $^*p < .05$. Adapted by permission.

had been paired with the soundtrack they were hearing, whereas infants in the other three training conditions showed no preference. Thus, infants learned to relate a film and soundtrack only when they shared two kinds of amodal temporal structure.

The Bahrick (1988) procedure provided an excellent test of the integration-association versus invariant detection views. Infants were given equal opportunity to associate the films and soundtracks during familiarization across the four conditions. However, learning only occurred when two kinds of amodal relations united the object motions and sounds. Learning did not occur through association, even when the film of a single object was played moving in synchrony with inappropriate sounds. The presence of an incongruent amodal relation (specifying object composition) was

apparently sufficient to preclude learning under these conditions. Thus, by 3 months intermodal learning seems to be guided by the detection of amodal invariant relations. These relations already exert meaningful constraints on the types of synchronous sights and sounds that can be perceived as united.

Another approach to assessing intermodal learning has been to test older infants who can already detect the relations in question without special training. Under what conditions does the infant's experience with audible and visible events lead to knowledge about the relationship between specific visual and acoustic attributes? Spelke (1979, 1981) addressed this question by presenting infants with a visual search test to measure what they had learned during a prior intermodal preference phase. Four-month-old infants viewed films of two stuffed animals (a kangaroo and a donkey) bouncing side-by-side along with arbitrarily selected impact sounds (thuds or gongs) emanating from a central speaker during the preference phase. The sounds shared a common tempo and/or synchrony relation with the motions of one object and were unrelated to the motions of the other object. Next, a search test was conducted where the animals were again shown side-by-side along with intermittent sounds from each. Spelke (1979) found that infants searched first more often and eventually in the direction of the film that belonged with the sound they were hearing. Because the sounds and objects were arbitrarily paired, infants could only have learned which animal went with each sound by detecting amodal relations (synchrony and/or tempo) during the preference phases. Further, they did not learn by associating co-occurring objects and sounds, because each sound co-occurred with the presentation of both stuffed animals, yet only one of the animals was perceived as related to each sound. Thus, learning during the intermodal preference phase must have occurred on the basis of detecting amodal relations. These results were replicated and extended in a series of further studies (Spelke, 1981), which eliminated the possibilities that successful search behavior was based on "place learning" or on detection of synchrony during the search phase, rather than detection of amodal relations during the preference phase. Infants demonstrated learning of the arbitrary relations, even when the search phase was conducted with asynchronous sounds, the lateral positions of the animals had been switched, and the films and soundtracks were played successively.

The finding that intermodal learning occurred on the basis of detecting amodal relations was replicated and extended to different amodal relations. Bahrick (1983), using a similar method, showed 4½-month-old infants films of wooden blocks banging and water-soaked sponges squishing. During a modified preference phase where synchrony was controlled, infants showed clear evidence of detecting the temporal information specifying rigidity and elasticity of substance. In the subsequent search phase, they were able to use this information to search first significantly more often to the sound-matched film. Infants apparently learned that the blocks made the banging sounds whereas the sponges made the squishing sounds.

Further, Bahrick (1987) conducted a developmental study using the films of the single large marble and the group of smaller marbles. By 6 months, infants were able to match the films and sounds in an intermodal preference phase solely on the basis of temporal information specifying object composition. By 7½ months they were able to search successfully for the sound-specified object after abstracting this information in the preference phase. Because synchrony was controlled in both the preference and search phases, and because age-matched control subjects who received no preference phase were unable to search successfully, the search performance was attributed to intermodal knowledge acquired by detecting amodal relations specifying object composition in the preference phase. Infants must have learned something about the relation between the visual appearance of the object and the type of sound it produced.

Thus, taken together, the intermodal preference and search studies provide strong evidence that infants acquire knowledge about the relation between visual and acoustic aspects of events by detecting amodal audiovisual relations. Detection of amodal relations in the preference phase of each study described earlier (temporal synchrony, tempo of action, composition, and substance information) preceded and guided learning about modality-specific visual and acoustic relations. This knowledge enabled infants to search successfully for an object upon hearing the sound it was previously related to. Learning did not occur by integrating and associating co-occurring films and soundtracks, either when the soundtrack was played with a single film (Bahrick, 1988) or with two side-by-side (Bahrick, 1987; Spelke, 1979, 1981). That infants selectively learn about multimodal events on the basis of amodal relations (and not when amodal information is disrupted) constitutes a convenient buffer against learning the numerous possible inappropriate relations from unrelated sights and sounds. These studies provide evidence that detection of amodal temporal relations is an important basis for perceptual learning in early infancy.

Detection of Amodal Versus Arbitrary Intermodal Relations

A multimodal event makes a number of different intermodal relations available. Some, as we have discussed, are amodal and invariant across sense modalities, whereas others are arbitrary and not invariant across sense modalities. For any given event, one can abstract a number of arbitrary, modality-specific relations that may vary from one object or context to the next. For example, the relation between the sight of a person's face and the particular sound of their voice is arbitrary; or the color and shape of a moving object and the pitch of its impact sound; or the shape of a container and the smell, taste, or temperature of its contents. A red plastic toy may produce an impact sound that is high or low, or sharp or dull, depending on the type of surface it strikes. A tall green bottle could just as easily contain something sweet or sour, strong or mild, or hot or cold. Although amodal relations need not be learned through experience, arbitrary intermodal relations must be learned. Adults, however, seem to easily learn and remember a multitude of arbitrary relations in every day life.

When and under what conditions do infants detect and learn arbitrary intermodal relations? Does detection of these relations developmentally parallel, precede, or succeed detection of amodal relations in the same events? Empirical investigation of this question is another promising approach for evaluating the importance of amodal relations in the development of intermodal perception. Given the limited generalizability of arbitrary relations across objects and contexts, detection of these relations seems less important for perceptual development than detection of amodal relations. Very little research, however, has directly investigated the infant's sensitivity to arbitrary intermodal relations. One study (Spelke & Owsley, 1979) found that infants by the age of 3½ months have already learned to relate the sight of their mother's face with the particular sound of her voice. Fernandez and Bahrick (in press) discovered that female infants at 4 months were able to learn the relation between the visual appearance of a toy and a distinctive odor. At 7 months, infants were able to learn the relationship between the color of a container and the taste of its food (Reardon & Bushnell, 1988). On the other hand, Bushnell (1986) found that infants of this age were unable to learn to pair the color of an object with its temperature. No clear pattern has yet emerged regarding the nature or timing of this developmental process.

How might arbitrary intermodal relations be learned? One possibility is that they are learned by association on the basis of co-occurrence. Bushnell (1986), consistent with the integration-association view, suggested that infants may treat arbitrary and amodal relations similarly. Both are experienced as "multimodal compounds," or as information in separate sense modalities that must be put together somehow. In contrast, our view is that only arbitrary or modality-specific relations must be learned through experience. Many events make both amodal and arbitrary relations available. Bahrick (1992) proposed that intermodal knowledge about arbitrary relations is differentiated only after amodal relations are detected. Several studies (Bahrick, 1983, 1987; Spelke, 1979, 1981, reviewed earlier) have shown that detection of amodal temporal relations during a preference phase made it possible for infants to detect the arbitrary relation between the visual appearance of the object and the particular sound that it produced, in a subsequent search phase. Further, Bahrick (1988) found that 3-month-olds learned to relate an object and a sound only after detecting two types of amodal invariant relations uniting their motions and sounds. We thus propose that detection of amodal invariants precedes and guides learning about arbitrary object–sound relations by directing infants' attention to appropriate object–sound pairings and then promoting sustained attention and further differentiation. Initial detection of an amodal relation (e.g., voice–lip synchrony, shared rhythm and tempo) enables the infant to focus on a unitary event (e.g., the mother's face and voice). This, in turn, may lead to differentiation of more specific, arbitrarily paired audible and visible attributes (e.g., the sound of the voice with the unique appearance of the face). In this way, detection of amodal relations can precede and guide learning about arbitrary relations. This pattern is consistent with an increasing specificity view of perceptual development (E. J. Gibson, 1969).

The studies reviewed in the prior section demonstrated that detection of amodal relations preceded and guided the acquisition of intermodal knowledge about arbitrary relations within a given testing session. Might there also be a developmental progression across age where infants detect amodal relations at a younger age than arbitrary relations from the same events? Only one recent set of studies has addressed this question. Bahrick (1992) presented 3-month-old infants with films of a single large object and a cluster of smaller objects, taken from one of six pairs (depicted in Fig. 9.5), striking a surface in an erratic pattern. The films portrayed two amodal invariant relations, temporal synchrony (SYNC) and temporal information specifying the composition of the objects (COMP), as well as one arbitrary, modality-specific relation, that between the pitch of the impact sounds and the color/shape of the objects (SOS). Infants were habituated to two of these events along with their natural, synchronous sounds, and then received test trials in which the relation between the visual and acoustic information was changed or mismatched. Infants showed significant visual recovery to a change in both amodal relations, but not to the change in the pairing of pitch with color/shape, relative to the performance of control subjects who received no change (see Fig. 9.6). Two further control studies demonstrated that the 3-month-olds could, in fact, discriminate the color/shape and pitch changes used. These findings suggested that by 3 months, infants were already sensitive to the amodal relations, but were not yet able to detect the arbitrary pitch–color/shape relations. It was thus proposed that detection of amodal temporal relations developmentally precedes detection of arbitrary relations.

At what age do infants detect the arbitrary relation between the pitch of an impact sound and the color/shape of an object? A further study using the same stimulus events (Bahrick, in press) revealed that it was not until 7 months of age that infants showed significant visual recovery to a change in these arbitrary relations. Three- and 5-month-olds did not. This suggests

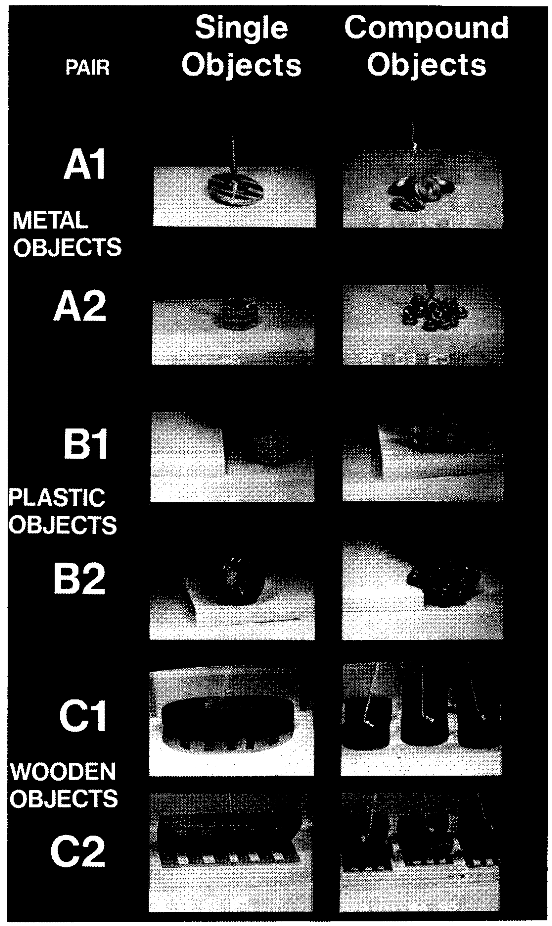

FIG. 9.5. The single and compound object pairs from Bahrick (1992). Reprinted by permission.

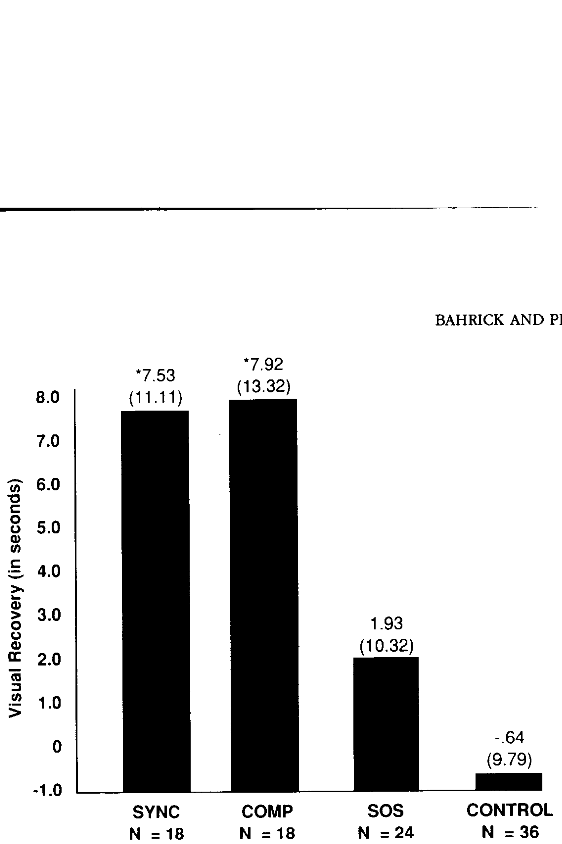

FIG. 9.6. Mean visual recovery and standard deviations to a change in synchrony (SYNC), composition (COMP), and color/shape-pitch (SOS) relations, as compared with no-change controls (from Bahrick, 1992). Significance: $^*p$ = or < .01 with respect to controls. Reprinted by permission.

a developmental lag between discrimination of unimodal stimulation and detection of arbitrary bimodal relations.

It is too early to determine how broad a phenomenon this developmental lag between detection of amodal and arbitrary relations will prove to be. To what other stimulus domains and conditions will it generalize? These are important questions for future research to address. Nevertheless, for the domains in which it does occur, this developmental lag is seen as adaptive in promoting the development of veridical perception. By detecting amodal relations first, infants can develop intermodal knowledge about persistent properties of objects and events prior to the acquisition of knowledge about more variable, idiosyncratic relations. This can provide appropriate constraints on learning about arbitrary relations that are typically context or stimulus specific. For example, by abstracting audiovisual synchrony and temporal information specifying composition, infants can learn and generalize that single objects produce single sounds and compound objects produce a more prolonged, "compound" sound. Detection of these relations can guide perceptual development appropriately. If infants learn that red, round objects produce a single sound, or a high-pitched sound, and attempt to generalize this across contexts, it would interfere with veridical perceptual development.

Thus, by first abstracting amodal relations, perceptual learning will be based on more permanent, context-free relations, and will not be disrupted by learning numerous relations that vary from one context to the next. In other words, detection of amodal relations in early development acts as a "buffer" against premature learning and inappropriate generalization of idiosyncratic relations.

CONCLUSIONS

The research reviewed in this chapter provides converging evidence from five domains that detection of amodal relations motivates and guides perceptual development in the first months of life. There is now abundant evidence that young infants detect a wide range of amodal relations in audible and visible stimulation, from temporal synchrony, and rhythm, to object substance, spectral information in speech, and changing distance relations. Nonetheless, the ability to detect many of these relations improves with age, and there are meaningful constraints on the perception of intermodal relations in infancy. Infants do not learn to pair just any co-occurring object and sound. Rather, they pair objects with sounds that are synchronous and "correct" with respect to the object's composition. Finally, amodal relations may be differentiated prior to arbitrary relations from the same event. Infants' unique sensitivity to amodal relations has been demonstrated across a diverse set of naturalistic events and different procedures, including the intermodal preference and search methods, infant-control habituation, or training and transfer, and across successive or simultaneous presentations of visual and acoustic stimulation. In our view, results of much of the research reviewed in this chapter seem inconsistent with the integration-association view, are difficult to explain on the basis of intensity matching, and occur too early in development to be accounted for on the basis of Piaget's action-centered view. Gibson's invariant-detection view appears to be most clearly consistent with all the research findings reviewed. However, none of the theories adequately describe what relations are detected first and how it is that inappropriate or irrelevant relations are not learned. What are the innate capacities of the infant that set the development of intermodal perception into motion such that it develops veridically within such a remarkably short period of time?

From our research and review of the literature we have elaborated a preliminary model that begins to address these questions. It is developed within the context of Gibson's invariant-detection theory and describes how detection of amodal relations can veridically guide perceptual development and intermodal learning:

1. Infants come into the world with a primitive intermodal coordination of audio-visual space (Wertheimer, 1961). How, though, does the infant

determine which of the many objects within his direction of gaze belong with the sound he is hearing?

2. Young infants are preadapted to selectively detect amodal relations and these relations guide perceptual exploration at first. By abstracting amodal relations, the infant explores and perceives unitary multimodal events.

3. Detection of further multimodal relations proceeds in order of increasing specificity (E. J. Gibson, 1969). That is, global, amodal relations may be differentiated prior to nested or more specific intermodal relations. This sequence may characterize the order in which infants abstract multimodal information in a given encounter with an event, as well as across age.

4. Selective tuning to amodal relations functions as a buffer against learning incongruent relations in early infancy. By detecting amodal relations first, learning will be based on more permanent, context-free relations that can be accurately generalized, whereas learning about arbitrary, idiosyncratic relations that do not generalize across contexts will be delayed until appropriate constraints are learned. Finally, once detection of amodal relations fulfills these functions, they presumably no longer play such a predominant role in directing perceptual selectivity.

In the introduction to this chapter we asked, how could infants, with no prior knowledge of the world around them, select, learn, and remember information that is relevant, meaningful, and coherent, and ignore the vast amount of stimulation that is not? The model just elaborated provides an answer. Selective tuning to amodal relations at first serves as an efficient and economical substitute for the knowledge that guides adult perception. Once sufficient knowledge about multimodal events is acquired, this knowledge can in part guide further exploration, and infants may then become more attuned to other aspects of stimulation.

It appears that research on intermodal perception has made an important shift: from that of cataloguing and mapping out intermodal abilities possessed by young infants, to addressing questions regarding the mechanism for and nature of development. Although different theoretical views will continue to drive this research, important questions have emerged and new, more promising approaches have evolved for answering them. We are asking questions about the basis and nature of intermodal learning in infancy; about the conditions under which infants respond to meaningful, qualitative properties of events; about which intermodal relations are differentiated first, and drive development, and which are detected later. Two especially promising approaches for addressing these questions are training and transfer studies such as the intermodal learning method used by Bahrick (1988), and Kluver's approach for establishing the nature of the stimulus information to which infants respond. In combination with developmental studies comparing performance across age, these approaches promise to reveal much more about the nature and basis of intermodal perception in years to come.

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