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Theories of Infant Development

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4 The Development of Perception in a Multimodal Environment

Lorraine E. Bahrick

Introduction

We live in a world of multimodal objects and events that present a constantly changing, richly structured flux of stimulation to all of our senses. Sounds typically come from visible, tangible objects. People provide an array of dynamic, concurrent, tactile, visual, auditory, and olfactory stimulation. The infant encounters this world of multimodal, dynamic objects and events and experiences it through a unified perceptual system (Gibson, 1969). Much early infant perception and learning emerges in the context of close face-to-face interactions with caretakers. This interaction scaffolds attention and provides a rich source of concurrent visual, vocal, tactile, vestibular, and kinetic stimulation. In these interactions, the adult's speech, facial movements, and gestures are typically temporally synchronous and coordinated, often accompanied by synchronous touch and movement of the infant ("multimodal motherese": see Gogate, Bahrick, & Watson, 2000; Zukow-Goldring, 1997), and intercoordinated with the temporal characteristics of the infant's behavior (e.g., Jaffee, Beebe, Feldstein, Crown, & Jasnow, 2001; Trevarthen, 1993). Infants also engage in active, self-directed, intermodal exploration of their own bodies

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(e.g., Butterworth & Hopkins, 1988; Rochat, 1993; van der Meer, van der Weel, & Lee, 1995) and the contingencies between their movements and those of the multimodal objects and events in their environment (e.g., Bahrick, 1995; Bahrick & Watson, 1985; Rochat & Morgan, 1995; Schmuckler, 1995). Exploration of the self provides the first and one of the most potent and reliable sources of multimodal stimulation, as proprioceptive feedback always accompanies self-generated visual, vocal, and tactile stimulation (see Rochat, 1995).

How and on what basis do infants begin to parse, perceive, and derive meaning from the flux of multimodal stimulation in a manner that lays a foundation for the perceptual world of the adult? How do infants determine which sights and sounds belong together and constitute unitary events and which patterns of stimulation are unrelated to one another? What enables young perceivers to attend to patterns of stimulation that are relevant and meaningful while ignoring patterns which are less relevant to their actions and needs? In other words, what are the factors that initially organize attention and perception such that its developmental trajectory provides the foundation for the knowledge base and perceptual and conceptual competencies of the adult perceiver?

Infant Perception of Amodal Information

Research has made some progress in addressing these questions. In the area of intersensory perception, research has now generated a solid data base demonstrating that infants are adept perceivers of multimodal stimulation across a variety of natural events. According to Gibson's (1969) invariant detection view of perceptual development, infants come into the world with a unified perceptual system, capable of detecting amodal, invariant information. Amodal information is information such as synchrony, tempo, rhythm, intensity, and so forth, that is common across several sense modalities. Through development infants differentiate increasingly finer aspects of stimulation (Gibson, 1969). This view has prompted a great deal of research investigating infant capabilities for perceiving amodal, invariant relations and has revealed that infants are adept at perceiving a host of amodal relations uniting the multimodal stimulation across different sense modalities (see Lewkowicz & Lickliter, 1994, for a review). For example, infants detect temporal synchrony, shared rhythm, and spectral information uniting movements of the mouth and the timing and nature of speech sounds (e.g., Dodd, 1979; Kuhl & Meltzoff, 1982, 1984; Lewkowicz, 1996). They detect common auditory-visual information conveying speaker gender and age (Bahrick, Netto, & Hernandez-Reif, 1998; Walker-Andrews, Bahrick, Raglioni, & Diaz, 1991) as well as affect common to the face and voice (e.g., Soken & Pick, 1992; Walker, 1982; Walker-Andrews, 1997). Infants also abstract common temporal information uniting the sights and sounds of moving objects including the synchrony between movements and their impact sounds (Bahrick, 1988, 1992; Lewkowicz, 1992; Spelke, 1979), their common tempo and rhythm (Allen, Walker, Symonds, & Marcell, 1977; Bahrick, Flom, & Lickliter, 2002; Bahrick & Lickliter, 2000; Gogate & Bahrick, 1998; see Lewkowicz, 2000, for a review), and amodal temporal information specifying the composition and substance of moving objects (Bahrick, 1983, 1987, 1988, 1992). Young infants are also adept at perceiving multimodal information specifying the self and their body motion (Butterworth, 1992; Rochat, 1995). They can adjust their posture in response to visual feedback (Butterworth & Hicks, 1977; Lee & Aronson, 1974), and they detect proprioceptive information resulting from their body motion and can relate it to the visual consequences of that motion (Bahrick & Watson, 1985; Rochat & Morgan, 1995). Young infants are adept perceivers of the rich flux of multimodal stimulation.

Although young infants appear to be quite capable of abstracting meaningful information and coherent multimodal events from the flow of sensory stimulation, the origins and nature of this developmental trajectory are still unclear. How do infants initially accomplish this, and what guides attention, perception, and learning such that meaningful, unitary events are abstracted in the first place? Which competencies are derived from earlier ones, and how? What are the principles that guide and constrain perceptual development such that infants develop the competencies of adult perceivers so early and in such an economical and veridical manner?

Principles of Perceptual Development

Recent evidence now addresses some of these important developmental questions. Consistent with Gibson's (1969) view of perceptual development, research from my laboratory has shown that learning about multimodal events proceeds in order of increasing specificity and this guides and provides important constraints for perceptual development (Bahrick, 1992, 1994, 2001).

In a series of studies, we found support for three basic principles of intersensory learning.

First, global, amodal relations are detected developmentally prior to nested amodal relations (Bahrick, 2001). Global relations include shared temporal synchrony (such as that uniting the sights and sounds of an object's impacts), and rhythm and tempo of intermodal events. Nested amodal relations are more specific and are detectable within each synchronous impact. They convey more detail about the intersensory event such as its substance (rigidity vs. elasticity), composition (that it is comprised of a single vs. an aggregate of elements), its weight or number. Bahrick (2001) habituated infants to naturalistic events depicting single and compound objects striking a surface, producing their natural impact sounds. Visual recovery tests were then given in which the sounds were presented out of synchrony with the objects' impacts, or the sounds and objects were mismatched so that the single object produced the sounds of the compound object at each impact and vice versa. Results (depicted in figure 4.1) demonstrated that infant detection of temporal synchrony was already evident by the age of 4 weeks and remained stable across age, whereas the detection of nested amodal temporal microstructure specifying the object's composition did not emerge until 7 weeks of age and increased dramatically across age such that, by 11 weeks, detection

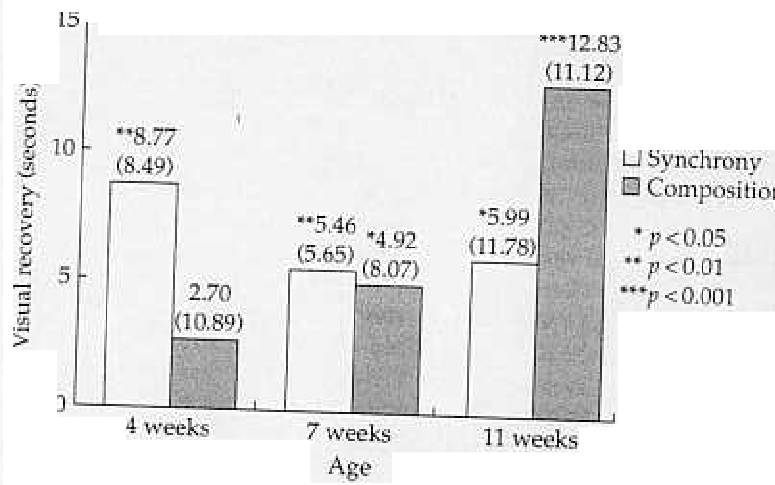

Figure 4.1 Mean visual recovery and standard deviations (in parenthesis) to test trials depicting a change in temporal synchrony and temporal microstructure specifying the composition of the objects at 4, 7, and 11 weeks of age (from Bahrick, 2001). Reprinted with permission of Elsevier.

of this nested amodal information was significantly greater than detection of global synchrony. Early detection of temporal synchrony is important because temporal synchrony can specify the unity of the audiovisual event. Once infants attend to a unitary event, differentiation of further relations can then proceed in a veridical manner. However, attention to a sound and a sight that do not belong together would be maladaptive and would lead to learning of incongruent intersensory relations.

A second developmental principle is that detection of amodal relations in a given domain developmentally precedes detection of arbitrary, modality-specific relations. Modality-specific information is information that is specified by only a single sense modality. For example, color and pattern are specific to vision, whereas pitch and timber are specific to audition. An intersensory relation between modality-specific information is typically arbitrary and must be learned. For example, the relation between the visual appearance of a woman's face and the particular sound of her voice is arbitrary. So is the relation between the pitch of an impact sound and the color of an object, or that between a speech sound and the appearance of the object it represents, or the relation between the visual appearance of a container and the temperature or taste of its contents. Bahrick (1992, 1994) found that by 3 months of age infants detected amodal temporal synchrony and temporal information specifying object composition in single and compound objects striking a surface. However, it was not until the age of 7 months that they detected the arbitrary, modality-specific relation between the pitch of the sounds and the colors and shapes of the moving objects, even though at 3 months of age infants could discriminate among all the objects and their sounds. Further, it was found that even when the modality-specific properties were made more highly discriminable, the amodal relations were nevertheless perceived developmentally prior to the arbitrary, modality-specific relations (Bahrick, 2000). There appears to be a developmental lag between the detection of amodal and modality-specific audiovisual relations provided by a given event.

A third developmental principle revealed by our research is that the infants' detection of amodal relations guides and constrains perceptual learning about arbitrary relations. For example, if an infant detects the amodal synchrony, rhythm, and/or tempo uniting a person's face and his or her voice, the infant is then likely to learn the unique and arbitrary relation between the pitch/timber of that individual's voice and the particular configuration of his or her face. In contrast, if no common synchrony, rhythm, or tempo is detected, the association between the appearance of the face and sound of the voice is less likely to be learned. This principle was found to apply to intersensory learning about the arbitrary relation between the appearance of an object and the speech sound paired with it (Gogate & Bahrick, 1998), the color/pattern of an object and its tactually experienced shape (Hernandez-Reif & Bahrick, 2001), and the visual appearance of a single or compound object striking a surface and the particular sound it produced (Bahrick, 1988, 1992, 1994). Even newborns show evidence of learning arbitrary audiovisual relations in the presence of amodal information but not in its absence (Slater, Quinn, Brown, & Hayes, 1999). Studies of a variety of events perceived through various sensory modalities now suggest that detection of amodal information such as temporal synchrony can promote further differentiation of the unitary event and lead to learning about nested properties and, finally, about arbitrary, modality-specific relations.

This developmental sequence where learning progresses in order of increasing specificity (from detection of amodal to arbitrary, modality-specific relations) is adaptive because it can promote learning about consistencies and regularities across the senses that are context-independent prior to learning about more context-dependent relations (see Bahrick, 2001). Early detection of amodal relations fosters appropriate, veridical generalizations and minimizes inappropriate generalizations about relations that vary across contexts and are specific to certain events. In this manner, detection of amodal relations can guide and constrain learning about modality-specific relations such that general principles (e.g., voices go with faces; male faces go with deeper voices and female faces go with higher voices; happy faces go with happy voices; single objects make single impact sounds; rigid objects make abrupt impact sounds) are well established prior to learning about more specific details of these events (e.g., John's face goes with a low, raspy voice; a particular speech sound goes with a particular object; the high squeaking sound is made by the yellow duck; the red object makes a musical sound when struck). This progression from global to specific is adaptive and provides a means of organizing, guiding, and constraining perceptual learning in a way that will efficiently lead to the intermodal knowledge of adult perceivers.

The above research has revealed important principles of perceptual development explaining attentional allocation, perception, and learning about events experienced multimodally. These principles were all derived in multimodal research paradigms where infants received simultaneous audible and visible stimulation, as is typical in the natural environment. However, stimulation from a given event does not always reach multiple sense modalities. For example, one might experience a voice from a nearby room, the sounds of unseen hands clapping, or the sight of a silent face. Although less typical in the infant's world, properties of events, including amodal properties (e.g., tempo, rhythm, substance, composition, intensity, etc.) and modality-specific properties (e.g., color, pattern, pitch, timber), can be experienced in the context of unimodal stimulation as contrasted with multimodal sensory stimulation.

Are the principles of perceptual learning derived from the study of multimodal events (described above) applicable to these unimodal contexts as well? Conversely, how does unimodal exploration of events generalize to exploration of the typical multimodal environment? This is not only an important theoretical question; it is significant for practical and methodological reasons as well.

Unimodal vs. Multimodal Stimulation

Developmental psychologists have traditionally studied the development of specific perceptual or cognitive abilities in one sense modality at a time and eliminated concurrent stimulation to other sense modalities in their research designs. Thus, theories of speech perception and language development have traditionally been formulated by focusing on the auditory stream devoid of the speaking face; theories of face perception have primarily been based on studies of unimodal, visual facial displays; memory has been studied for static visual displays or for auditory information separately; early communication has been studied by examining joint visual attention without the vocal accompaniment, and so forth, to name a few examples (for a review of this type of research, see Kuhn & Siegler, 1998). However, all these capabilities emerge in a primarily multimodal context of people who coordinate speech, gesture, facial movements, and touch, and of objects and events that can typically be seen and heard. As a consequence, we know little from these studies about how perception and cognition actually develop in the context of the multimodal environment (Lickliter & Bahrick, 2001). Because of this nearly exclusive historical focus on the development of capabilities in single sense modalities, and because of the growing appreciation of the "unity of the senses" even in young infants, the area of intersensory perception emerged and has grown

into an important area of research in its own right. However, the field of psychology continues to reflect this dichotomy, with "intersensory" research delineated as a separate area, as if it were a content area unto itself. Thus, research on intersensory perception has been for the most part segregated from research on the same questions explored in unimodal stimulation. Research on the development of a particular competence (be it speech or face perception, memory, or categorization, etc.) is likely to be conducted in separate studies of unimodal vs. multimodal perception, and undertaken by separate investigators. Consequently, the research findings from the two areas are not easily integrated and studies of unimodal and multimodal perception are difficult to compare, typically employing methods and measures that differ. Further, few studies actually compare responsiveness in one sense modality to responsiveness in two or more sense modalities, and thus it is not known how detection of properties of events generalize from unimodal to multimodal contexts or from multimodal to unimodal contexts. Moreover, it is not known whether the principles of perceptual learning derived from the study of multimodal events (such as those described above) are generalizable to unimodal contexts and, conversely, whether theories and findings derived from unimodal exposure to events generalize to the typical multimodal environment. Research findings from "multimodal" and "unimodal" studies of the development of attention, perception, cognition, and social competencies are badly in need of integration.

Insights from Psychobiology and Neuroscience

Research from the area of developmental psychobiology on animal infants provides some insight into this important issue. In comparative studies of perceptual development, conditions of multimodal and unimodal stimulation have typically been included in single designs and compared. Research from this area suggests that unimodal and multimodal stimulation are functionally different for the developing system, and information presented to the different senses interacts in complex ways. For example, at the neural level of analysis, it has been found that visual orienting in cats is dramatically affected by a co-located auditory stimulus (Meredith & Stein, 1986; Stein, Meredith, & Wallace, 1994). Stein and Meredith (1993) proposed a "multiplicative" effect where the magnitude of neural responsiveness from bimodal (audiovisual) stimulation exceeds the magnitude predicted by adding together the responsiveness from each modality alone. At the neural level, unimodal and multimodal stimulation (for a given stimulus location) are responded to differently.

Research at the behavioral level also points out that significantly different consequences result from multimodal vs. unimodal stimulation in the period just following hatching. For example, the pioneering work of Gottlieb and his colleagues on species identification in birds (Gottlieb, 1971a; Johnston & Gottlieb, 1981; Lickliter, Dyer, & McBride, 1993; Lickliter & Gottlieb, 1988) has demonstrated that multimodal experience from conspecifics (i.e., auditory, visual, and tactile) in the period just following hatching is a key component in the development and maintenance of normal perceptual and social preferences underlying species identification. Research with precocial bird embryos and hatchlings has also demonstrated that uncoupling multimodal experience can lead to changes in the young organism's normal developmental pattern (Columbus, Sleigh, Lickliter, & Lewkowicz, 1998; Sleigh, Columbus, & Lickliter, 1998). For example, quail chicks who received only unimodal auditory or visual stimulation just after hatching show abnormal perceptual responsiveness to auditory, visual, and multimodal maternal stimulation during the early postnatal period. Even visual responsiveness (as well as multimodal responsiveness) is delayed if chicks have unimodal visual stimulation just after hatching, demonstrating the complex interdependencies among the developing senses (Sleigh et al., 1998). Further, it has been established that in prenatal development the senses become functional in an invariant sequence across species. First the tactile, vestibular, then chemical senses emerge. Late in gestation, audition becomes functional, and not until after birth or hatching does vision become functional. Researchers (Gottlieb, 1971b; Turkewitz & Kenney, 1982) have proposed that the sequential onset of function of the various senses has important consequences for perceptual development. It allows earlier-developing systems to differentiate and mature without competition from other senses. Consequently, the development of audition occurs *in utero/ovo* without competition from visual input. Just after birth, typically vision becomes functional and this likely creates a sudden increase in the degree and nature of intersensory interactions. This principle underscores that important interdependencies exist among the senses, but it has received little attention from researchers of human infant development.

The neural and comparative findings point out important differences in both behavioral and neural outcomes resulting from unimodal vs. multimodal exposure to events. These differences should be taken as a caution against generalizing research findings from unimodal to multimodal contexts, and vice versa, in human infants without an empirical basis (Lickliter & Bahrick, 2001). They point out the need and importance for researchers of the development of perception and cognition in human infants to limit generalizations to the context (unimodal vs. multimodal) in which the investigation was conducted. Thus, research based on unimodal stimulation (e.g., such as that from speech or from faces) should be limited to generalizations regarding unimodal contexts (e.g., faces in the absence of speech; the speech stream devoid of faces). Conversely, research based on multimodal stimulation (e.g., coordinated faces and voices) should be generalized to multimodal contexts (multimodal faces and voices). Research will be ecologically valid to the extent that generalizations are appropriate to these important contextual differences. Second, the comparative findings point out the need for investigations of human perceptual and cognitive development to incorporate conditions of unimodal and multimodal stimulation into single designs and to examine the nature of resulting interactions.

To this end, and as a first step toward integrating research from the areas of "unimodal" vs. "multimodal" paradigms, we (Bahrick & Lickliter, 2000, 2002) have developed a framework for investigating the development of perception in unimodal and multimodal contexts. This framework is called the "intersensory redundancy hypothesis" and explains how perceptual development unfolds as a consequence of unimodal and multimodal exploration of events. It is a systems perspective in that it takes into account the organism and the nature of its exploratory activity in relation to the environment and the nature of the sensory stimulation it provides for exploration. In the remainder of this chapter, I describe the intersensory redundancy hypothesis, data generated from studies with young infants, and consequences for theories of attention, perception, and cognition of this way of thinking about development.

The Intersensory Redundancy Hypothesis: Integration of Unimodal and Multimodal Research Paradigms

The "intersensory redundancy hypothesis" (Bahrick & Lickliter, 2000, 2002) holds that in early development, information presented redundantly and in temporal synchrony to two or more sense modalities recruits infant attention and facilitates perceptual differentiation of that information more effectively than does the same information presented to one sense modality at a time. Intersensory redundancy refers to the spatially coordinated and concurrent presentation of the same information (e.g., tempo, rhythm, intensity change, temporal microstructure, etc.) across two or more sense modalities. Only amodal properties of events can be presented redundantly since, by definition, amodal information is information that can be conveyed by more than one type of sensory stimulation. Thus, consistent with Gibson's (1969) invariant detection view, the hypothesis emphasizes that the concurrent pick-up of the same information in two sense modalities is highly salient to young organisms and directs exploration. This causes amodal, redundant stimulus properties to become "foreground" and other properties to become "background," and promotes earlier processing of redundant stimulation than other types of stimulation. Since intersensory redundancy is typically available, this causes perception, learning, and memory for amodal properties to develop prior to other properties. This amodal processing precedence, in turn, has long-range effects on perception, cognition, social, and emotional development.

However, at times, intersensory redundancy is not available, either because the organism is not actively exploring a particular event with multiple senses, or because the environment is not providing redundant stimulation for a particular event at that point in time. In this case, amodal information (e.g., rhythm or rate) from a given event may be available to only a single sense modality (e.g., the sounds of hands clapping an irregular rhythm, or the sight of a light flashing at a rapid rate). The amodal property would then not be redundantly specified, and therefore it would not be expected to be salient. Further, according to the hypothesis, when redundancy is not available, and consequently unimodal stimulation from the event is provided, infant attention is likely to be recruited toward modality-specific properties of the event (color, pattern, orientation, pitch, timber, etc.), at the expense of other properties. This unimodal exploration enhances perceptual differentiation of modality-specific information (as compared with the same information presented in the context of redundancy).

Thus, the nature of the exploration (unimodal vs. bimodal) afforded to the organism interacts with the type of property explored (amodal vs. modality-specific) to determine the attentional salience of various properties. Figure 4.2 depicts this relationship. As can be seen from the figure, there is an advantage given to

Stimulation available for exploration	Stimulus property: Amodal	Stimulus property: Modality-specific
Multimodal (auditory-visual)	+	–
Unimodal (auditory or visual)		+

Figure 4.2 Predictions of the intersensory redundancy hypothesis. Facilitation vs. attenuation of attention and perceptual processing for amodal vs. modality-specific properties of stimulation as a function of the type of stimulation (multimodal vs. unimodal) available for exploration (from Bahrick & Lickliter, 2002). Reprinted with permission of Elsevier.

bimodal exploration of amodal properties and to unimodal exploration of modality-specific properties, whereas processing will be disadvantaged for bimodal exploration of modality-specific properties (e.g., listening to the pitch and timber of a voice while also seeing the speaking face), and for unimodal exploration of amodal properties (e.g., seeing a rhythm displayed visually without sound, or hearing a rhythm in sound without visual accompaniment).

Perceptual development is thus characterized by an intercoordination between exploration of amodal and modality-specific properties of events, and because of the prevalence of redundancy, detection of amodal information leads and constrains learning about modality-specific properties of stimulation. It should be noted that the terms "amodal" and "modality-specific" have a broad and context-sensitive meaning in the present framework in the sense that they are dependent on the modality context of stimulation. Thus, in the present framework where the modalities used for exploration are auditory and visual, "modality-specific" refers to properties that are available in visual but not auditory stimulation, and in auditory but not visual stimulation, and "amodal" refers to properties that can be redundantly specified by both auditory and visual stimulation. Some properties, therefore, are classified as modality-specific in the context of audiovisual stimulation, such as texture or direction and orientation of motion, even though they could also be conveyed tactually. In the context of visual-tactile exploration, they would be classified differently.

Intersensory redundancy impacts the organism first at the level of attention. The effects of redundancy on perception, learning, and memory appear to derive from differential attentional allocation to various properties of events as a function of multimodal vs. unimodal stimulation. When redundancy is present, it is highly salient and attention will be promoted to amodal properties of stimulation. It should also be noted, however, that attention can be impacted by a variety of other factors (e.g., the internal state of the organism, sudden movement or changes in intensity of stimulation, violation of expectancies, etc.), and the effects of intersensory redundancy would likely be attenuated or, alternatively, maximized by these factors. However, once attention is captured by intersensory redundancy, exploration of amodal properties of the event is promoted, and this in turn promotes attention to nested amodal properties of the event, and, eventually, to modality-specific properties. Thus, perceptual development proceeds in order of increasing specificity across development (Bahrick, 2001; Gibson, 1969).

Further, this sequence of increasing specificity and the amodal processing precedence observed across development likely has its roots in a similar processing sequence that occurs within a given episode of exploration at any given age. Within an episode of exploration, attention also likely proceeds in order of increasing specificity. If an event provides intersensory redundancy and captures attention, then, according to this hypothesis, attention will first be focused on global amodal relations, followed by nested amodal relations, and, eventually, on modality-specific properties. Once the infant has explored the redundant amodal relations uniting the multimodal stimulation from an event, this promotes continued processing of the unitary event and guides attention to nested, increasingly more specific levels of stimulation. If exploration is not terminated, it may eventually proceed to modality-specific aspects of stimulation. Thus, just as perceptual development proceeds from detection of global to specific aspects of stimulation, perceptual processing within a given episode of exploration may proceed from global to specific aspects of stimulation. A similar global processing precedence within an episode of exploration has been demonstrated for exploration of unimodal visual stimuli (see Freeseman, Colombo, & Coldren, 1993; Frick, Colombo, & Allen, 2000). However, if exploration is interrupted, the event changes or terminates, or the infant disengages, then the more specific levels of stimulation will remain unexplored and greater processing time will have been devoted to more global levels of stimulation. Consequently, in early phases

of development, when attention is more limited and it takes longer to process information, it is the global, amodal relations that will receive maximum attention. This is hypothesized to lead to the developmental pattern of increasing specificity observed in our studies (e.g., Bahrick, 2001). This global processing advantage is adaptive in very young organisms and promotes veridical perceptual development. However, these are important empirical questions and should be tested across a variety of domains. If the global to specific sequence reflects a general pattern of multimodal processing, according to the intersensory redundancy hypothesis, the advantage of intersensory redundancy should be most evident and pronounced during early phases of exploration or processing a particular event. Research is currently underway to test this prediction.

It should also be emphasized that the facilitating effects of intersensory redundancy on differentiation of amodal properties will be most apparent when infants or organisms are first learning a skill and when detection of the information is difficult. Once the skill is mastered or the perceptual discrimination is easier, the information in question (e.g., a rhythmic sequence) can be detected rapidly and can likely be discriminated in both unimodal and bimodal stimulation. At this point, results generated from unimodal and bimodal conditions would be indistinguishable due to this ceiling effect. Thus, the effects of intersensory redundancy should be most apparent when the organism is first learning to differentiate information. That the effects of redundancy appear to be most pronounced in early development has important implications for attention, perception, learning, and memory. Since these capabilities emerge primarily in a multimodal context, and initial conditions can have important influences on the trajectory and organization of development, the effects of intersensory redundancy are likely to have lasting effects on the nature and course of later development across a variety of areas. Because sensitivity to intersensory redundancy occurs so early in development and so pervasively, it can create a cascading effect across development such that its consequences manifest in an ever-widening trajectory across a variety of domains during the course of ontogeny (see Michel & Moore, 1995, and Moore, 1990, for examples of such cascading effects). The intersensory redundancy hypothesis can thus potentially serve as a model to guide appropriate interventions for developmental delays in a variety of areas as a function of the type of property in question (amodal vs. modality-specific) and the likely basis of the developmental delay.

Empirical Support for the Intersensory Redundancy Hypothesis

The intersensory redundancy hypothesis has received recent empirical support from a variety of studies. The attentional salience of intersensory redundancy and ability of redundancy to direct the flow of attention are illustrated in an early study of selective attention in infancy (Bahrick et al., 1981). Infants were shown two films of naturalistic events (hands clapping, a toy slinky being manipulated, or a xylophone being played). The films were shown superimposed upon one another and accompanied by the natural soundtrack to one of them. When adults viewed the superimposed events silently, they appeared to be like two ghostly images passing through one another (see figure 4.3). However, when the soundtrack was turned on, the sound-specified film seemed to jump out from the background of the silent event, creating a strong impression of figure and ground. When the other soundtrack was played, the second event immediately became figure and the other, background. Attention seemed compelled by the sound. The addition of sound created intersensory redundancy for properties such as the rhythm, tempo, intensity shifts, and synchrony of the visible and audible events. In the experiment, we explored

Figure 4.3 Photograph of two superimposed images (from Bahrick et al., 1981). Reprinted with permission of Elsevier.

whether infant attention was similarly directed by the soundtrack and the redundancy it created. Infants viewed the superimposed events along with a soundtrack, and then received test trials where the films were separated and played silently side by side. Infants demonstrated that they had attended to the sound-specified event and ignored the silent one by showing a visual preference for the novel, previously "unseen" event during test trials. A second study confirmed this interpretation. When infants were shown only one centrally projected film along with its soundtrack, and then received silent, side-by-side test trials as before, they again showed a novelty preference of the same magnitude (figure 4.4

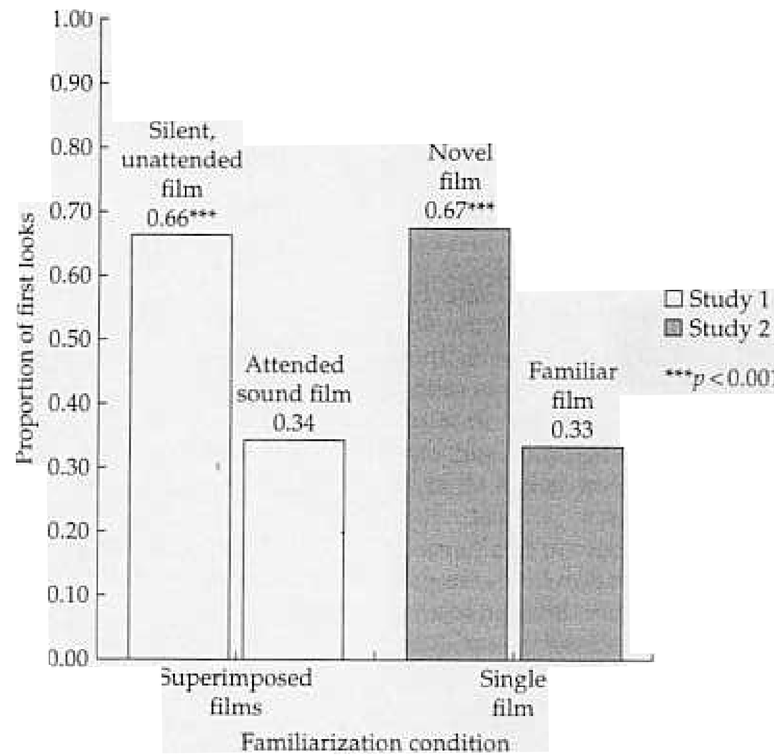

Figure 4.4 Proportion of first looks during the test trials when the films were presented separately and side by side as a function of the infant's familiarization condition. In one condition, familiarization was conducted to two superimposed films along with a soundtrack that belonged with one of them, and in the other condition, familiarization was conducted to a single film along with its soundtrack. Results indicate novelty preferences for the silent, unattended, superimposed film and for the novel, unseen film (from Bahrick et al., 1981).

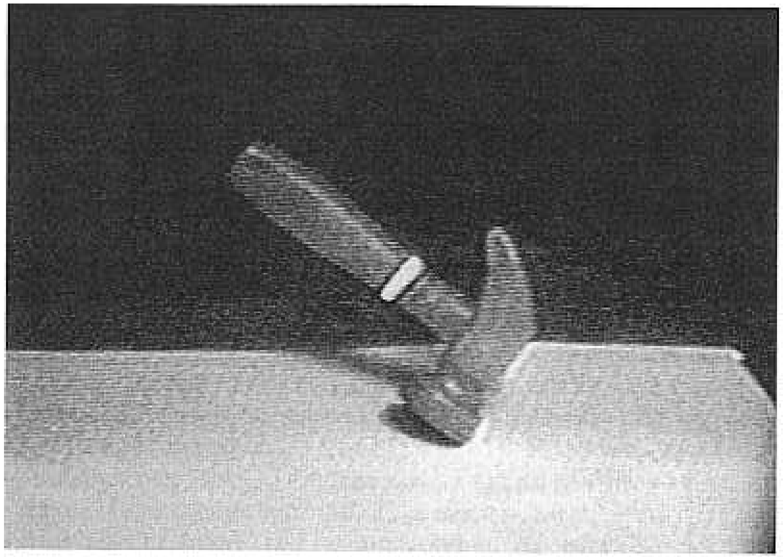

Figure 4.5 Photograph of the red hammer used to display the rhythmic sequences (from Bahrick & Lickliter, 2000).

depicts the results of these two studies). Infants appeared to respond to the events in the way adults did, by attending to the sound-specified film, even though another event was visually superimposed upon it. Intersensory redundancy across vision and audition can direct the flow of attention, allowing redundancy to become foreground and other visual stimulation to become background, even when all visual stimulation occupies the same spatial location.

Several recent studies have demonstrated the effectiveness of intersensory redundancy for promoting attention and facilitating perceptual differentiation of amodal properties of events. Bahrick and Lickliter (2000) assessed the ability of 5-month-old infants to discriminate complex, amodal, rhythmic patterns in bimodal, redundant stimulation as compared with unimodal stimulation. Infants were habituated to videos of a red plastic hammer (depicted in figure 4.5) tapping out a distinctive rhythm under conditions of bimodal, redundant stimulation (they could see and hear the hammer), unimodal visual stimulation (they could only see the hammer moving), or unimodal auditory stimulation (they could only hear the soundtrack to the hammer). Infants then received test trials depicting a new rhythm. Results are depicted in figure 4.6. They indicated that infants who received the bimodal,

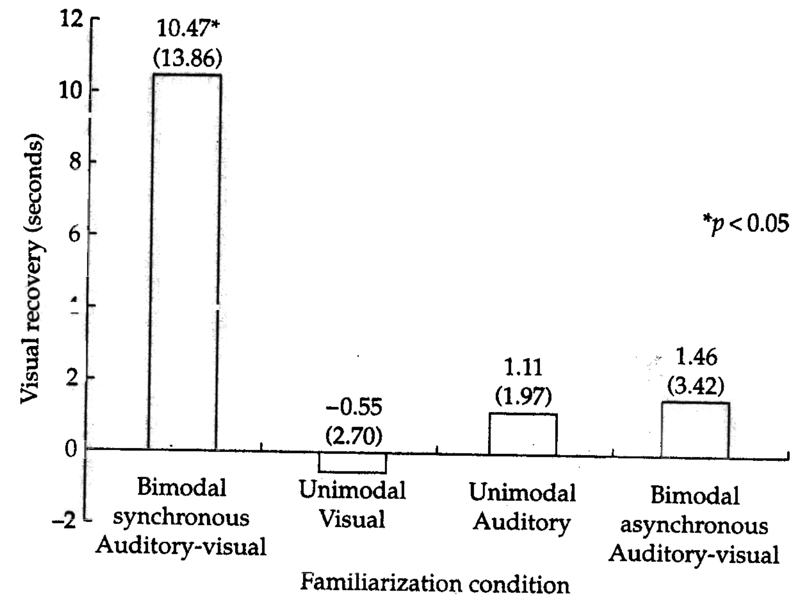

Figure 4.6 Infants' visual recovery to a change in rhythm following bimodal synchronous audiovisual habituation, asynchronous audiovisual habituation, unimodal visual, and unimodal auditory habituation (from Bahrick & Lickliter, 2000).

redundant stimulation showed robust, significant visual recovery to the change in rhythm, whereas those who received unimodal visual and those who received unimodal auditory stimulation showed no recovery to the change in rhythm. These findings demonstrated that only infants who received redundant, bimodal stimulation from a rhythm were able to perceive the rhythm and discriminate it from a similar one, whereas those who received unimodal stimulation were not. A further study assessed rhythm discrimination for bimodal, nonredundant stimulation (asynchronous films and soundtracks of the hammers tapping) and found no evidence of rhythm discrimination (see figure 4.6). Infants required redundancy in the form of temporal synchrony between the visual and acoustic stimulation for discrimination of rhythm.

A second study replicated and extended the findings of Bahrick and Lickliter (2000) documenting the facilitating effects of intersensory redundancy for the detection of amodal information, by testing detection of a different amodal property with infants of a younger age. Bahrick, Flom, and Lickliter (2002) assessed

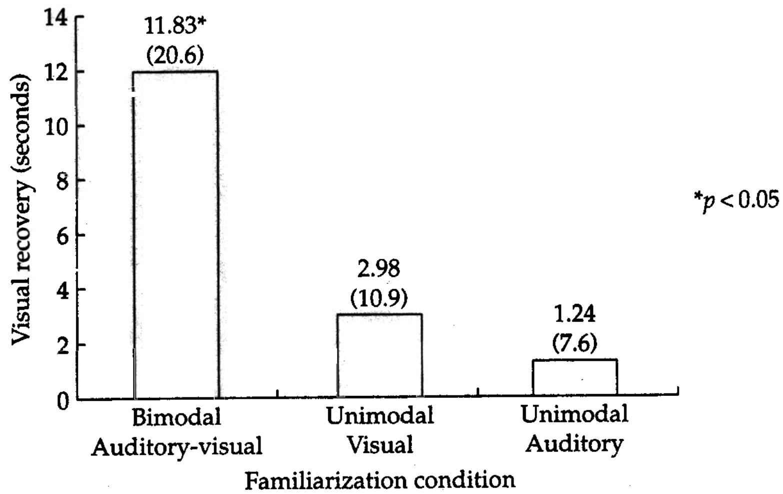

Figure 4.7 Infants' visual recovery to a change in tempo following bimodal audiovisual habituation, unimodal visual, or unimodal auditory habituation (from Bahrick, Flom, & Lickliter, 2002).

discrimination of tempo in 3-month-old infants, in a similar paradigm. Infants were habituated to films of the red hammer tapping out a rhythmic sequence in one of two tempos (55 bpm vs. 120 bpm). The same tempo could be detected visually by watching the hammer, or acoustically by listening to its impact sounds. Infants received bimodal, redundant, audiovisual stimulation, unimodal visual stimulation, or unimodal auditory stimulation during habituation. Then they received test trials depicting a novel tempo. Results are depicted in figure 4.7, and are remarkably similar to those of the prior study assessing rhythm discrimination with older infants. They demonstrated discrimination of the tempos following bimodal, audiovisual stimulation, but not following unimodal visual or unimodal auditory stimulation. These findings converge with those of rhythm discrimination and demonstrate the facilitating effects of intersensory redundancy for guiding attentional selectivity and fostering perceptual differentiation in early infancy. It should be noted that the stimulus events in these studies were chosen to be difficult for infants of the ages tested. The five-element rhythms differed only in relative timing (the arrangement of elements) and were chosen to be difficult for 5-month-olds. Tests of tempo were considered easier than rhythm and thus 3-month-olds were tested since these tests were likely to challenge infants of this age. Together, these

studies suggest that when infants first learn to differentiate specific amodal properties, differentiation is facilitated by intersensory redundancy. However, it was not known to what extent the facilitating effects of intersensory redundancy would persist across development. According to the intersensory redundancy hypothesis, the advantage of intersensory redundancy should be most pronounced when infants are first learning a skill, and attenuated later in development. That is, once infants become proficient at detecting a particular property, perception of that property should become increasingly flexible and should no longer require redundancy. An amodal property may then be detected in unimodal stimulation.

Bahrick, Lickliter, and Flom (2002) tested this hypothesis. We assessed the ability of 8-month-old infants to discriminate complex rhythms in a task just like that experienced by the 5-month-olds in our prior study. Infants received videos of the hammer tapping out one of the two rhythms, as before. Infants were habituated to the rhythmic sequences in the context of bimodal, redundant audiovisual stimulation or unimodal, visual stimulation. Test trials depicted a novel rhythm. Results indicated that infants in both the redundant audiovisual and the unimodal visual condition showed significant visual recovery to the change in rhythm. These findings contrast with those of the 5-month-olds and demonstrate that by 8 months, infants no longer required intersensory redundancy for discriminating complex rhythmic sequences. Together, they support the intersensory redundancy hypothesis and our developmental prediction, that perception of amodal properties emerges in the context of redundancy and is later extended to nonredundant, unimodal contexts. Further research is underway to determine whether, once infants detect amodal relations in unimodal stimulation, there still exists a facilitating effect of redundancy. It is expected that if the task is made more difficult, or the processing time shortened, the advantage of redundancy would become apparent. In any event, the facilitating effects of redundancy are apparently most pronounced when infants are younger and first learning a particular skill. This initial salience of redundancy has important implications for the development of perception and cognition. It creates a developmental precedence for detection of properties that are amodal and redundantly specified and this guides early attention, perception, and learning.

Additional research has also focused on the perception of modality-specific properties of events perceived in unimodal vs. bimodal, redundant stimulation (the right-hand quadrants of figure 4.2). According to the intersensory redundancy hypothesis, information experienced in one sense modality selectively recruits attention to modality-specific properties of events and facilitates perceptual differentiation of those properties at the expense of other properties. To evaluate this hypothesis, we again tested 5-month-old infants, this time assessing detection of orientation, a property available visually but not acoustically. We expected that infants would discriminate changes in orientation during unimodal visual, but not bimodal audiovisual, stimulation. Infants were again habituated to films of the hammer tapping out a rhythm; however, this time the movements of the hammer were depicted in one of two orientations (upward vs. downward). Either the hammer hit downward against a wooden floor, or it hit upward against a wooden ceiling. Infants received habituation to videos of the hammers in one of the two orientations in the bimodal, audiovisual condition (where they could see and hear the hammer moving) or the unimodal, visual condition (where they could only see the hammer moving). Then infants received test trials, under their respective conditions, where the orientation of the hammer was changed. Results indicated significant visual recovery to the change in orientation following unimodal visual habituation, but not following bimodal audiovisual habituation. Thus, consistent with predictions of the intersensory redundancy hypothesis, 5-month-olds discriminated changes in orientation, a visual property, following unimodal visual exposure, but not following redundant, bimodal exposure. Apparently, the addition of the soundtrack created intersensory redundancy and selectively recruited attention away from unimodally conveyed properties and toward redundantly specified properties of stimulation (as in Bahrick & Lickliter, 2000, and Bahrick, Flom, & Lickliter, 2002). In contrast, the unimodal, visual stimulation promoted attention to visual properties of the event without competition from salient redundant properties. Thus, attention to modality-specific or nonredundantly specified properties is likely best fostered in the context of unimodal exploration when competition from concurrent redundantly specified properties is minimized.

This observation is consistent with insights gained from comparative studies regarding the sequential onset of the functioning of the senses (Gottlieb, 1971b; Turkewitz & Kenney, 1982). In prenatal development, earlier-developing senses are able to differentiate without competition from later-developing senses. Thus, auditory perception develops during the last trimester of gestation without competition from visual stimulation. Similarly, competition appears to play an important role in regulating attentional allocation to different properties of events during postnatal development. Our research suggests that after birth, unimodal exploration (of a face or voice, for example) is promoted when there is little competition from concurrent, amodal, redundant stimulation. This unimodal exploration likely fosters differentiation of auditory or visual information in a manner that is not supported when redundant stimulation is available. Thus, differentiation of the appearance of a face would be best promoted when the face is silent and relatively still, whereas when the individual is speaking and moving, competition from audiovisual redundancy would be more likely to focus attention on amodal properties such as prosody, rhythm, tempo, and intensity variations common to the speech and facial movement.

The attentional salience of intersensory redundancy and its facilitation of perceptual learning have also been observed recently in comparative studies of animal infants. Lickliter et al. (2002) found that intersensory redundancy facilitates prenatal auditory learning in bobwhite quail chicks. Bobwhite quail embryos were exposed to an individual maternal call for 6, 12, or 24 hours, under conditions of unimodal auditory stimulation, concurrent but asynchronous auditory and visual stimulation, or redundant and synchronous auditory and visual stimulation. They were then tested one day after hatching to determine if they preferred the familiar maternal call over an unfamiliar version of the maternal call. Results are depicted in figure 4.8. They indicated that chicks who received the redundant audiovisual exposure significantly preferred the familiar maternal call following all exposure durations, whereas those who received the nonredundant audiovisual exposure showed no preference for the familiar call after any exposure duration. Chicks who received the unimodal auditory familiarization showed eventual learning and preferred the familiar call following the longest period (24 hours) of prenatal exposure. These results demonstrate that bobwhite quail chicks show greatly enhanced learning of the maternal call when amodal information (tempo, rhythm, duration) is presented redundantly, across two sense modalities. These findings extend the facilitating effects of intersensory redundancy to the prenatal period and to a different species.

This converging evidence across species, developmental periods, and properties of events highlights the fundamental importance of intersensory redundancy for promoting attention and fostering perceptual differentiation of amodal properties of events. Further, it explains how, in a predominantly multimodal

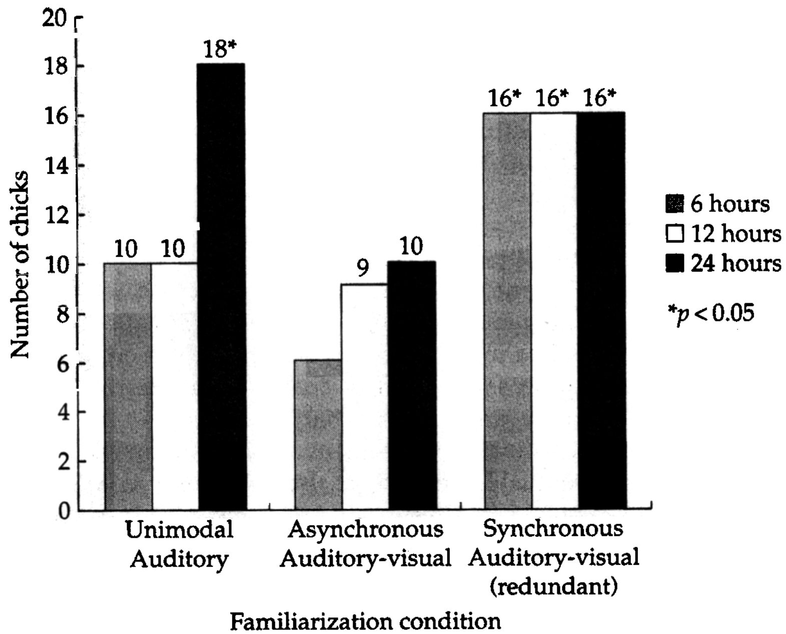

Figure 4.8 Number of chicks showing a preference for the maternal call with which they were familiarized during prenatal development under conditions of unimodal auditory stimulation, concurrent but asynchronous audiovisual stimulation, or redundant and synchronous audiovisual stimulation. Note: in each group 26 chicks were tested and their data were classified into one of three categories, a preference for the familiar call (shown here), a preference for the novel call, or a preference for neither/both calls (from Lickliter et al., 2002).

environment, perceptual learning is guided and constrained by detection of amodal relations. These findings also converge to demonstrate that there are conditions under which attention to amodal properties is not facilitated, and attention to modality-specific properties and nonredundant aspects of stimulation is favored. That is, when a given event provides stimulation to only a single sense modality, attention and learning about unimodally specified properties of events are enhanced. Modality-specific properties are best differentiated when competition from intersensory redundancy is not present. This important interaction between attention to amodal vs. modality-specific properties in unimodal vs. multimodal stimulation underlies the concurrent and interrelated course of development of intersensory and unimodal perceptual capabilities across the period of infancy.

Conclusion

In this chapter, I have described a number of basic principles underlying the development of attention, perception, and cognition as it emerges in a multimodal environment. The intersensory redundancy hypothesis provides a working framework for viewing the allocation of attention and its effects on the development of perception and learning in an environment that provides both redundancy across the senses and modality-specific information about objects and events in an interdependent system. The intersensory redundancy hypothesis highlights an important and previously unexplored interaction (depicted in figure 4.2) between the stimulation provided by an event for infant exploration (unimodal vs. multimodal) and the selective processing of different properties of stimulation (amodal vs. modality-specific). Under conditions of multimodal stimulation where redundancy is routinely available, attention is likely to be initially and primarily focused on amodal properties of stimulation. Since multimodal stimulation is typical, this creates a processing priority for amodal stimulation and promotes earlier perceptual differentiation, learning, and memory for properties of events that are amodal (e.g., synchrony, intensity, rhythm, tempo, temporal microstructure). In contrast, when an event provides stimulation to only a single sense modality, the infant's attention to modality-specific and nonredundant properties of stimulation is likely to be promoted. This fosters attention to and differentiation of properties such as color, pattern, timber, pitch, and orientation, without competition from the more salient redundantly specified properties. Together, these principles portray a developmental trajectory where differentiation of amodal and modality-specific properties emerges in a coordinated and interdependent manner, with detection of amodal properties leading and constraining learning about more specific properties of events. These principles have now received support from a number of recent studies (e.g., Bahrick, 1992, 1994, 2001; Gogate & Bahrick, 1998; Hernandez Reif & Bahrick, 2001).

The perceptual precedence of amodal stimulation and the intercoordinated exploration of amodal and modality-specific properties of events are adaptive for perceptual development in several respects. First, the prevalence and salience of intersensory redundancy fosters attention to unitary multimodal events. This facilitates further processing of visual, acoustic, and tactile stimulation that belong together. Perceptual differentiation can thus proceed in order of increasing specificity, with attention to global, amodal relations, followed by nested amodal relations, and finally modality-specific, arbitrary relations, as demonstrated in recent research (Bahrick, 1992, 1994, 2001). Second, the salience of redundancy and detection of amodal relations serves as a buffer against premature learning of specific details that vary from one context or event to another. Relations between modality-specific properties across the senses are often arbitrary and not generalizable across contexts or events. For example, the color or shape of an object does not consistently go with the pitch or timber of its sound. The salience of redundancy focuses attention on amodal intersensory relations that are global and invariant across events and contexts. For example, single objects produce single impact sounds; faces go with voices; happy faces go with happy voices. Thus, learning about specific details is likely to be delayed until the organism has a multimodal framework from which to make sense of the details, and therefore, generalizations based on specific details are likely to be appropriately constrained.

Thus, the advantage of intersensory redundancy should be most apparent in early development when new skills and knowledge first emerge. Clearly, though, infants eventually become skilled at detecting amodal and modality-specific properties in both unimodal and multimodal stimulation and thus, later in development, the facilitating effects of redundancy would be less apparent. However, even in later development when individuals first learn a new skill or when a task is difficult, redundancy may also benefit learning. For example, adults learning to speak a new language or disambiguate speech sounds in a noisy environment may benefit from detection of amodal, audiovisual information (Massaro, 1998).

These findings regarding the salience of intersensory redundancy and its importance for learning about global aspects of events are consistent with the recent body of research from comparative studies (e.g., Lickliter et al., 2002; Sleigh et al., 1998) and from neural studies demonstrating the existence of multisensory neurons and the heightened neural responsiveness to redundant, multimodal stimulation (e.g., Stein & Meredith, 1993). Thus, converging evidence across species and across levels of analysis points to the attentional salience of intersensory redundancy and its importance for perceptual learning.

In response to the question posed in the introduction concerning which factors initially organize attention and perception such that its developmental trajectory provides the foundation for the knowledge base and competencies of the adult perceiver, several answers have been put forth in this chapter. In brief, detection of amodal relations in the context of redundancy provides an economical and effective avenue for initiating and organizing perceptual development along a trajectory that can effectively lead to the knowledge of adult perceivers. It guides and constrains detection of more specific information so that unitary events are explored in a coordinated manner and specific details are perceived in the context of more general principles that organize those details. This amodal processing precedence in turn has an effect on the development of perceptual, conceptual, social, and linguistic competence.

The intersensory redundancy hypothesis and the empirical findings that support it also provide a basis and a framework for integrating the bodies of research generated from studies of unimodal perception with those of multimodal perception. Typically, research in these areas has been conducted by different investigators with different methods and has enjoyed little cross-fertilization. The present framework suggests several important generalizations and avenues for cross-fertilization. In an environment that provides both redundancy across the senses and modality-specific information about properties of objects and events, the intersensory redundancy hypothesis provides a framework for understanding how unimodal and multimodal exploration of our environment interacts with and differentially affects perceptual learning. Multimodal exploration promotes attention and learning of amodal properties, whereas unimodal exploration promotes attention and learning of modality-specific aspects of stimulation. Given the prevalence of multimodal stimulation, detection of amodal information typically leads and constrains learning about modality-specific stimulation. Thus, detection of amodal and modality-specific properties of events progresses as part of an interrelated system that is dependent on the nature of the organism's exploration and the nature of stimulation provided by the event.

This insight calls for more research that includes both unimodal and multimodal conditions in single designs. It points out the need for sensitivity to variables such as the nature of infant exploration (unimodal or multimodal) and the type of stimulus properties explored (amodal vs. modality-specific). This insight also underscores the importance of limiting generalizations of research findings to contexts and factors that closely resemble those of the research setting. Thus, research on unimodal stimulation (such as that from speech or faces) should be limited to generalizations regarding unimodal stimulation (faces in the absence of speech, and speech in the absence of moving faces). Similarly, research on the perception of multimodal stimulation (e.g., coordinated face–voice stimulation) should be generalized to conditions of multimodal stimulation (coordinated faces and voices). Attention to the importance of modality and context in research settings, and limiting generalizations appropriately, will foster a more meaningful integration of the bodies of research generated from unimodal vs. multimodal perception (Lickliter & Bahrick, 2001).

REFERENCES

Allen, T. W., Walker, K., Symonds, L., & Marcell, M. (1977). Intrasensory and intersensory perception of temporal sequences during infancy. *Developmental Psychology*, 13, 225–9.

Bahrick, L. E. (1983). Infants' perception of substance and temporal synchrony in multimodal events. *Infant Behavior and Development*, 6, 429–51.

Bahrick, L. E. (1987). Infants' intermodal perception of two levels of temporal structure in natural events. *Infant Behavior and Development*, 10, 387–416.

Bahrick, L. E. (1988). Intermodal learning in infancy: Learning on the basis of two kinds of invariant relations in audible and visible events. *Child Development*, 59, 197–209.

Bahrick, L. E. (1992). Infants' perceptual differentiation of amodal and modality-specific audio-visual relations. *Journal of Experimental Child Psychology*, 53, 180–99.

Bahrick, L. E. (1994). The development of infants' sensitivity to arbitrary intermodal relations. *Ecological Psychology*, 6, 111–23.

Bahrick, L. E. (1995). Intermodal origins of self-perception. In P. Rochat (Ed.), *The self in early infancy: Theory and research* (pp. 349–73). Amsterdam: North Holland-Elsevier.

Bahrick, L. E. (2000, July). The role of attentional salience in infants' detection of arbitrary intermodal relations. Paper presented at the International Conference on Infant Studies, Brighton, UK.

Bahrick, L. E. (2001). Increasing specificity in perceptual development: Infants' detection of nested levels of multimodal stimulation. *Journal of Experimental Child Psychology*, 79, 253–70.

Bahrick, L. E., Flom, R., & Lickliter, R. (2002). Intersensory redundancy facilitates discrimination of tempo in 3-month-old infants. *Developmental Psychobiology*, 41, 352–63.

Bahrick, L. E., & Lickliter, R. (2000). Intersensory redundancy guides attentional selectivity and perceptual learning in infancy. *Developmental Psychology*, 36, 190–201.

Bahrick, L. E., & Lickliter, R. (2002). Intersensory redundancy guides early perceptual and cognitive development. In R. Kail & H. Reese (Eds.), *Advances in child development and behavior* (Vol. 30, pp. 153–87). New York: Academic Press.

Bahrick, L. E., Lickliter, R., & Flom, R. (2002, April). Intersensory redundancy is most effective when skills are first learned. Paper presented at the International Conference on Infant Studies, Toronto, Canada.

Bahrick, L. E., Netto, D., & Hernandez-Reif, M. (1998). Intermodal perception of adult and child faces and voices by infants. *Child Development*, 69, 1263–75.

Bahrick, L. E., Walker, A. S., & Neisser, U. (1981). Selective looking by infants. *Cognitive Psychology*, 13, 377–90.

Bahrick, L. E., & Watson, J. S. (1985). Detection of intermodal proprioceptive-visual contingency as a potential basis of self-perception in infancy. *Developmental Psychology*, 21, 963–73.

Butterworth, G. (1992). Origins of self-perception in infancy. *Psychological Inquiry*, 3 (2), 103–11.

Butterworth, G., & Hicks, L. (1977). Visual proprioception and postural stability in infancy: A developmental study. *Perception*, 6, 255–62.

Butterworth, G., & Hopkins, B. (1988). Hand–mouth coordination in the new-born baby. *British Journal of Developmental Psychology*, 6, 303–14.

Columbus, R. F., Sleigh, M. J., Lickliter, R., & Lewkowicz, D. J. (1998). Unimodal sensory experience interferes with responsiveness to the spatial contiguity of multimodal maternal cues in bobwhite quail chicks. *Infant Behavior and Development*, 21, 397–409.

Dodd, B. (1979). Lip reading in infants: Attention to speech presented in- and out-of-synchrony. *Cognitive Psychology*, 11, 478–84.

Freeseman, L. J., Colombo, J., & Coldren, J. T. (1993). Individual differences in infant visual attention: Four-month-olds' discrimination and generalization of global and local stimulus properties. *Child Development*, 64, 1191–1203.

Frick, J. E., Colombo, J., & Allen, J. R. (2000). Temporal sequence of global–local processing in 3-month-old infants. *Infancy*, 1, 375–86.

Gibson, E. J. (1969). *Principles of perceptual learning and development*. New York: Appleton-Century-Crofts.

Gogate, L. J., & Bahrick, L. E. (1998). Intersensory redundancy facilitates learning of arbitrary relations between vowel sounds and objects in seven-month-old infants. *Journal of Experimental Child Psychology*, 69, 1–17.

Gogate, L. J., Bahrick, L. E., & Watson, J. D. (2000). A study of multimodal motherese: The role of temporal synchrony between verbal labels and gestures. *Child Development*, 71, 878–94.

Gottlieb, G. (1971a). *Development of species identification in birds*. Chicago: University of Chicago Press.

Gottlieb, G. (1971b). Ontogenesis of sensory function in birds and mammals. In E. Tobach, L. Aronson, & E. Shaw (Eds.), *The biopsychology of development* (pp. 67–128). New York: Academic Press.

Hernandez-Reif, M., & Bahrick, L. E. (2001). The development of visual-tactile perception of objects: Amodal relations guide learning about arbitrary relations. *Infancy*, 2, 51–72.

Jaffee, J., Beebe, B., Feldstein, S., Crown, C. L., & Jasnow, M. D. (2001). Rhythms of dialogue. *Monographs of the Society for Research in Child Development*, 66 (2, Serial No. 265), 1-132.
Johnston, T., & Gottlieb, G. (1981). Development of visual species identification in ducklings: What is the role of imprinting? *Animal Behaviour*, 29, 1082–99.
Kuhl, P. K., & Meltzoff, A. N. (1982). The bimodal perception of speech in infancy. *Science*, 218, 1138–41.
Kuhl, P. K., & Meltzoff, A. N. (1984). The intermodal representation of speech in infants. *Infant Behavior and Development*, 7, 361–81.
Kuhn, D., & Siegler, R. S. (Eds.). (1998). *Handbook of child psychology. Vol. 2. Cognition, Perception, and Language*. New York: Wiley.
Lee, A. N., & Aronson, E. (1974). Visual proprioceptive control of standing in human infants. *Perception and Psychophysics*, 15, 529–32.
Lewkowicz, D. J. (1992). Responsiveness to auditory and visual components of a sounding/moving compound stimulus in human infants. *Perception and Psychophysics*, 52, 519–28.
Lewkowicz, D. J. (1996). Perception of auditory-visual temporal synchrony in human infants. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 1094–1106.
Lewkowicz, D. J. (2000). The development of intersensory temporal perception: An epigenetic systems/limitations view. *Psychological Bulletin*, 126, 281–308.
Lewkowicz, D. J., & Lickliter, R. (Eds.). (1994). *The development of intersensory perception: Comparative perspectives*. Hillsdale, NJ: Erlbaum.
Lickliter, R., & Bahrick, L. E. (2001). The salience of multimodal sensory stimulation in early development: Implications for the issue of ecological validity. *Infancy*, 2, 451–67.
Lickliter, R., Bahrick, L. E., & Honeycutt, H. (2002). Intersensory redundancy facilitates prenatal perceptual learning in bobwhite quail embryos. *Developmental Psychology*, 38, 15–23.
Lickliter, R., Dyer, A. B., & McBride, T. (1993). Perceptual consequences of early social experience in precocial birds. *Behavioral Processes*, 30, 185–200.
Lickliter, R., & Gottlieb, G. (1988). Social specificity: Interaction with own species is necessary to foster species-specific maternal preference in ducklings. *Developmental Psychobiology*, 21, 311–21.
Massaro, D. W. (1998). *Perceiving talking faces: From speech perception to a behavioral principle*. Cambridge, MA: Harvard University Press.
Meredith, M. A., & Stein, B. E. (1986). Spatial factors determine the activity of multisensory neurons in the cat superior colliculus. *Brain Research*, 365, 350–4.
Michel, G. R., & Moore, C. L. (1995). *Developmental psychobiology*. Cambridge MA: MIT Press.
Moore, C. L. (1990). Comparative development of vertebrate sexual behavior: Levels, cascades, and webs. In D. A. Dewsbury (Ed.), *Contemporary issues in comparative psychology* (pp. 278–99). Sunderland, MA: Sinauer.

Rochat, P. (1993). Hand–mouth coordination in the newborn: Morphology, determinants, and early development of a basic act. In G. Savelsbergh (Ed.), *The development of coordination in infancy* (pp. 265–88). Amsterdam: Elsevier.
Rochat, P. (Ed.). (1995). *The self in infancy: Theory and research*. Amsterdam: Elsevier.
Rochat, P., & Morgan, R. (1995). The function and determinants of early self-exploration. In P. Rochat (Ed.), *The self in early infancy: Theory and research* (pp. 395–415). Amsterdam: North Holland-Elsevier.
Schmuckler, M. A. (1995). Self-knowledge of body position: Integration of perceptual and action system information. In P. Rochat (Ed.), *The self in early infancy: Theory and research* (pp. 221–41). Amsterdam: North Holland-Elsevier.
Slater, A., Quinn, P. C., Brown, E., & Hayes, R. (1999). Intermodal perception at birth: Intersensory redundancy guides newborn infants' learning of arbitrary auditory-visual pairings. *Developmental Science*, 2, 333–8.
Sleigh, M. J., Columbus, R. F., & Lickliter, R. (1998). Intersensory experience and early perceptual development: Postnatal experience with multimodal maternal cues affects intersensory responsiveness in bobwhite quail chicks. *Developmental Psychology*, 34, 215–23.
Soken, N., & Pick, A. (1992). Intermodal perception of happy and angry expressive behaviors by seven-month-old infants. *Child Development*, 63, 787–95.
Spelke, E. S. (1979). Perceiving bimodally specified events in infancy. *Developmental Psychology*, 15, 626–36.
Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses*. Cambridge, MA: MIT Press.
Stein, B. E., Meredith, M. A., & Wallace, M. (1994). Development and neural basis of multisensory integration. In D. J. Lewkowicz & R. Lickliter (Eds.), *The development of intersensory perception: Comparative perspectives* (pp. 81–105). Hillsdale, NJ: Erlbaum.
Trevarthen, C. (1993). The self born of intersubjectivity: The psychology of an infant communicating. In U. Neisser (Ed.), *The perceived self: Ecological and interpersonal sources of self-knowledge* (pp. 121–73). New York: Cambridge University Press.
Turkewitz, G., & Kenney, P. A. (1982). Limitations on input as a basis for neural organization and perceptual development: A preliminary theoretical statement. *Developmental Psychobiology*, 15, 357–68.
van der Meer, A. L. H., van der Weel, F. R., & Lee, D. N. (1995). The functional significance of arm movements in neonates. *Science*, 267, 693–5.
Walker, A. S. (1982). Intermodal perception of expressive behaviors by human infants. *Journal of Experimental Child Psychology*, 33, 514–35.
Walker-Andrews, A. (1997). Infants' perception of expressive behaviors: Differentiation of multimodal information. *Psychological Bulletin*, 121 (3), 437–56.

Walker-Andrews, A. S., Bahrick, L. E., Raglioni, S. S., & Diaz, I. (1991). Infants' bimodal perception of gender. *Ecological Psychology*, 3, 55–75.
Zukow-Goldring, P. (1997). A social ecological realist approach to the emergence of the lexicon: Educating attention to amodal invariants in gesture and speech. In C. Dent-Read & P. Zukow-Goldring (Eds.), *Evolving explanations of development: Ecological approaches to organism-environment systems* (pp. 199–252). Washington, DC: American Psychological Association.

5 Neuroscience Perspectives on Infant Development

Mark H. Johnson and Annette Karmiloff-Smith

Biology and Cognitive Development

Throughout the history of developmental psychology the field has been influenced by thinking and findings from the biological sciences, particularly developmental neuroscience and evolutionary theory. Why has developmental psychology been so closely related to these areas of biology? One reason is that underlying both disciplines is the fundamental question about how complex organic structures, such as the human brain and mind, can arise from apparently much simpler matter – such as a mere bunch of undifferentiated cells. Ideas regarding the mechanisms of evolution influenced leaders in developmental psychology from early on, the clearest example of which can be found in the writings of Piaget (Piaget, 1954, 1971). In addition to his own training as a biologist, Piaget was heavily inspired by the developmental biologist C. H. Waddington (Piaget, 1971). It was from observation of embryological growth that Waddington developed his concept of the "epigenetic landscape" (e.g., Waddington, 1975). Interestingly, some of Waddington's concepts have recently been resurrected by researchers interested in nonlinear dynamic

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