

Intersensory Redundancy Guides the Development of Selective Attention, Perception, and Cognition in Infancy

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ABSTRACT—*That the senses provide overlapping information for objects and events is no extravagance of nature. This overlap facilitates attention to critical aspects of sensory stimulation, those that are redundantly specified, and attenuates attention to nonredundantly specified stimulus properties. This selective attention is most pronounced in infancy and gives initial advantage to the perceptual processing of, learning of, and memory for stimulus properties that are redundant, or amodal (e.g., synchrony, rhythm, and intensity), at the expense of modality-specific properties (e.g., color, pitch, and timbre) that can be perceived through only one sense. We review evidence supporting this hypothesis and discuss its implications for theories of perceptual, cognitive, and social development.*

KEYWORDS—*intersensory perception; multimodal stimulation; intersensory redundancy*

The world provides a richly structured, continuous flux of multimodal stimulation to your senses. Objects and events can be simultaneously seen, heard, smelled, and felt as you interact with your environment. Scientists have long been intrigued and challenged by issues arising from the specificity of stimulation from the different senses and the overlap among them. How are objects and events experienced as unitary when they stimulate receptors that give rise to different forms of information? How are different modes of sensory stimulation bound together? How do infants determine which sights, sounds, tastes, and smells belong together and constitute unitary events, and which are unrelated? Adults can use prior knowledge about objects and events to guide selective attention to meaningful, unitary patterns of stimulation. Experienced perceivers know that faces go with voices, that the

sound of footsteps foretell the approach of a person, and that the breaking glass made the sharp crashing sound. How does the infant, who begins life with no prior knowledge to guide attention, make sense of this flow and focus on stimulation that is meaningful, coherent, and relevant? What guides and constrains perceptual development and provides the foundation for the knowledge of the adult perceiver?

One answer to these questions arises from the fact that the senses pick up overlapping, redundant information for objects and events in the environment. In a radical move from traditional perceptual theory, J.J. Gibson (1966) proposed that different forms of sensory stimulation are not a problem for the perception of unitary events but instead provide an important basis for it. He argued that the senses should be considered as a perceptual system whose components work together to pick up stimulation that is common across the senses.

In this view, the fact that the senses provide overlapping information for objects and events is therefore no extravagance of nature. Moreover, from our perspective, it is a cornerstone of perceptual development. One type of overlap involves *amodal* information, that is, information that is not specific to a single sense modality, but is completely redundant across more than one sense. The dimensions of time, space, and intensity are typically conveyed by multiple senses. For example, the rate and rhythm of hands clapping are conveyed visually and acoustically. The sights and sounds of a ball bouncing are synchronous, originate in the same location, and share a common rate, rhythm, and intensity pattern. Picking up this redundant, amodal information is fundamental to perceptual development. It allows naive perceivers to selectively attend to related aspects of stimulation that constitute unitary events and ignore concurrent stimulation from unrelated events nearby (Bahrick & Lickliter, 2002; E.J. Gibson & Pick, 2000).

For example, the face and voice of a person speaking share temporal synchrony, rhythm, tempo, and changing intensity. By selectively attending to these amodal properties, perceivers can attend to the unitary event, the person speaking, and ignore unrelated faces and

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objects nearby. This selectivity allows perception to get started on the right track in early development, providing a foundation for learning about meaningful, unitary objects and events.

Converging evidence from comparative and developmental psychology has shown that both animal and human infants are adept perceivers of amodal information (Lewkowicz & Lickliter, 1994; Lickliter & Bahrick, 2000). Infants detect temporal aspects of stimulation such as synchrony, rhythm, and tempo, as well as the spatial correspondence of objects and their sound sources. They also detect synchrony, affect, prosody, and changes in intensity of stimulation from faces and voices. Infants also participate in multimodal, temporally coordinated interactions with adults.

Despite the fact that perceptual, cognitive, social, and emotional development emerge within and rely upon this sensory overlap, most research in developmental psychology has focused on development of capabilities involving only a single sense modality (unimodal research). Such research demonstrates that infants are excellent perceivers of visual stimulation such as color, pattern, and faces and of acoustic stimulation such as the sounds of speech. Because of the historical focus on the specificity of the senses, there is currently a lack of integration between research on unimodal perception and emerging research on multimodal perception, and recent discoveries of important neural and behavioral interdependencies among the senses are not generally appreciated (Lickliter & Bahrick, 2000).

Consequently, no theories have yet addressed how and under what conditions people perceive amodal information versus modality-specific information (information that can be conveyed by only a particular sense) when events typically provide both types of information. For example, a bouncing soccer ball provides amodal synchrony, rhythm, and tempo across sights and sounds of impacts, as well as color and pattern that can be perceived only visually, and pitch and timbre that can be perceived only acoustically. How is detection of amodal information coordinated with detection of modality-specific information across development in a world that provides a constant flux of multimodal and unimodal stimulation from objects and events? How do people perceive faces in the context of speech, or voices in the context of moving faces? To date, research has not directly addressed the coordination of attention to different aspects of events in unimodal and multimodal stimulation.

THE INTERSENSORY REDUNDANCY HYPOTHESIS

We have proposed an intersensory redundancy hypothesis (IRH), which addresses the nature of this coordination across development and bridges the gap between theories of unimodal and multimodal functioning. The IRH explains how the detection of amodal information can guide selective attention and learning during early infancy and how this process is coordinated with perception of information specific to a single sense (Bahrick & Lickliter, 2000, 2002). Intersensory redundancy refers to the spatially coordinated and temporally synchronous presentation of the same information across two or more senses and is therefore possible only for amodal properties (e.g., tempo, rhythm, duration, intensity). Thus, the sights and sounds of hands clapping provide intersensory redundancy because they are temporally synchronous, originate in the same place, and convey the same rhythm, tempo, and intensity patterns in vision and audition.

According to the IRH, during early infancy intersensory redundancy promotes detection of amodal information in multimodal

events, and this causes amodal stimulus properties to become “foreground” and other properties to become “background.” Intersensory redundancy affects selective attention, promoting earlier processing of redundantly specified properties than of other stimulus properties in early development. Thus, the infant’s initial sensitivity to amodal information provides an economical way of guiding perceptual processing to focus on meaningful, unitary events.

Of course, not all exploration of objects and events makes multimodal stimulation available. Sometimes only unimodal stimulation is provided (e.g., when listening to the radio or touching a hidden toy), and in this case, no intersensory redundancy is available. This unimodal stimulation makes modality-specific properties stand out. Attention to properties that are specific to vision is facilitated when an object is seen but not heard, and attention to properties that are specific to audition is facilitated when an event is heard but not seen. This facilitation occurs partly because there is no competition from intersensory redundancy, which makes amodal properties salient. Unimodal stimulation can also provide amodal information (e.g., the rhythm of music or a rapidly flashing light), but when amodal information is not redundantly specified, it is not particularly salient. Thus, amodal properties are less salient in unimodal stimulation than when they are experienced redundantly across two senses.

PREDICTIONS OF THE IRH

Given that all events provide both amodal and modality-specific information, when and under what conditions do people perceive each type of information? According to the IRH, the nature of exploration (unimodal vs. multimodal) interacts with the type of property explored (amodal vs. modality-specific) to determine the attentional salience and processing priority given to various properties of sensory stimulation. As can be seen in Figure 1, multimodal (bimodal or trimodal) exploration of amodal properties and unimodal exploration of modality-

		Stimulus Property	
		Amodal	Modality-Specific
Stimulation Available for Exploration	Multimodal (auditory-visual)	+	-
	Unimodal (auditory or visual)	-	+

Fig. 1. Predictions of the intersensory redundancy hypothesis. The combination of stimulus properties (amodal vs. modality-specific) and the nature of exploration (multimodal vs. unimodal) determines whether attention and perceptual processing are facilitated (plus signs) or attenuated (minus signs). Reprinted from “Intersensory Redundancy Guides Early Perceptual and Cognitive Development,” by L.E. Bahrick and R. Lickliter, in R. Kail (Ed.), *Advances in Child Development and Behavior*, Vol. 30, p. 166, New York: Academic Press. Copyright 2002 by Academic Press. Reprinted with permission from Elsevier.

specific properties should receive processing priority. The IRH makes two specific predictions regarding which stimulus properties (amodal vs. modality-specific) are detected in multimodal versus unimodal stimulation. The first prediction is that processing and learning of amodal properties is facilitated in multimodal stimulation (in which intersensory redundancy is available) compared with unimodal stimulation (in which no redundancy is available; cf. the two left-hand quadrants in Fig. 1). In contrast, the second prediction is that processing and learning of modality-specific properties is facilitated when information is experienced unimodally, as compared with when stimulation is multimodal and redundant (cf. the two right-hand quadrants in Fig. 1). The IRH also makes a developmental prediction; as perceivers become more experienced, perceptual processing becomes increasingly flexible, such that both amodal and modality-specific properties are detected in unimodal and multimodal contexts. Thus, according to the IRH, the facilitation of attention we have described is most pronounced in early development (or when a task is difficult). These initial conditions can have far-reaching consequences for how perception is organized and develops.

RESEARCH SUPPORTING THE IRH

Research indicates that human infants attend to different properties of an event depending on whether redundant bimodal stimulation or only unimodal stimulation is available (Lewkowicz, 2000; Lickliter & Bahrick, 2000). In this research, infants are typically tested in what is called a habituation procedure. They are repeatedly presented with an event until they are habituated to it, that is, until their amount of looking at the event decreases to some criterion (e.g., 50% of their initial looking level). Once this criterion has been met, the event is changed in some way on test trials. If infants notice the change, their level of looking at the novel event should increase significantly above the habituated level.

Using this procedure, we found greater sensitivity to amodal properties when intersensory redundancy was available than when it was not, supporting the first prediction of the IRH. Three-month-old infants discriminated a change in the tempo of a toy hammer tapping during redundant bimodal (audiovisual) but not during unimodal (auditory or visual) stimulation (Bahrick, Flom, & Lickliter, 2002). Similarly, 5-month-old infants discriminated a change in a complex rhythm in bimodal but not unimodal presentations (Bahrick & Lickliter, 2000). We also obtained results consistent with the developmental prediction of the IRH: Perception became more flexible with additional experience, and older infants discriminated the amodal properties of rhythm and tempo in both bimodal and unimodal stimulation (Bahrick & Lickliter, 2003).

Findings from studies of nonhuman animals converge with results obtained with human infants (Lickliter & Bahrick, 2000). Research with animals has shown enhanced neurophysiological and behavioral responsiveness to coordinated bimodal stimulation as compared with unimodal stimulation. Animal studies also indicate that the attenuation or uncoupling of multimodal experience can modify perceptual organization during early development. For example, results from studies of birds and mammals indicate that temporally or spatially separating auditory and visual stimulation alters infants' sensitivity to both unimodal and multimodal information. Further, animal-based research has demonstrated a dramatic facilitation of perceptual

learning and memory following exposure to redundant, bimodally specified information, even during the prenatal period. Quail embryos learned an individual maternal call four times faster and remembered the call four times longer when intersensory redundancy was provided by synchronizing a light with the rate and rhythm of the maternal call than when the call was desynchronized with the light or presented alone (Lickliter, Bahrick, & Honeycutt, 2002).

Research has also illustrated the organizing influence of intersensory redundancy on early social and linguistic processing. Walker-Andrews (1997) reviewed evidence that infants initially need input from more than one sensory modality to recognize emotional expressions, but at a later age can use the voice alone and eventually facial expressions alone. Evidence for the importance of intersensory redundancy (e.g., synchrony between speech sounds and motions of objects) for the initial detection of the relation between speech sounds and the objects to which they refer has also been demonstrated (Gogate & Bahrick, 1998). The early emergence of infant sensitivity to prosody (Cooper & Aslin, 1989), a composite of amodal properties such as rhythm, tempo, and intensity changes in audiovisual speech, also highlights the salience of intersensory redundancy in guiding attention.

The complementary prediction of the IRH, that processing of modality-specific properties is facilitated in unimodal compared with multimodal stimulation, has also been supported by studies of human infants (Bahrick & Lickliter, 2002). We tested 5-month-olds' detection of orientation (a property available visually but not acoustically) under conditions of bimodal (audiovisual) and unimodal (visual) stimulation. After being habituated to films of a hammer tapping in one of two orientations (upward vs. downward), infants detected a change in orientation following unimodal visual habituation, but not following bimodal audiovisual habituation (Bahrick, Lickliter, & Flom, 2003). Optimal differentiation of visible qualities of an event occurs when there is no concurrent auditory stimulation, which creates intersensory redundancy and competes for attention.

This principle is especially apparent in the domain of person perception. In early development, differentiation of the appearance of a person's face (i.e., on the basis of facial features and their arrangement) should be optimal when the individual is silent, and differentiation of the person's particular voice (i.e., on the basis of pitch and timbre) should be optimal when his or her face is not visible. Research in progress in our lab indicates that this is indeed the case. Young infants differentiate among moving faces under conditions of visual but not audiovisual stimulation and differentiate among voices under conditions of audio but not audiovisual stimulation. After a few months of additional perceptual experience, infants appear to discriminate among the faces and the voices when they experience either unimodal or multimodal stimulation. Enhanced unimodal discrimination of modality-specific properties thus characterizes early attention, and with experience perception becomes more flexible, such that modality-specific properties can be detected in unimodal and multimodal stimulation.

IMPLICATIONS FOR THEORY AND RESEARCH

Converging evidence across species, developmental periods, tasks, and amodal properties suggests that the organizing influence of intersensory redundancy in guiding early attention, perception,

and cognition likely constitutes a general developmental principle. Whether there remains a processing advantage for amodal properties in multimodal stimulation and for modality-specific properties in unimodal stimulation through childhood and adulthood is a topic worthy of investigation. Adults may retain the processing advantages of infancy when stimulation is novel or particularly difficult. These processing advantages likely have significant implications for perceiving, learning, and remembering and, if so, may have potential for educational applications across the life span.

The research highlighted here raises several important challenges for theories of learning and development. First, research on unimodal and multimodal functioning needs to be better integrated to develop unified theories relevant to the world outside the laboratory. Given that studies of multimodal functioning and studies of unimodal functioning often obtain different results, and that the environment is intrinsically multimodal, findings from unimodal research must translate to their natural, multimodal contexts to be more relevant (Lickliter & Bahrick, 2001). The IRH bridges this gap by promoting investigations of both unimodal and multimodal functioning in single research designs, making comparisons across these domains feasible. Second, theories of attention need to be better integrated with those of perception, learning, and memory. Selective attention provides the foundation for what is perceived and learned, and an understanding of what guides this process and how it changes developmentally seems essential for theories of learning and memory. The IRH provides testable predictions of how the allocation of attention affects the development of perception, learning, and memory. A third challenge is to develop more integrative theories; traditional divisions between areas, species, and levels of inquiry have allowed bodies of research to develop in isolation from other relevant knowledge. For example, behavioral research will benefit from incorporating recent discoveries from physiology and the neurosciences regarding interactions among the senses and the multimodal nature of the brain. The convergence of findings across species and levels of analysis will foster more biologically plausible theories and the discovery of more fundamental principles of development.

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