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Learning to Attend Selectively: The Dual Role of Intersensory Redundancy

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Abstract

Selective attention is the gateway to perceptual processing, learning, and memory and is a skill honed through extensive experience. However, little research has focused on how selective attention develops. Here, we synthesize established and new findings from studies assessing the central role of redundancy across the senses in guiding and constraining this process in infancy and early childhood. We highlight research demonstrating the dual role of intersensory redundancy—its facilitating and interfering effects—in the detection and perceptual processing of various properties of objects and events.

Keywords
selective attention, development of perception, intersensory redundancy, attentional salience

The environment provides a flux of changing, concurrent stimulation to all our senses, far more than can be attended to at any given moment in time. Consequently, we must selectively attend to some aspects of objects and events while ignoring others. Adults are highly skilled at directing selective attention to information that is relevant to their needs, goals, and interests while ignoring a vast array of irrelevant stimulation. For example, we can easily pick out a friend in a crowd, follow the flow of action in a ball game, and attend to the face and voice of a single speaker in the context of competing conversations. These attention skills, however, must be learned and honed through experience and practice. Much of this learning takes place in early development. Infants quickly learn to coordinate their patterns of looking and listening to determine which sights and sounds belong together and which do not. They learn to parse the visual array into coherent objects and speech into meaningful words by attending to invariant patterns across variation in input. Such selective attention is widely recognized as the gateway to successful information pickup and processing (Neisser, 1976).

The Dynamics of Selective Attention

An obvious but important insight is that selective attention to stimulation generated from exploratory activity provides the basis for what is perceived, learned, and remembered. In turn, what is perceived, learned, and remembered influences what is attended to in subsequent bouts of exploration, in continuous cycles from attention, to perception, to learning, to memory, to attention, and so on. Figure 1 illustrates this dynamic system of influences and the often overlooked but fundamental role of selective attention in perception, learning, and memory. Moreover, action is tightly coupled with these processes, providing new stimulation for attention, perception, learning, and memory across continuous bidirectional feedback loops (Fig. 1; see also Adolph & Berger, 2005; E. J. Gibson & Pick, 2000). This system of dynamic, interactive influences evolves over time, with concurrent changes in neurodevelopment that go hand in hand with changes in perception and action. Simply put, we create our *effective* environment (Schneirla, 1966) by what we attend to.

Infants face a particularly daunting challenge: They must learn to attend selectively to the vast array of changing multimodal stimulation with limited attentional resources and limited experience with objects and events to guide them. "Selective attention" here refers to a focus

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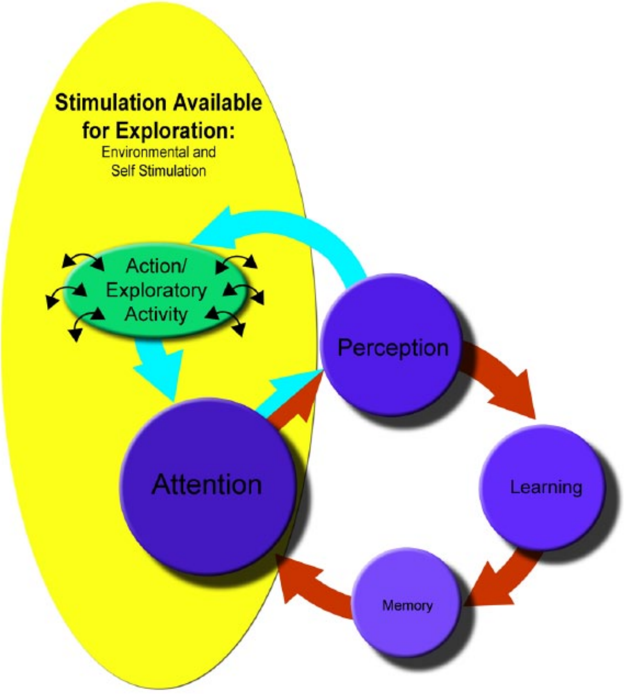

Fig. 1. The central role of selective attention in perception, action, learning, and memory in two interrelated, concurrent attention-system feedback loops: from attention to perception to learning to memory (red arrows) and from attention to perception to action (light blue arrows). The arrows illustrate the primary direction of the flow of information, but each component process (and each system) is involved in continuous, bidirectional feedback loops with the other components (and systems). Stimulation available for exploration is generated through action/exploratory activities (e.g., eye movements, reaching, posture changes), which in turn produce more stimulation for exploration in continuous cycles. Selective attention to this stream of stimulation provides the basis for what is perceived, and thus what can be learned and remembered, and this affects what is attended to next and in subsequent encounters with similar forms of stimulation. Reprinted from "Intermodal Perception and Selective Attention to Intersensory Redundancy: Implications for Typical Social Development and Autism" (p. 123), by L. E. Bahrick, in G. Bremner and T. D. Wachs (Eds.), *Blackwell Handbook of Infant Development* (2nd ed., pp. 120–166), 2010, Oxford, England: Wiley/Blackwell. Copyright 2010 by Wiley/Blackwell. Reprinted with permission.

on particular aspects of sensory stimulation (external or internal) at the expense of other aspects, leading to enhanced neural activity and readiness for information pickup. The control of attention can be overt or covert, conscious or unconscious, endogenous or exogenous, bottom-up or top-down. Selective attention develops with experience and becomes increasingly more economical (E. J. Gibson, 1969; E. J. Gibson & Pick, 2000).

What guides selective attention to relevant aspects of stimulation in early infancy? Despite its obvious importance for perceptual, cognitive, social, and linguistic development, the degree and nature of attentional honing required for typical perception is underappreciated, and little is known about the principles that govern these important processes (but see Courage, Reynolds, & Richards, 2006; Richards, Reynolds, & Courage, 2010). For experienced perceivers, top-down factors such as prior knowledge, categories, goals, and expectations primarily guide information pickup (e.g., Neisser, 1976; Schank & Abelson, 1977). In contrast, early attention development is more influenced by bottom-up factors, including sensitivity to salient properties of stimulation such as contrast, movement, intensity, statistical regularities, and redundancy across the senses (Bahrick & Lickliter, 2000, 2012; Kellman & Arterberry, 1998; Lewkowicz & Turkewitz, 1980). With experience, selective attention gradually becomes more adultlike, endogenous, and modulated by top-down processes (Colombo, 2001; Plude, Enns, & Brodeur, 1994; Ruff & Rothbart, 1996).

The Salience of Intersensory Redundancy

One feature of stimulation that has received growing appreciation for its role in guiding attentional allocation during early development is intersensory redundancy (Bahrick & Lickliter, 2000, 2012; Bremner, Lewkowicz, & Spence, 2012). Intersensory redundancy, which is provided by most naturalistic events, refers to the simultaneous availability and temporal synchronization of the same information across two or more sensory systems. For example, when the rhythm and tempo of speech can be perceived by looking and listening, they are redundantly specified. By definition, only *amodal properties* (information not specific to a particular sensory system; e.g., tempo, rhythm, duration, intensity) can be redundantly specified across the senses. Young infants readily perceive amodal information (Bahrick & Pickens, 1994; Lewkowicz, 2000), and detecting amodal information eliminates the need to learn to integrate stimulation across the senses to perceive unified objects and events (e.g., a person speaking, a ball bouncing), as originally proposed by constructivist accounts of early cognitive development (Piaget, 1952). Instead, as argued by James Gibson (1969) and Eleanor Gibson (1966), sensory stimulation is already united in these events, and this amodal information is detected through a unified perceptual system.

The perception of redundant amodal information, combined with an increasing sensitivity to the statistical regularities of the environment, ensures that inexperienced perceivers selectively attend to unified multimodal events, such as people speaking or keys jingling (as opposed to looking to one event while listening to another). In fact, multimodal redundancy is so effective in directing selective attention and unitizing audiovisual stimulation that it can "tell" infants which of two superimposed video events to watch and which to ignore. The sound-synchronized event appears to "pop out" from the background of the silent superimposed visual event and directs attentional selectivity (Bahrick, Walker, & Neisser, 1981). Infant sensitivity to the salience of intersensory redundancy plays a key role in the early development of a number of cognitive/perceptual skills, including operant learning (Kraebel, 2012), emotion discrimination (Flom & Bahrick, 2007), rhythm and tempo discrimination (Bahrick, Lickliter, Castellanos, & Vaillant-Molina, 2010), numerical discrimination (Jordan, Suanda, & Brannon, 2008), sequence detection (Lewkowicz, 2004), abstract-rule learning (Frank, Slemmer, Marcus, & Johnson, 2009), and word comprehension and segmentation (Gogate & Bahrick, 2001; Hollich, Newman, & Jusczyk, 2005).

The Intersensory-Redundancy Hypothesis

Detecting intersensory redundancy gives rise to attentional salience hierarchies. The *intersensory-redundancy hypothesis* (IRH; Bahrick & Lickliter, 2000, 2012) is a theory of selective attention that addresses how attentional-salience hierarchies organize and guide early selective attention and perceptual processing. According to the IRH, events provide far more information than can be attended at a given time, and attention and perceptual processing are therefore directed to the most salient aspects of stimulation first and to less salient aspects later in exploratory time. All multimodal events provide both redundant, amodal information and nonredundant, modality-specific information, such as color, pattern, pitch, or timbre—aspects available to only a particular sense. The IRH describes the conditions under which we attend to and process amodal versus modality-specific information and how this changes across development. According to the IRH, during the multimodal exploration of events using more than one sense, amodal properties such as synchrony, rhythm, and tempo are most salient and are processed first (*intersensory facilitation*), but during the unimodal exploration of events (e.g., talking on the phone, viewing a silent person), modality-specific properties are most salient and are processed first *(unimodal facilitation*; Bahrick, 2010; Bahrick & Lickliter, 2012). Thus, the nature of exploratory behavior (multimodal, unimodal) and the stimulation provided (multimodal, unimodal) dictate the properties of stimulation (amodal, modality specific) that are most salient.

The principles of intersensory and unimodal facilitation were established and documented across species (human and avian) a decade ago (Bahrick, Lickliter, & Flom, 2004). They have recently been extended from nonsocial to social events and to new domains. Below, we briefly review these principles, illustrating them with more recent examples from social events, and then focus on findings from new domains, including task difficulty, educating attention, neural evidence, and the roles of developmental change in attention allocation.

Intersensory Facilitation of Amodal Properties

Intersensory facilitation is a phenomenon whereby amodal properties are detected more readily and earlier in development when they are redundantly specified in multimodal stimulation than when they are detected in unimodal stimulation. This was originally demonstrated for the amodal property of rhythm. At 5 months of age, infants can detect the rhythm of a toy hammer tapping in audiovisual synchronous, but not unimodal visual, unimodal auditory, or asynchronous, stimulation (Bahrick & Lickliter, 2000). This principle was subsequently extended to social events. For example, by 4 months of age, infants discriminate affect (specified by a combination of amodal properties) in synchronous audiovisual speech but not in unimodal auditory, visual, or asynchronous audiovisual speech (Flom & Bahrick, 2007). Similarly, quail embryos learn and remember the rhythm and tempo of a maternal call following synchronous prenatal audiovisual exposure, but not following an equivalent amount of unimodal auditory or asynchronous audiovisual exposure (Lickliter, Bahrick, & Honeycutt, 2002).

The importance of intersensory redundancy for infant perceptual processing has recently been demonstrated at the neural level using measures of event-related potentials. Five-month-old infants showed heightened attentional salience (increased amplitude in midline negative wave) and longer and deeper processing (decreased amplitude in late slow wave) for synchronous audiovisual speech than asynchronous or unimodal visual speech (Reynolds, Bahrick, Lickliter, & Guy, 2014). This new finding broadens the conceptual frame of the IRH by revealing that intersensory redundancy not only promotes selective attention to certain (amodal) event properties but also promotes longer engagement and deeper processing.

Unimodal Facilitation of Modality-Specific Properties

During unimodal stimulation, such as watching a silent event or hearing a person speak over the phone, attention is not captured by salient intersensory redundancy and is free to focus on modality-specific properties, making the pitch and timbre of a voice or the appearance and features of a person's face most salient. This principle of the IRH, *unimodal facilitation*, holds that modality-specific properties (e.g., color, pattern, pitch, timbre) are detected more readily and earlier in development when they are explored through only one sense than when they are detected in synchronous multimodal stimulation.

This principle was first documented for infant perception of spatial orientation for nonsocial events (Bahrick, Lickliter, & Flom, 2006). More recently, it has provided new information about early face perception. Bahrick, Lickliter, and Castellanos (2013) demonstrated that 2-month-old infants discriminate between the faces of two women best when the women are speaking silently, as compared with speaking audibly (and moving their mouths in synchrony with their voices). Even more striking, face discrimination is enhanced during asynchronous as compared with synchronous audiovisual speech, which highlights the interfering role of intersensory redundancy in the detection of modality-specific information such as facial configuration. During audiovisual speech, intersensory redundancy captures attention, directing it to amodal properties of speech. In contrast, in our asynchronous control condition (in which intersensory redundancy was eliminated but the amount and type of stimulation were preserved), infants discriminated between the two faces. Researchers often overlook this dual role of intersensory redundancy (both facilitating and interfering), instead assuming that intersensory redundancy enhances attention to all aspects of an event. Recent data from quail chicks provide parallel findings in the auditory modality: Chicks learned the pitch of a maternal call in unimodal auditory stimulation or when the call was presented multimodally with an asynchronous flashing light, but not when intersensory redundancy was provided by synchronizing the notes of the call with the flashing light (Vaillant-Mekras, Bahrick, & Lickliter, 2014).

Developmental Change and the Role of Task Difficulty: New Findings

Research generated by the IRH initially focused on selective attention in early development because during this period attentional resources are most limited, attention progresses slowly along the salience hierarchy, and resulting attentional trade-offs and hierarchies are most evident. However, the principles of the IRH also likely apply across the life span whenever attentional resources are limited (e.g., by difficult tasks or high cognitive load). Recent research has indicated that in later development, as attention becomes more efficient and flexible, it progresses along the salience hierarchy more quickly and infants can detect both amodal and modality-specific aspects of stimulation in unimodal and multimodal stimulation within a single bout of exploration (Bahrick, 2010; Bahrick & Lickliter, 2004). For example, Bahrick, Castellanos, and colleagues (2013) demonstrated that although 2-month-olds showed unimodal visual facilitation for face discrimination, by 3 months of age, they discriminated faces under all conditions, including in the presence of intersensory redundancy.

However, salience hierarchies are evident in later development if a task is difficult or attentional resources are taxed. For example, although 5-month-olds showed no intersensory facilitation for discriminating tempo changes of low difficulty, they did for tempo changes of moderate and high difficulty (Bahrick et al., 2010). Further, preschoolers show unimodal facilitation for face discrimination in a difficult task with short familiarization times and memory load, paralleling the performance of infants in a task with lengthy familiarization times and no memory load (Bahrick, Krogh-Jespersen, Argumosa, & Lopez, 2013). Newer evidence indicates that even adults show intersensory facilitation for discrimination of tempo when the contrasts are difficult, but not when they are easier (Bahrick, Todd, & Martin, 2013).

Educating Attention: New Findings

Recent findings from both human and nonhuman-animal studies have indicated that intersensory redundancy can educate selective attention and provide a mechanism for promoting developmental change (Bahrick & Lickliter, 2012). Once amodal properties (e.g., synchrony, rhythm, tempo) "pop out" in multimodal stimulation as a result of intersensory redundancy, infants can then detect these same amodal properties in subsequent unimodal stimulation, at younger ages and under exposure conditions that would otherwise not support the detection of amodal properties. This is similar to a priming effect but longer lasting. Lickliter, Bahrick, and Markham (2006) found that quail chicks showed no preference for a familiar maternal call after a brief prenatal unimodal auditory familiarization. In contrast, when exposed as embryos to a redundant audiovisual presentation (a call synchronized with flashing light) before the unimodal auditory presentation (i.e., first bimodal, then unimodal), chicks preferred the familiar auditory maternal call 2 days after hatching. Embryos that were exposed to the reverse sequence (first unimodal, then bimodal) showed no preference. This education of attention was effective even after delays of 2 or 4 hours between initial bimodal exposure and subsequent unimodal exposure, and it continued to affect learning and memory days later (Lickliter et al., 2006).

Studies of human infants have shown parallel findings. Four-month-olds detect a change in the tempo of a toy hammer tapping in unimodal visual stimulation only if they received a brief preexposure to the tempo in redundant (synchronous audiovisual) stimulation, which educates their attention to the tempo information. Infants fail to detect the tempo change following nonredundant (unimodal visual or asynchronous audiovisual) preexposure (Castellanos, Vaillant-Molina, Lickliter, & Bahrick, 2006). By educating attention to amodal properties, animal and human infants can continue to detect these amodal properties in the same events, even when redundancy is no longer available. This expands the conceptual frame of the IRH, suggesting that education of attention can foster flexible processing and serves as a mechanism for promoting developmental change in attentional selectivity, from the detection of amodal properties in multimodal stimulation to the detection of amodal properties in all types of stimulation.

Putting It All Together: The Dual Role of Intersensory Redundancy

Taken together, studies generated by the IRH reveal a bidirectional or dual role (both facilitating and interfering) of intersensory redundancy in attention and the perceptual processing of event properties. Consequently, multimodal and unimodal stimulation have opposite effects: Multimodal events facilitate the detection of amodal properties at the expense of modality-specific properties, whereas unimodal stimulation facilitates the detection of modality-specific properties at the expense of amodal properties. Because competition for attentional and processing resources underlies these effects, they are most evident in early development, but they are also at play in later development for difficult tasks or under conditions of high cognitive load. The convergence of data across species, developmental periods, event types, and methods provides strong evidence for these conclusions. Alternative models or hypotheses—including the proposal that the greater amount or complexity of stimulation from multimodal compared with unimodal events can account for findings—can be discounted, as they do not explain both the facilitating and interfering roles of multimodal stimulation. Such arguments are also discounted by data from our asynchronous control groups.

Infants' real-time exploration of events illustrates the dual role of intersensory redundancy and its application to naturalistic settings. For example, if an infant looked and listened to a novel person speaking, he or she would likely first attend to and process amodal properties such as rhythm, tempo, affect, or prosody of audiovisual speech at the expense of modality-specific details. In contrast, if the person were silent, the infant might shift his or her attention to the appearance of the person's face, clothing, and hair, and if the person or the infant turned away, the infant's attention would likely shift to the particular sound of the person's voice. Attention may thus shift across exploratory time as a function of the changing context, nature of exploration, and type of stimulation available. Further, with increasing experience, infants show more flexible, rapid shifting along the salience hierarchy, which results in their attending to multiple properties of events (including both amodal and modality-specific properties) in a single bout of exploration. Of course, factors such as complexity, novelty, difficulty, the length of exploratory time, and expertise also affect the speed of progression through this salience hierarchy. Future research is needed to explore how changes in selective attention to event properties progress along the salience hierarchy in real time for individual infants.

New Directions

Infant sensitivity to intersensory redundancy has thus far been assessed at the group level, which has limited our understanding of the nature and basis of developmental change and how it applies in real-world learning settings. We are currently focusing on establishing individual-difference measures of intersensory functioning (Bahrick, Castellanos, et al., 2013). This approach will allow systematic explorations of early developmental trajectories and their relations with cognitive, social, and language outcomes in both typical and atypical populations. Moreover, this grain of analysis will advance theories of attention and perception by revealing the pathways through which simple attentional skills and trade-offs cascade into complex cognitive, social, and language skills.

Recommended Reading

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Bremner, A. J., Lewkowicz, D. J., & Spence, C. (2012). (See References). An edited volume providing a comprehensive overview of the development of multisensory perception.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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