11 The Development of Multisensory Attention Skills

Individual Differences, Developmental Outcomes, and Applications

Lorraine E. Bahrick, Robert Lickliter,
and James T. Torrence Todd

The world presents an array of constantly changing sights and sounds, tactile and vestibular experiences, far too much to be attended and processed at any one time. Perceivers must make sense of this dynamically changing flux of stimulation by selecting events and properties of events that provide information that is meaningful and relevant to their needs, goals, and actions as they change across time. Adults are highly skilled at selectively attending to this multisensory stimulation in a way that optimizes perception and learning and supports their actions and goals. However, this selective attention presents a remarkable challenge for young infants – how to learn to attend to the dimensions of stimulation that optimize meaningful perception and action and to filter out stimulation that is less relevant.

Social events are particularly demanding of attentional resources. Social interactions, including the faces and voices of persons speaking, provide a rich source of stimulation for infants. Social partners and caregivers offer a wealth of information about the world, scaffolding the development of language, emotion, object exploration, and social interaction. Infants must quickly learn to detect which sights and sounds belong together and constitute unitary events (e.g., the face and voice of a person speaking) and which are separate and unrelated, in order to accurately parse the stream of available stimulation and make use of the rich information provided by the social environment.

One way young infants get this process off the ground is by detecting "amodal information," dimensions of time, space, and intensity that can be specified across multiple senses. For example, rate, rhythm, duration, and temporal synchrony are common to the movements of the face and sounds of the voice during speech. By detecting the rhythm and synchrony common to a face and voice during speech (intersensory matching), infants can pick out a speaker in a crowd. Typically developing infants are adept perceivers of amodal information (see Section 11.3 Intersensory Redundancy as a Cornerstone for Perceptual Development). In the social world, infants must also learn to sustain attention to faces and voices during speech in the face of competing stimulation from concurrent events and to quickly disengage from less relevant stimulation to attend to the source of a sound. We call these "multisensory attention skills" – accuracy of matching sights and sounds from unitary events, speed of disengaging or switching away from concurrent events, and duration of sustained attention to multisensory events – in the context of competing stimulation to the various senses. These multisensory attention skills provide a foundation for infants to quickly assimilate the social and linguistic information provided by caregivers. Typically developing infants show a rapid improvement in these fundamental skills across the first year of life (Bahrick, Lickliter, & Castellanos, 2013; Bahrick, Todd, Castellanos, & Sorondo, 2016; Lewkowicz, 1992; Walker-Andrews, 1997). Although, in this chapter, we focus on the development of audiovisual multisensory attention, other modalities, particularly tactile, vestibular, and proprioception, also play an integral role in the development of multisensory attention and in turn language, cognitive, and social outcomes.

In contrast to the typical development of attention and perception, the past decade has witnessed an alarming increase in the prevalence of neurodevelopmental and attention impairments in childhood, including autism spectrum disorder (ASD), attention-deficit hyperactivity disorder (ADHD), and reading disorders. These impairments are also coupled with deficits in multisensory attention and intersensory processing skills (for reviews, see Bahrick & Todd, 2012; Hill, Crane, & Bremner, 2012). Thus, it is critical that scientists learn more about (1) how multisensory attention skills (e.g., matching, shifting, and sustaining attention to audible and visible events) typically develop across infancy and childhood; and (2) how they serve as building blocks for typical language, cognitive, and social development. In particular, we need to specify the pathways through which multisensory attention skills cascade to more complex skills at a level of detail that is appropriate for identifying risk for atypical development and guiding interventions.

A primary obstacle to this effort has, until recently, been the lack of fine-grained individual difference measures of multisensory attention skills appropriate for infants and young children. The field of multisensory processing has been dominated by a group-level approach in which groups of children are tested and data are averaged to characterize skills at specific ages. Unlike domains of language and social development, there have been no tests designed to assess the skill of one child relative to another, or to characterize developmental trajectories. To address this gap, we recently developed the first two individual difference measures of multisensory processing. The availability of measures that can characterize the competence of individual children opens the door to assessing developmental change and pathways from multisensory attention skills to more complex skills that rely on this foundation. This level of analysis can provide a basis for revealing pathways to optimal developmental outcomes, and inform theory, policy, and interventions. In this chapter, we briefly review the history, theory, and research on multisensory development, and then focus on new directions afforded by this shift to a science of the study of individual differences in these capabilities, developmental outcomes, identification of children at risk for atypical development, implications for sociocultural issues, education, policy, interventions, and the importance of fostering optimal development in children.

11.1 History and Conceptual Issues

Two prevailing theoretical views, known respectively as the integration view and the differentiation view, dominated the field of intersensory development during the last half of the twentieth century (see Bahrick & Pickens, 1994; Lewkowicz, 1994, for brief reviews). The "integration view" held that the different sensory modalities function as separate sensory systems in early development and become integrated across time through the infant's activity and experience with concurrent stimulation from different sensory modalities (Birch & Lefford, 1963; Piaget, 1952). In contrast, the "differentiation view" held that the senses form a primitive unity in early development; with experience, the modalities, and the sensory information arising from them become increasingly differentiated. From this view, infants are thought to differentiate finer and more complex multimodal relations across development (Bower, 1974; E. J. Gibson, 1969; J. J. Gibson, 1966). As a result of these opposing views, the most prominent questions guiding research on early intersensory development for several decades focused on whether intersensory development (a) proceeds from integration of information across initially separate senses to coordinated multimodal experience (integration view), or (b) is a process of differentiation and increasing specificity (differentiation view; Lewkowicz & Lickliter, 1994; Rose & Ruff, 1987).

Consistent with the differentiation view, there is now compelling neuroanatomical, neurophysiological, and behavioral evidence of significant interaction among the senses in newborns and young infants from a variety of species (Lewkowicz & Turkewitz, 1980; Lickliter, 1993; Mellon, Kraemer, & Spear, 1991). For example, infant animals are more likely to show intersensory integration than older animals, and in infants (both human and animal) the sensory modality through which an event is processed is not treated as an important attribute of the event for encoding and memory (i.e., amodal encoding; see Spear & McKinzie, 1994). Similarly, work with human infants indicates that newborns (but not adults) typically equate auditory and visual stimuli on the basis of the amodal property of intensity (Lewkowicz & Turkewitz, 1980). Newborns also coordinate audio/visual space, moving their eyes in the direction of a sound (Mendelson & Haith, 1976; Muir & Field, 1979) and infants detect temporal synchrony uniting sights and sounds of speech (e.g., Kuhl & Meltzoff, 1982).

This more "integrated" view of sensory organization can be traced to the ground-breaking work of the perceptual psychologists James J. Gibson and Eleanor Gibson. In a sharp break from the traditional association views of perceptual development described above, the Gibsons recognized that the existence of different forms of sensory stimulation was not a problem for the perception of unitary events, but instead provided an important foundation for it. They argued that all senses should be considered as a single “perceptual system” that interact and work together to pick up invariant aspects of stimulation. One important type of invariant information is *amodal* information, dimensions of time, space, and intensity that can be specified across multiple senses. For example, the rhythm or tempo of a ball bouncing can be conveyed visually or acoustically and is completely redundant across the two senses. One can detect the same rhythm and tempo by watching the ball’s motion or by listening to its impact sounds. The sight and sound of hands clapping likewise share temporal synchrony, a common tempo of action, and a common rhythm.

We know from developmental research conducted over the past three decades, inspired in large part by the Gibsons’ innovative approach to perception, that young infants are adept perceivers of amodal information (Bahrick & Lickliter, 2002; Bahrick & Pickens, 1994; Lewkowicz, 2000). Infants readily detect the temporal aspects of stimulation such as synchrony, rhythm, tempo, and prosody that unite visual and acoustic stimulation from objects and events, as well as spatial colocation of objects and their sound sources and changes in intensity across the senses during the first 6 months following birth (Bahrick, 1988; Lewkowicz, Leo, & Simion, 2010; Slater, Quinn, Brown, & Hayes, 1999; for a review, see Bahrick & Lickliter, 2012). Such demonstrations of infants’ detection of amodal information seriously question the notion that young perceivers slowly learn to coordinate and somehow put together separate and distinct sources of information. By detecting higher-order amodal information common to more than one sense modality, even naive perceivers can explore a unitary multimodal event in a coordinated manner. The major task of perceptual development then becomes to differentiate increasingly more specific information through detecting invariant patterns of stimulation. Importantly, during early development selective attention appears to be biased toward stimulus properties that are common or redundant across sensory modalities (Bahrick & Lickliter, 2002, 2014). By attending to such amodal information, there is no need to learn to integrate stimulation across the senses in order to perceive unified objects and events, as proposed by integrationist accounts of early perceptual and cognitive development.

11.2 Neural and Physiological Evidence of Intersensory Processing

In keeping with available behavioral evidence, research findings obtained from neurophysiological research over the last several decades indicates that the brain is remarkably skilled at integrating input from the different sensory systems to maximize the information available for perception and action, even during infancy (Lewis & Noppeney, 2010; Werchan, Baumgartner, Lewkowicz, & Amso, 2018). Further, the ability to integrate information from different senses is not limited to any particular brain structure. Multisensory integration has been found in neurons at multiple locations in the nervous system, including subcortical areas like the superior colliculus, early cortical areas like the primary visual and auditory cortices, and higher cortical levels like the superior temporal sulcus and intraparietal areas (Ghazanfar & Schroeder, 2006). Available evidence from human brain imaging studies also indicate that cortical pathways once thought to be sensory specific can be modulated by signals from other sensory modalities (Feng, Stormer, Martinez, McDonald, & Hillyard, 2014; Macaluso, 2006; Schroeder & Foxe, 2005). It is now clear that multisensory processes are more broadly distributed throughout the nervous system than traditional views of sensation and perception allowed (see Stein, 2012).

Further, it is well documented that multisensory neurons are highly responsive to the spatial and temporal properties of multisensory stimulation. Stimuli that are spatially and temporally redundant give rise to enhanced neural responsiveness, and stimuli that are separated in space or time result in reduced levels of neural responsiveness (Stein & Meredith, 1993). Neurons are sensitive to timing information, responding strongest to inputs from different modalities arriving simultaneously.

We now know that the senses function in concert even in infancy. Brains are organized to use the information they derive from the various sensory systems to enhance the likelihood that objects and events will be detected rapidly, identified correctly, and responded to appropriately, even during very early development (Calvert, Spence, & Stein, 2004). For example, the role of multisensory processing in selective attention has recently been demonstrated in infants at the neural level using measures of event-related potentials. Five-month-old infants show heightened attentional salience (greater amplitude Nc) and longer and deeper processing (reduction in late slow wave) for synchronous audiovisual speech than asynchronous or unimodal visual speech (Reynolds, Bahrick, Lickliter, & Guy, 2014). This reveals that intersensory redundancy (the same information simultaneously available and temporally synchronized across two or more sensory systems) not only promotes selective attention to certain event properties, but also promotes longer engagement and deeper processing. A physiological index of infant attention, heart rate, has also shown similar results. Curtindale, Bahrick, Lickliter, and Colombo (2019) found that intersensory redundancy (provided by dynamic videos of a woman speaking with a temporally matching soundtrack) attracted and held 4- and 8-month-old infants' attention as measured by greater heart-rate decelerations when compared to infants in a similar condition that provided no intersensory redundancy (the soundtrack was delayed with respect to the video). This suggests that auditory and visual events presented in synchrony and out of synchrony elicit physiological changes that are associated with differing levels of attention and processing in infants (see also Pizur-Barnekow, Kraemer, & Winters, 2008). Taken together these neurophysiological findings point to the effectiveness of intersensory redundancy in capturing attention and promoting perceptual processing in early development.

11.3 Intersensory Redundancy as a Cornerstone for Perceptual Development

Intersensory redundancy (the same information simultaneously available and temporally synchronized across two or more sensory systems) is provided by most naturalistic events. For example, when the rhythm and tempo of speech can be perceived by looking and listening, the rhythm and tempo 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. Consistent with the view advanced by the Gibsons (E. J. Gibson, 1969; J. J. Gibson, 1966), this is not a problem for perception, but instead is a central foundation for accurate perception. It is also important to note that *all* multimodal events not only provide redundant, amodal information, but they also provide nonredundant, modality-specific information (attributes available to only a specific sensory system) such as color, pattern, pitch, or timbre. Selective attention to amodal information in early development can thus guide and constrain perceptual learning such that more global properties are differentiated first, and later more specific details are detected (Bahrick, 2001; Bahrick & Lickliter, 2002). This promotes veridical perceptual processing in order of increasing specificity, and fosters appropriate generalization of learning, allowing details (which vary across events) to be perceived in the context of more global properties that show less variability (Bahrick, 2001, 2010; E. J. Gibson, 1969).

We have known for over three decades that young infants are adept perceivers of intersensory redundancy across auditory and visual stimulation. Behavioral studies using traditional group-level methods such as the intermodal preference method (Bahrick, 1988; Lewkowicz, 1992) and the infant-controlled habituation procedure (methods that typically provide a single measure designed for statistical approaches that average across a group of participants; Bahrick, 1992; Gogate & Bahrick, 1998) have revealed a great deal about capabilities of infants at different ages. They demonstrate that early detection of intersensory redundancy provides a foundation for important achievements such as detection of object composition and substance (Bahrick, 1987, 1988), word mapping (Gogate & Bahrick, 1998; Gogate & Hollich, 2010), emotion perception (Flom & Bahrick, 2007; Walker-Andrews, 1997), communicative intent (approval and prohibition; Bahrick, McNew, Pruden, & Castellanos, 2019), and social referencing (Vaillant-Molina & Bahrick, 2012). For example, 7-month-old infants learn to relate speech sounds with objects when adults provide synchronous (but not asynchronous) object movements and labeling (Gogate & Bahrick, 1998, 2001). Five-month-old infants learn to preferentially approach a toy an adult responds to with positive emotion (but not negative emotion) early in development if they receive synchronous audiovisual information rather than visual information alone (Vaillant-Molina & Bahrick, 2012). In sum, a rich body of data from studies such as these has revealed that infants possess a wide range of intersensory processing skills in early development and that these skills provide a foundation for more complex language, cognitive, and social competencies. However, without the availability of fine-grained individual difference measures, the specific pathways and processes involved have remained unclear.

Given that events provide both amodal and modality-specific information, and infants are adept perceivers of amodal information, how and under what conditions do infants learn to detect modality-specific information? How is detection of different levels of information inter-coordinated? For example, infants perceive the emotion and communicative intent in audiovisual speech, but under what conditions do they attend to the appearance of the face or the sound of the voice? Infants detect the substance (rigid vs. elastic) and composition (single vs. compound object) of objects striking a surface, but under what conditions do they detect their color and shape, or the pitch of their impact sound? These are modality-specific properties (e.g., facial features and their spatial arrangement; color and shape of an object; or the pitch and timbre of a particular voice or impact sound). In line with Gibson's principle of increasing specificity, early research (Bahrick, 1992, 2001) demonstrated that detection of properties of stimulation develops in order of increasing specificity across development, from amodal, global properties (e.g., amodal temporal information for object substance and composition) to later detection of modality-specific information (e.g., object color/shape and pitch of impact sound). Consistent with this perspective, a more recent conceptual framework, the Intersensory Redundancy Hypothesis (IRH), was proposed to explore and reveal specific developmental principles guiding the inter-coordination of amodal and modality-specific information (Bahrick & Lickliter, 2000, 2012, 2014).

11.3.1 The Intersensory Redundancy Hypothesis (IRH)

The IRH is a theory of selective attention that describes how attention is allocated to various properties of objects and events – amodal and modality specific – in multimodal and unimodal stimulation. The IRH was derived from a convergent-operations approach (Lickliter & Bahrick, 2000) in which parallel research questions are explored across human and nonhuman animal subjects to identify common developmental principles of early intersensory perception. Research consistently demonstrates that intersensory redundancy available in multimodal stimulation is highly salient to young infants (see Bahrick & Lickliter, 2012, for a review). This creates attentional salience hierarchies favoring detection of amodal information at the expense of modality-specific information in early development when attentional resources are most limited. Thus, the IRH describes how the detection of *amodal information* can guide selective attention and learning during early infancy and how this process is coordinated with perception of *modality-specific information*. During multimodal (but not unimodal) exploration of events, amodal properties such as synchrony, tempo, and rhythm are most salient and are processed first. This is referred to as *intersensory facilitation*, the principle that amodal properties are detected more readily and earlier in development when they are redundantly specified in multimodal stimulation than when the same amodal properties are detected in unimodal stimulation (Bahrick & Lickliter, 2000, 2012). In contrast, in unimodal exploration of events (e.g., viewing a silent person; talking on the phone), attention is not captured by salient intersensory redundancy and is thus free to focus on modality-specific properties. This makes the pitch and timbre of a voice, or the appearance and features of a face most salient and processed first. This is referred to as *unimodal facilitation*, the principle 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 the same information is detected in multimodal, synchronous stimulation (Bahrick, 2010; Bahrick & Lickliter, 2012).

The principal of *intersensory facilitation* was originally demonstrated for the amodal property of rhythm. At 5 months, infants detect the rhythm of a toy hammer tapping in audiovisual synchronous, but not unimodal visual, auditory, or asynchronous stimulation (Bahrick & Lickliter, 2000). This principle was subsequently extended to social events. For example, by 4 months, 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 the equivalent amount of unimodal auditory or asynchronous audiovisual exposure (Lickliter, Bahrick, & Honeycutt, 2002).

The principle of *unimodal facilitation* was first documented for infant perception of spatial orientation for nonsocial events (Bahrick, Lickliter, & Flom, 2006) and more recently has provided new information about early face perception. Bahrick et al. (2013) demonstrated that 2-month-old infants are best at discriminating between the faces of two women speaking when their speech is silent as compared with when it is audible and synchronous with their voices. Even more striking, face discrimination is enhanced during asynchronous as compared with synchronous audiovisual speech, highlighting the interfering role of intersensory redundancy for detecting modality-specific information such as facial configuration. During audiovisual speech, intersensory redundancy captures attention, directing it to amodal properties of speech. In contrast, in the asynchronous control (in which intersensory redundancy was eliminated but the amount and type of stimulation were preserved), infants discriminated between the two faces. This *dual role* of intersensory redundancy (both facilitating and interfering) is often overlooked and instead it is assumed that intersensory redundancy enhances attention to *all* aspects of an event. Alternative hypotheses, including that the greater amount or complexity of stimulation from multimodal than 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 asynchronous control groups, which show no facilitating effects.

Although principles of the IRH are most apparent in early development because attentional resources are limited, and task difficulty is high in relation to skills of the perceiver, these principles also apply across the life span, particularly when attentional resources are challenged and task difficulty is high. As attention becomes more efficient and flexible across development, it can progress along the attentional salience hierarchy more quickly, and infants can then detect both amodal and modality-specific properties of stimulation in both multimodal and unimodal contexts within a single bout of exploration. Thus, infants of 2 months show unimodal facilitation of face discrimination (discriminating faces only when presented visually but not audiovisually), but by 3 months of age they no longer show unimodal facilitation. Instead, they discriminate the faces when presented visually as well as audiovisually (in the context of highly salient intersensory redundancy; Bahrick et al., 2013). Further, when task difficulty is high, the effects of salience hierarchies become evident in later development. Thus, although 5-month-olds show no intersensory facilitation for discriminating tempo contrasts of low difficulty, they do show intersensory facilitation when discriminating tempo contrasts of moderate and high difficulty (Bahrick, Lickliter, Castellanos, & Vaillant-Molina, 2010).

Taken together, studies generated by the IRH reveal a bidirectional or dual role (both facilitating and interfering effects) of the salience of intersensory redundancy on attention and perceptual processing of event properties (Bahrick & Lickliter, 2014). Specifically, multimodal and unimodal stimulation have opposite effects: Multimodal events facilitate detection of amodal properties at the expense of modality-specific properties, whereas unimodal stimulation facilitates detection of modality-specific properties at the expense of amodal properties. Because competition for processing resources underlies these effects, they are most evident in early development, but are also at play in later development for difficult tasks or conditions of high cognitive load. The convergence of data across species, developmental periods, event types, and methods provides strong evidence for these conclusions.

11.3.2 Educating Attention

Intersensory redundancy has also been shown to "educate attention" to amodal properties of events, much like transfer of training effects. Specifically, once intersensory redundancy directs attention to amodal properties in multimodal stimulation, infants can detect the same amodal properties in subsequent unimodal stimulation, at younger ages and under exposure conditions that would otherwise not support detection of amodal properties in unimodal stimulation. Studies of bobwhite quail embryos and chicks illustrate this effect. Lickliter, Bahrick, and Markham (2006) found that quail chicks showed no preference for a familiarized maternal call when they had received relatively brief prenatal unimodal auditory familiarization. In contrast, by first exposing embryos to a redundant audiovisual presentation of the maternal call (call synchronized with flashing light) followed by a unimodal auditory presentation (bimodal → unimodal), chicks showed a significant preference for the familiar auditory maternal call 2 days after hatching. Embryos who received the reverse sequence of exposure to the maternal call (unimodal → bimodal) showed no preference for the familiarized maternal call in postnatal testing. Intersensory redundancy (in bimodal stimulation) apparently highlighted the temporal features of the call and educated attention to these features in subsequent unimodal stimulation. This education of attention to redundant temporal properties was effective even after delays of 2 or 4 hours between initial bimodal stimulation and subsequent unimodal stimulation (Lickliter et al., 2006).

Recent work with human infants has likewise shown the education of attention to specific properties of events. Bahrick, Lickliter, and Castellanos (2020) assessed if 2-month-old human infants could detect the amodal property of tempo in dynamic unimodal visual presentations of a toy hammer tapping (a task typically too difficult for 2-month-olds) if infants had first been exposed to audiovisual stimulation from the same toy hammer tapping, providing intersensory redundancy, thereby educating attention to tempo. Infants were all habituated to a visual-only display of the toy hammer tapping at a given tempo and tested for detection of a change in tempo. There were three "pre-exposure" conditions in which infants received a short exposure to the toy hammer before the unimodal visual habituation session. Intersensory redundancy was either provided (audiovisual synchronous presentation of the hammer tapping) or not provided (unimodal visual presentation of the hammer tapping; asynchronous audio and visual presentation of the hammer). Results paralleled those of the study with quail embryos and chicks (Lickliter et al., 2006) and indicated that only infants who received the synchronous audiovisual pre-exposure (and not those who received the unimodal visual or asynchronous audiovisual pre-exposure) showed evidence of detecting the change in tempo in the unimodal visual habituation test. These findings suggest that intersensory redundancy available in the audiovisual pre-exposure educated infant attention to the amodal property of tempo. This attentional bias was then extended to the subsequent unimodal visual habituation session and promoted discrimination of tempo under conditions that would otherwise be too difficult for 2-month-old infants. Taken together, our convergent results suggest that education of attention can foster flexible perceptual processing and promote developmental change in attentional selectivity, from detection of amodal properties in multimodal stimulation to the detection of amodal properties in unimodal stimulation. As we discuss next, this insight remains unexplored in applications to educational settings.

11.3.3 Intersensory Redundancy, Educational Applications, and Implications for Policy

The IRH has advanced our understanding of the emergence and maintenance of a range of perceptual and cognitive skills observed during infancy, including the development of affect and prosody discrimination (Bahrick, McNew et al., 2019; Flom & Bahrick, 2007), rhythm and tempo discrimination (Bahrick, Flom, & Lickliter, 2002; Bahrick & Lickliter, 2000), numerical discrimination (Jordan, Suanda, & Brannon, 2008), sequence detection (Lewkowicz, 2004), abstract rule learning (Frank, Vul, & Johnson, 2009), and word mapping and segmentation (Gogate & Hollich, 2010; Hollich, Newman, & Jusczyk, 2005).

Facilitating effects of intersensory redundancy should also be apparent during early phases of learning for a variety of tasks across the life span. In other words, intersensory facilitation would be expected for learning in domains that are novel, for tasks that require effort, executive function, or discrimination of fine detail, for speeded responses, and for problems of relatively high cognitive load. Children and adults continue to develop expertise across the life span, acquiring new information and learning to perceive finer distinctions such as learning a new language or playing a new musical instrument. In early stages of learning, expertise is low in relation to task difficulty, and consequently task demands are high. Under these conditions, attention progresses more slowly along the processing salience hierarchy, and like infants, children and adults should experience intersensory facilitation. Similarly, unimodal facilitation (the interfering effects of intersensory redundancy) should also be evident across the life span when modality-specific tasks are difficult and cognitive load is high.

In educational settings, we propose that teachers carefully match learning strategies to the amodal and modality-specific properties of the information to be learned. For example, when learning material that is best conveyed visually (e.g., colors, numbers, the alphabet; discriminating between faces or complex objects), processing this modality-specific information will be enhanced in the absence of intersensory redundancy (i.e., without accompanying sounds that create salient audiovisual redundancy). Intersensory redundancy would interfere with learning by directing attention away from distinctive visual properties and toward properties common across sights, sounds, and tactile impressions (rhythm tempo, intensity patterns). If learning of visual material is accompanied by sound, the sound should not be coordinated with object movement (thereby not creating intersensory redundancy). For example, an unrelated sound (bell; utterance, look!) could engage attention without directing it away from the information to be learned. Similarly, when learning material best conveyed acoustically (e.g., letter sounds, verbal content, melody, language accent) learning about the nature of the sound (e.g., pitch, timbre) and speech content will also be enhanced in the absence of salient intersensory redundancy that directs attention away from modality-specific acoustic information.

In contrast, when learning material that relies on detecting amodal information (e.g., rhythm, tempo, intensity; prosody or affect in audiovisual speech), learning will be enhanced by presenting temporally coordinated multisensory information. For example, detecting communicative intent in utterances of prohibition will be facilitated by providing the natural, dynamic, temporally coordinated face and voice. This fosters unitized perception of the emotional expression and directs attention to salient properties of rhythm, tempo, and intensity changes across the face and voice that convey prohibition. Some material, including that supporting detecting emotion and communicative intent, provides both distinctive amodal as well as modality-specific properties. Thus, directing attention to a particular facial expression (e.g., a furrowed brow or frown) when conveying prohibition, would be facilitated in the absence of intersensory redundancy.

Finally, educating attention to amodal properties of events may also enhance learning. Teaching children to first perceive the target information in multimodal stimulation (e.g., emotion or prosody in the synchronous face and voice) and once it is detected, then presenting it in unimodal stimulation (face or voice alone; a more difficult learning context) may facilitate faster and more flexible learning about amodal properties that also extends beyond initial learning contexts. Recall, however, that across development, children become better at detecting both modality-specific and amodal properties in either multisensory or unimodal stimulation. Thus, the above principles are most applicable when tasks are difficult, attentional resources are challenged, or in teaching new skills. In typical exploration, perceivers seamlessly shift between detecting amodal and modality-specific properties as events become visible and audible or audible and visible together, and in accordance with their goals and intentions.

11.4 Intersensory Processing as a Foundation for Cognitive, Social, and Language Development

Intersensory processing serves as a critical foundation upon which more complex social, cognitive, and language skills can develop (Bahrick & Lickliter, 2012; Bahrick, Todd, & Soska, 2018; Barutchu et al., 2010; Pons, Bosch, & Lewkowicz, 2019). Rapidly shifting attention to locate the source of a sound allows children to unitize the sights and sounds of speech or object events, to pick out the speaker in a crowd, or attend to the object that is labeled. This selective attention, in turn, provides a basis for meaningful processing of these multimodal events. However, without reliable individual difference measures, researchers can only explore the capabilities of the average infant (derived from mean performance of a group) at a particular age, with no attention to individual variability. Variability across individuals in foundational skills, however, is a cornerstone for predicting developmental outcomes in individual children. Individual difference measures make use of this variability.

11.4.1 The Importance of Individual Difference Measures in Developmental Science

Developmental science has been undergoing an important shift in theory and methodology toward an individual difference approach, critical to addressing key questions about developmental change and pathways to outcomes (Lerner, Agans, DeSouza, & Hershberg, 2014; Overton, 2014). There have been significant advances in both theory and application from the creation of individual difference measures in many areas (e.g., language, cognition, clinical science) with assessments ranging from working memory to symptoms of autism and externalizing behaviors (Eyberg, Nelson, Duke, & Boggs, 2004; Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998; Lord, Rutter, DiLavore, & Risi, 2002; Rose, Feldman, & Jankowski, 2011). This has allowed researchers to link individual differences in these skills with later outcomes and to discover important developmental cascades. For example, greater language processing efficiency (speed/accuracy of looking to a labeled object) in toddlers has been found to predict accelerated vocabulary growth across early childhood and in turn, greater language proficiency and academic performance, even years later (Fernald & Marchman, 2012; Fernald, Perfors, & Marchman, 2006; Marchman & Fernald, 2008). We propose that the development of multisensory attention skills underlies developmental cascades leading to optimal language and social functioning. By creating and refining novel individual difference measures, we can dramatically enhance research, theory, and application of multisensory development to these critical domains. They will provide tools necessary for characterizing developmental trajectories and pathways from early developing skills to later outcomes.

11.4.2 Individual Difference Measures of Intersensory Processing

In particular, we have proposed that individual differences in the speed and accuracy of attention to intersensory redundancy should predict social, cognitive, and language competence (Bahrick, 2010; Bahrick & Lickliter, 2002; Bahrick & Todd, 2012). For example, intersensory processing is thought to underlie word mapping (Gogate & Hollich, 2010). Research using traditional approaches has shown that synchronous, but not asynchronous, object movement and verbal labeling promotes object–label mapping (Gogate & Bahrick, 1998; Jesse & Johnson, 2016), and this provides a gateway for further processing of object–label relations (Gogate, 2010; Gogate & Maganti, 2016). Moreover, children show improved word learning if parents more often spontaneously synchronize object movement and labeling (Nomikou, Koke, & Rohlfing, 2017; Suarez-Rivera, Smith, & Yu, 2018). These findings suggest that intersensory processing skills may promote a variety of downstream developmental improvements. Individual differences in the accuracy and speed of intersensory skills, such as face–voice or object–sound matching, as well as quickly shifting to and sustaining attention to these audiovisual events should predict individual performance in domains that rely on this foundation – from vocabulary growth and literacy skills, to social competence and school readiness.

However, until recently there were no commonly accepted measures of intersensory processing that were sufficiently fine-grained nor designed for assessing individual differences in infants or children. Without fine-grained individual differences measures, it has not been possible to determine if one child shows better intersensory processing skills than another, how these skills change across development, nor identify the pathways from these skills to later developmental outcomes. Consequently, we do not yet have a database documenting the typical development of these skills from infancy to childhood (the period across which identifying delays and disorders is most needed for intervention). An individual differences approach can reveal typical developmental trajectories of intersensory processing skills in infants and children, pathways between these basic skills and later developmental outcomes, and in turn, help identify performance that is atypical and outside the normal range of variability. The lack of fine-grained individual difference measures has thus limited advancement of developmental theory and application to education and to identifying developmental delays in these foundational skills. If multisensory attention skills (i.e., intersensory matching, shifting, maintaining attention to unitary multimodal events) are not well established in infancy, there may be far-reaching consequences for later language, social, and cognitive development (Bahrick, 2010; Bahrick & Lickliter, 2012; Bahrick & Todd, 2012; Bremner, Lewkowicz, & Spence, 2012; Falck-Ytter, Nyström, Gredebäck, Gliga, & Bölte, 2018).

We have therefore developed two new protocols for assessing individual differences in multisensory attention skills appropriate for preverbal participants. Both measures assess attention to audiovisual social and nonsocial events. The Multisensory Attention Assessment Protocol (MAAP; Bahrick, Todd et al., 2018) indexes intersensory processing (accuracy) as well as attention maintenance (duration), and shifting/disengaging (speed) for audiovisual events. The Intersensory Processing Efficiency Protocol (IPEP; Bahrick, Soska, & Todd, 2018) is more difficult and provides more fine-grained measures of just intersensory processing (accuracy and speed). In each of these protocols, both infants and children can be assessed using the same methods. These protocols now open the door to exploring the foundational role of intersensory processing and basic attention skills in ways not previously possible with traditional group-level approaches. Combining several measures within a protocol can reveal how basic attention skills (shifting, disengaging, maintaining attention) typically studied individually using primarily static or silent stimuli interact in individual children in overlapping, multisensory events. Because stimulation most salient to infants in multisensory events differs markedly from that of silent dynamic or static stimuli (Bahrick, Gogate, & Ruiz, 2002; Bahrick & Lickliter, 2014; Bahrick et al., 2013, 2016; Otsuka et al., 2009), the use of these protocols should yield new knowledge, generalizable to real-world, multisensory learning environments.

11.4.2.1 *The Multisensory Attention Assessment Protocol (MAAP)*

The Multisensory Attention Assessment Protocol (MAAP; Bahrick, Todd et al., 2018) assesses three multisensory attention skills, and the impact of competing visual stimulation on each, in a single protocol: duration of looking, accuracy of matching audio and visual stimulation, and speed of shifting, to social and nonsocial events (for a sample video, visit https://nyu.databrary.org/volume/326). It is designed to characterize fine-grained individual differences in attention to audiovisual events for infants and children. It is the only protocol to assess intersensory processing (matching sights and sounds) in the context of two other basic attention skills (shifting and maintaining attention to audiovisual events). Although attention is typically viewed as multifaceted (Colombo, 2001; Posner & Petersen, 1990; Ruff & Rothbart, 1996), attention and its development have typically been studied piecemeal, with various measures assessed in separate studies using different methods and stimuli, making comparisons across age and studies challenging. The MAAP provides a basis for assessing interrelations among all three attention skills and fosters comparisons across studies and ages. The MAAP adapts traditional looking-time measures and thus requires no verbal instructions or responses and is suitable for both nonverbal and verbal participants. Typically, nonverbal methods are used with infants (e.g., Colombo, Shaddy, Richman, Maikranz, & Blaga, 2004; Fagan, Holland, & Wheeler, 2007), whereas methods for children have required verbal responses or following instructions. The MAAP provides a single, common protocol for assessing development across infancy and early childhood, the period during which symptoms of developmental disorders (e.g., ASD, ADHD) emerge and are most responsive to intervention.

In the MAAP protocol (see Figure 11.1), each trial begins with a 3-second dynamic central visual stimulus (silent, colorful moving shapes) followed by two 10-second side-by-side lateral events. Social (two women speaking) and nonsocial events (two objects striking a surface) are played in different trial blocks with a natural soundtrack synchronous with one of the two events. On half of the trials, the central competing stimulus remains on during the lateral events, serving as the visual distractor (high-competition trials), and on the other half, it is turned off when the lateral events appear (low-competition trials). *Duration* of looking to the two events, *accuracy* of matching the audible and visual stimulation, and *speed* of shifting to the

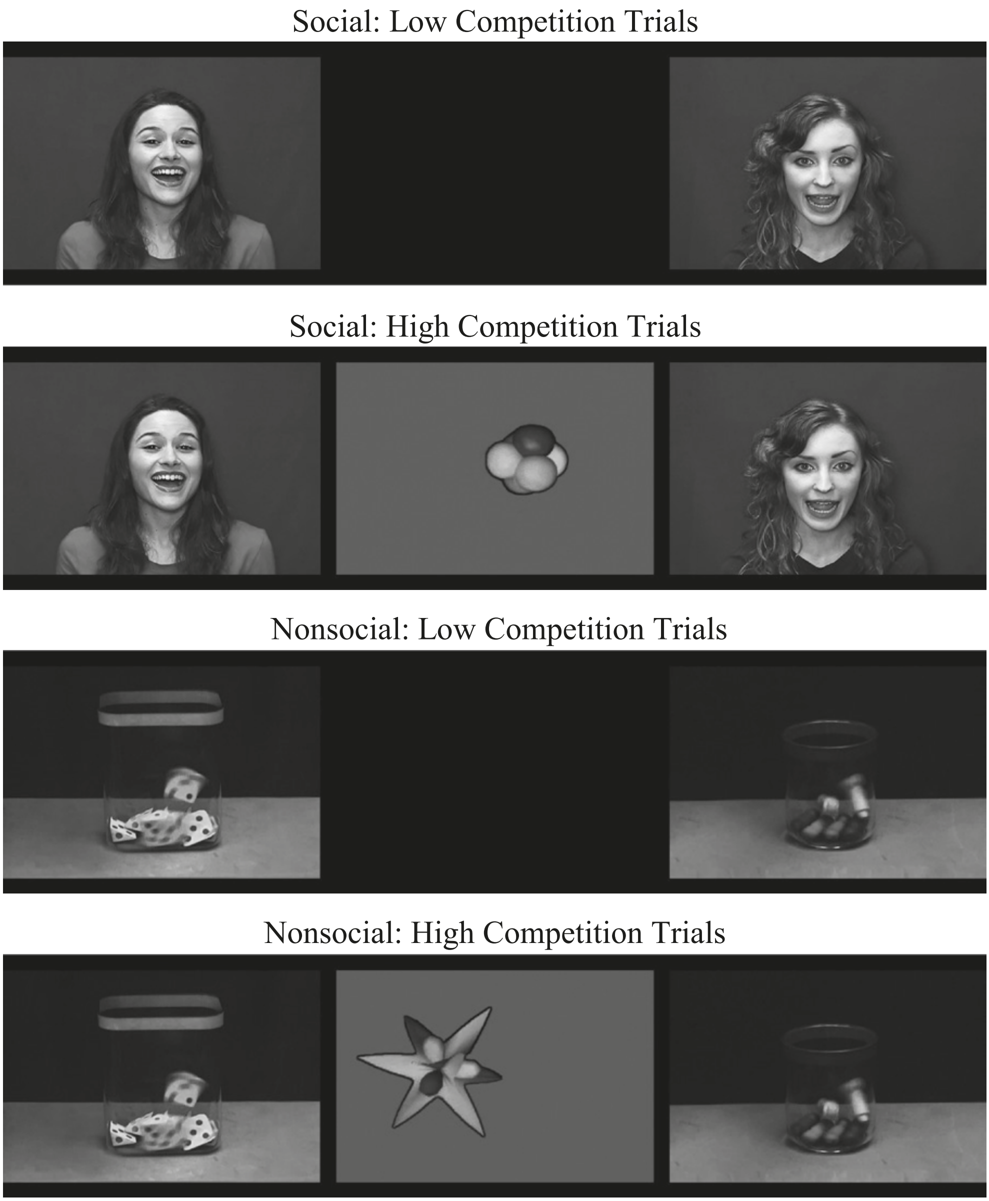

Figure 11.1. *Static images of the dynamic audiovisual events from the MAAP. On all trials, a 3-second central stimulus (computerized geometric shape) was followed by two side-by-side lateral events (social, nonsocial), one of which was synchronous with its appropriate soundtrack. On low-competition trials, the central stimulus was turned off during the lateral events, whereas on high-competition trials, the central stimulus remained on during the lateral events.*

visual events is assessed under conditions of high and low competition. This design allows assessing relations among multisensory attention skills (duration, accuracy, speed) and the effects of concurrent, distracting events on these skills.

11.4.2.2 *The Intersensory Processing Efficiency Protocol (IPEP)*

The Intersensory Processing Efficiency Protocol (IPEP; Bahrick, Soska et al., 2018) focuses exclusively on intersensory processing (for a sample video, visit https://nyu.databrary.org/volume/326). It leverages traditional looking-time measures to derive indices of speed and accuracy (using remote eye tracking) in a context of multiple, concurrent events, both social and nonsocial. In the IPEP, participants attempt to locate an acoustically synchronized target event amid five competing visual distractors. The IPEP thus indexes intersensory processing in the context of multiple competing, naturalistic events, providing a meaningful basis for generalizing intersensory skills to natural, multimodal learning contexts. In traditional methods only one or two events are shown together, often with simple repetitive sounds, limiting their relevance to complex, real-world learning settings. In the IPEP (see Figure 11.2), participants see six concurrent events, while hearing the synchronous and appropriate soundtrack to one of them, simulating the "noisiness" of the natural world of overlapping events. The audiovisual events are rich and varied, depicting women speaking fluid, child-directed speech (social events) and objects of various shapes and compositions striking a surface in varied temporal patterns (nonsocial events). The events provide both macro-synchrony (onset and offset of head and large lip movements or object impacts against a surface) and micro-synchrony (specific speech sounds and fine-grained lip movements, or fine-grained temporal structure of object impacts). The protocol resembles the task of picking out a speaker in a crowd. The IPEP does not require verbal responses or understanding language, and thus can be administered at any age across the life span.

11.4.2.3 *Developmental Change in Multisensory Attention Skills (MAAP and IPEP Measures)*

Ongoing research in our lab is focusing on establishing developmental trajectories for multisensory attention skills in typically developing infants and young children to characterize the emergence of these skills and their refinement across early childhood. Thus far, findings reveal significant developmental improvements across 6 to 24 months in intersensory processing accuracy as assessed by the IPEP (McNew, Todd, Edgar, & Bahrick, 2018). Also, between 3 and 12 months, infants show improvements in multisensory attention skills assessed by the MAAP (maintaining attention, speed of attention shifting) in the presence of competing stimulation. Findings demonstrate a significant

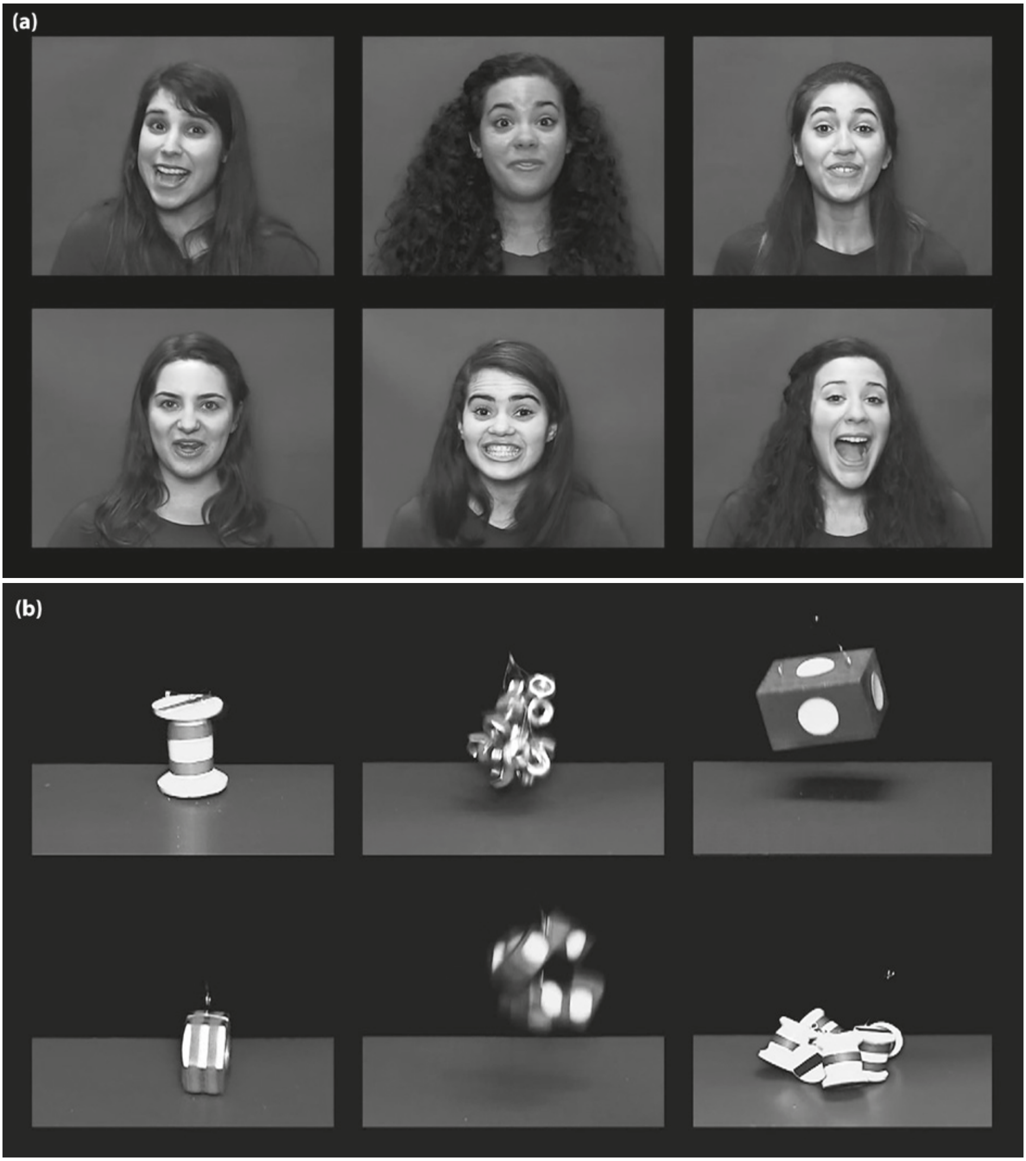

Figure 11.2. *Static images of the dynamic social (A) and nonsocial (B) events from the IPEP. On all trials, all six events (women, objects) were shown moving, but on each trial the movements of a different woman or object were synchronized with the accompanying, natural soundtrack.*

cost of competing stimulation on attention that decreases across age as infants become better at filtering out irrelevant stimulation (e.g., visual distractors; Todd, McNew, Soska, & Bahrick, 2016). Further studies indicate that multisensory attention skills continue to improve across age in older children, particularly for social events (Bahrick, Todd et al., 2018).

11.5 Links Between Multisensory Attention Skills and Language and Social Outcomes

The development of individual difference measures that show meaningful changes across age in multisensory attention skills opens the door to studies that can assess relations among these skills and language and social outcomes. We and others have argued that multisensory attention skills – matching sights and sounds from unitary events (e.g., a person speaking) and shifting and sustaining attention to these events in the presence of distractors – are foundational for both language and social development (Bahrick & Lickliter, 2012; Gogate & Hollich, 2010; Lewkowicz, 2014; Mundy & Burnette, 2005). For instance, intersensory processing (e.g., detecting synchrony between naming and gesturing to an object) helps infants link speech sounds with objects, serving as a basis for "word mapping" (Gogate & Hollich, 2010; Gogate, Walker-Andrews, & Bahrick, 2001). Multisensory attention skills also promote social development during face-to-face interactions between infants and caregivers. Fine-grained intersensory processing skills are required to coordinate the timing and intensity patterns across visual vocal, tactile, and affective communication (Beebe et al., 2016; Feldman, 2007). Caregivers are highly responsive to these infant behaviors, and the temporally coordinated and contingent responses provided by caregivers predict infant language learning (Tamis-LeMonda, Kuchirko, & Song, 2014).

Our working model (see Figure 11.3) illustrates the important role of basic attention skills (speed of shifting/disengaging, attention maintenance) and the mediational role of intersensory processing in language, social, and cognitive development during infancy. Basic attention skills (speed of shifting/disengaging, attention maintenance) predict accuracy of intersensory processing (selective attention to a sound synchronous event in the context of distracting events), which in turn predicts language, social, and cognitive outcomes. The relation between intersensory processing and language, social, and cognitive outcomes is moderated by the quality and quantity of infant–caregiver social interaction.

Recent findings are consistent with our model and provide support for the proposal that individual differences in multisensory attention skills are associated with individual differences in language and social functioning in both typically and atypically developing children. In one study, 2- to 5-year-old typically developing children received the MAAP along with the Mullen Scales of Early Learning (MSEL; Mullen, 1995), a standardized measure of cognitive and language functioning (Bahrick, Todd et al., 2018). Interrelations among MAAP measures and MSEL scores were evident. A structural equation model (SEM) revealed that children who showed longer maintenance of attention (duration) to social events showed greater intersensory matching (accuracy) of audiovisual speech events, and in turn higher scores on the receptive and expressive language scales of the MSEL, even after controlling for chronological age. Thus, consistent with our working model, accuracy of matching

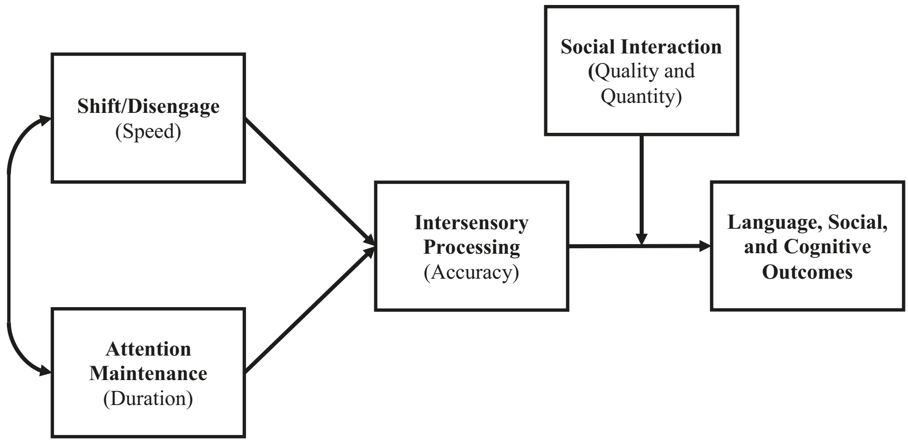

Figure 11.3. *Working model illustrates the mediational role of intersensory processing in language, social, and cognitive development during infancy. Basic attention skills (speed of shifting/disengaging, attention maintenance) predict accuracy of intersensory processing (selective attention to a sound synchronous event in the context of distracting events), which in turn predicts language, social, and cognitive outcomes. The relation between intersensory processing and language, social, and cognitive outcomes is moderated by the quality and quantity of multimodal social interaction.*

auditory and visual stimulation across faces and voices mediates the relation between sustained attention to speech events and receptive and expressive language functioning.

Individual differences in multisensory attention skills to social events assessed by the MAAP also predict social competence in typically developing children. At 6 months of age, longer attention maintenance to faces, greater intersensory matching of faces and voices, and faster speed of attentional shifting predict 18-month social competence scores on the Infant–Toddler Social Emotional Assessment (Carter & Briggs-Gowan, 2000). These preliminary findings are also consistent with our working model that multisensory attention skills are foundational for social functioning (Todd et al., 2018). These exciting findings illustrate the important new directions afforded by the availability of individual difference measures of multisensory attention skills and the inclusion of multiple measures within a single protocol. Models such as those described above can inform application and guide interventions to enhance language and social development.

Relations among multisensory attention skills and social-communicative functioning are also evident in atypically developing children. In one study, 2- to 5-year-old children with a diagnosis of autism on the Autism Diagnostic Observation Schedule (ADOS) (Lord et al., 2002) received the MAAP along with multiple outcomes measures (Bahrick & Todd, 2012; Todd & Bahrick, in preparation). MAAP measures including attention maintenance, speed of disengagement, and intersensory matching predicted symptom severity (ADOS standard scores). These MAAP measures also predicted social functioning on several standard scales including the Social Responsiveness Scale (Constantino & Gruber, Charles, 2005), the Social Communication Questionnaire (Rutter, Bailey, & Lord, 2003), and ESCS (a measure of joint attention; Mundy et al., 2003). Analyses revealed that attention maintenance to social events mediates relations among other multisensory attention skills (accuracy of matching, speed of shifting) and language and social outcomes (Todd & Bahrick, in preparation). Greater accuracy and faster speed may cascade into enhanced social attention, which in turn leads to better language and social functioning. These novel findings demonstrate the viability of the MAAP as a potential predictor of ASD symptomology and social functioning in children at risk for atypical development.

Finally, in kindergarten children at risk for reading delays, individual differences in multisensory attention skills predict school readiness skills (preliteracy, self-regulation) that are central for academic success. Intersensory processing is a foundation for word mapping (Gogate & Bahrick, 1998; Gogate & Hollich, 2010), which in turn promotes preliteracy skills (letter name and sound mapping), and in turn, reading abilities (Whitehurst & Lonigan, 1998). Intersensory processing also requires attention control and filtering out irrelevant stimulation (e.g., asynchronous visual movement), skills that are also critical for behavioral self-regulation. We tested a sample of 66 Latino children from predominately low-income families (rising K and first graders) with a touchscreen tablet version of the IPEP along with tests of letter names and letter sounds (Oral Reading Fluency, ORF; Fuchs, Fuchs, & Hosp, 2001) and a measure of behavioral self-regulation (the Head, Toes, Knees, and Shoulders Task, HTKS; Ponitz, McClelland, Matthews, & Morrison, 2009). Accuracy of target selection predicted performance on tests of letter names and sounds on the ORF, even after controlling for chronological age (Bahrick et al., 2017) and greater performance predicted better self-regulation on the HTKS (McNew, Todd, Zambrana, Hart, & Bahrick, 2019). These exciting findings suggest that intersensory processing provides an important foundation for a developmental cascade leading to preliteracy skills, behavioral self-regulation, and potentially to academic success.

11.6 Atypical Development

11.6.1 Intersensory Processing in Autism and Implications for Policy

Children with ASD show early disturbances in intersensory processing (Bahrick & Todd, 2012; Falck-Ytter et al., 2018; Stevenson et al., 2014), but links between intersensory processing impairments and ASD are not yet well understood. Bahrick and Todd (2012) proposed that an intersensory processing disturbance was one critical basis for this worsening cascade of social and communicative impairments across development. Given that social events are highly demanding of multisensory attention skills (with rapidly changing, temporally coordinated faces, voices, and gestures), impairments in intersensory processing may lead to selective impairments in social attention, including reduced attentional salience of audiovisual speech (social orienting impairment; Dawson, Meltzoff, Osterling, Rinaldi, & Brown, 1998; also see Bahrick, 2010; Bahrick & Todd, 2012; Mundy & Burnette, 2005). These selective impairments in social attention would then lead to language and social functioning impairments. In our view, symptoms of autism worsen in part because small deficits in basic “building blocks” of attention and intersensory processing amplify across development, reduce attention maintenance to social events, and impact social and communication skills that rely on these foundations (Bahrick, 2010; Bahrick & Todd, 2012; Mundy & Burnette, 2005).

Consistent with this proposal, children with ASD, who show impairments in social and language functioning, also show impairments in intersensory processing (for reviews, see Bahrick & Todd, 2012; Hill et al., 2012; Stevenson et al., 2014). Compared to typically developing children, children with ASD show impairments in matching visual and auditory stimulation from speech, have an enlarged audiovisual temporal binding window for audiovisual speech, and perform poorly on speech-in-noise tasks (Bebko, Weiss, Demark, & Gomez, 2006; Foxe et al., 2013; Stevenson et al., 2014). Finally, findings from our lab demonstrate that accuracy of intersensory matching and speed of attention shifting predict attention to social events, which in turn predicts language and social impairments in children with ASD (Todd & Bahrick, in preparation). These findings are consistent with an early intersensory processing disturbance in children with ASD.

Impairments in intersensory processing have also been identified in other developmental disorders of attention. For example, children with dyslexia show impaired intersensory processing skills (Hairston, Burdette, Flowers, Wood, & Wallace, 2005; Wallace, 2009). Similarly, research from our lab described above demonstrates intersensory processing predicts knowledge of letter names and letter sounds in children who are at risk for reading delays.

Early disturbances of intersensory processing – especially of social events, which provide extraordinary amounts of intersensory redundancy across faces and voices – could induce a cascade leading to poor integration of faces and voices, piecemeal processing of multimodal events, and delayed social, cognitive, and language development (Bahrick, 2010; Bahrick & Todd, 2012; Stevenson et al., 2018). Identifying the potential cascades stemming from poor early intersensory processing requires fine-grained measures of individual differences in intersensory processing. Such measures are key to early detection of risk for delays and for guiding interventions.

Given the importance of multisensory attention skills for the typical development of higher-level skills, we propose that infants routinely be screened for multisensory processing and basic attention impairments, along with basic tests of unisensory auditory and visual functioning. It is also important to determine if delayed intersensory processing skills stem from impairments in unimodal sensory functioning (auditory or visual) or in the integration of auditory and visual information, or both. Once the typical developmental trajectories for measures indexed by the MAAP and IPEP are established (data collection in progress in our lab), the MAAP and IPEP can serve as a basis for screening for intersensory processing impairments. However, this will also require developing screener tests assessing the same auditory and visual information separately (e.g., dynamic faces, speaking voices) to rule out impairments in unisensory skills as a source of an intersensory impairment.

11.6.2 Preterm Birth and Implications for Policy

The significant modifications of sensory experience that come with preterm birth are likely to have a range of effects on the normal course of sensory and perceptual development (Lickliter, 2000, 2011). That being said, investigators are a long way from understanding the particulars. Given that auditory experience is typically available prenatally and that patterned visual experience is not normally available until after birth, is there some necessary period or level of auditory experience without competing visual experience needed in the period before birth to ensure the emergence of normal patterns of postnatal perception? Does the unusually early visual experience associated with preterm birth and the resulting dramatic increase in the intensity and amount of auditory and visual stimulation present in the neonatal intensive care unit (NICU) interfere with normal auditory or visual development? What kinds of sensory stimulation is the fetus, preterm infant, and full-term infant particularly sensitive to? These important questions remain mostly unanswered at present.

We do know that the full-term fetus experiences intersensory stimulation across the auditory, vestibular, and tactile senses during the third trimester of gestation. For example, when the mother walks, the sounds of her footsteps can be coordinated with tactile feedback as the fetus experiences changing pressure corresponding with the temporal patterning and shifting intensity of her movements, as well as the accompanying and coordinated vestibular changes. In addition, the mother's speech sounds, her laughter, heartbeat, or sounds of breathing may create tactile stimulation that shares the temporal patterning of her sounds as a result of changes in the musculature involved in producing the sounds. Interestingly, this may provide a foundation for fetal learning – in the third trimester of gestation, fetuses can discriminate auditory stimulation on the basis of temporal patterning such as prosody (e.g., DeCasper & Spence, 1991).

The conditions in the NICU, coupled with the limited motor skills of the preterm infant, minimize the preterm's exposure to temporally coordinated stimulation in two or more sensory modalities. In the full-term newborn, auditory stimulation typically elicits an orienting response; infants turn their eyes in the direction of the sound source. This allows the infant to unitize the audiovisual stimulation and perceive the visual characteristics of the audible event. In the NICU, however, sound sources are often not visible to the infant, even if the infant is able to turn toward them. Sounds (such as respiratory and monitoring equipment) typically occur independent of stimulation to other sensory modalities and provide little if any opportunity for the infant to match a particular sound with its visual and tactile referents. Similarly, the dramatically reduced tactile and vestibular stimulation available to the preterm infant limits the opportunities for synchronous tactile and auditory stimulation. The short-term and possible long-term consequences of these reduced opportunities for intersensory redundancy on the preterm infant's emerging patterns of selective attention, perceptual processing, and learning are presently unknown and merit further research attention.

We propose that a shift in research focus from the effects of modifications to individual sensory modalities in the NICU (e.g., reducing visual stimulation, increasing tactile stimulation) to a focus on how redundant multisensory experiences at particular times and stages of development influence the course of intersensory development is needed. Such a timeline could provide a road map to promoting optimal development in this high-risk population by contributing to progress in the design of care *and* intervention programs for infants born at different levels of prematurity.

11.7 Social Context, Culture, and Implications for Policy

As described above, early experiences, starting *in utero*, shape and promote the development of infant multisensory attention skills. Opportunities for further developing and enhancing multisensory attention skills abound through reciprocal, bidirectional interactions as the infant interacts with objects, events, and people. Active exploration of objects provides coordinated visual, auditory, and tactile feedback and promotes an understanding of object affordances (E. J. Gibson, 1988; Lockman & Kahrs, 2017) and the development of multisensory attention skills. And social interactions with responsive caregivers provide infants one of the richest sources of input for developing multisensory attention skills (Bahrick & Lickliter, 2012; Tamis-LeMonda et al., 2014). Caregivers engage in face-to-face communication with infants, generating multisensory and temporally coordinated speech, gesture, eye gaze, facial movement, and touch (Beebe et al., 2016; Feldman, 2007). They scaffold the development of selective attention and attention control and promote language development by creating infant–caregiver social feedback loops. Caregivers provide feedback contingent on infant vocalizations and gestures and coordinate verbal labels with synchronous showing and naming objects. In response, infant vocalizations increase in frequency and become more adult-like (Gogate & Hollich, 2010; Goldstein & Schwade, 2008; Tamis-LeMonda et al., 2014; Tamis-LeMonda, Kuchirko, & Tafuro, 2013; Warlaumont, Richards, Gilkerson, & Oller, 2014). Through contingent responsiveness, engaging in affective communication, and establishing emotional attunement, caregivers also promote a sense of competence in infants and foster the development of self-regulation skills. These interactions with significant caregivers provide the foundation for developmental cascades leading to language and social outcomes.

However, there are large differences across families in the quality and quantity of interactions. Research indicates that parents with greater education and income, in general, are more responsive (by providing prompt feedback contingent on infant actions), interact more, and provide higher-quality speech input (richness, complexity) than parents with lower education and income (Hart & Risley, 1995; Hirsh-Pasek et al., 2015; Rowe, 2018; Tamis-LeMonda et al., 2014). In fact, the powerful role of "parent language input" for promoting speech and vocabulary growth in infants and young children has recently been highlighted by automated measures of child-directed speech using language environment analysis (LENA) (e.g., Warlaumont et al., 2014; Weisleder & Fernald, 2013). This has catalyzed nationwide efforts for parents (particularly of low socioeconomic status, SES) to increase language to infants to offset the "30-million word gap" (Hart & Risley, 1995) and in turn, to enhance language, school readiness, literacy, and academic achievement (Leffel & Suskind, 2013; National Early Literacy Panel, 2008; Whitehurst & Lonigan, 1998).

We propose that along with "language input" (the quantity and quality of words spoken to the child), more emphasis should be placed on the amount and richness of *multisensory face-to-face interaction* in promoting optimal social, cognitive, and language outcomes (see Figure 11.3). Language in the context of face-to-face interaction with responsive caregivers should promote the development of multisensory attention skills, and in turn language growth and self-regulation skills across childhood (Tamis-LeMonda et al., 2014). Further, promoting object exploration, especially in the context of interaction with responsive caregivers, should likewise enhance multisensory attention skills and language growth. For example, scaffolding infant object exploration with coordinated gaze and contingent naming facilitates word mapping (Gogate & Hollich, 2010; Gogate et al., 2001). Thus, we suggest that optimal growth of multisensory attention skills will be fostered by (1) providing opportunities for infants to explore objects in their environment in the context of responsive caregiver interactions that support their natural curiosity; and (2) engaging in face-to-face interactions with responsive caregivers, which include bidirectional, coregulated interactions involving contingent responsiveness and affective communication. In line with developmental systems perspectives (e.g., Gogate et al., 2001; Goldstein & Schwade, 2008; Suanda, Smith, & Yu, 2016; Tamis-LeMonda et al., 2014), by actively engaging in these interactions involving coordinating attention to people and objects in multimodal, interactive settings, caregivers in effect train infant attention, and scaffold social feedback loops whereby infant responses generate the input needed (from both caregivers and the environment) for supporting language, social, and cognitive development.

11.8 Future Directions

The use of individual difference measures of multisensory attention skills promises to enhance our understanding of developmental processes and how they lead to optimal language, cognitive, and social outcomes. This will make research on multisensory processing and the resulting knowledge base more relevant to application for education and intervention. Several future research directions are needed to effect this change.

11.8.1 Developmental Cascades to Outcomes

We must clarify the developmental pathways through which these basic multisensory skills cascade to more complex language, cognitive, and social skills by assessing relations between individual differences in these skills, the role of multimodal social interaction with caregivers (quality and quantity of language input, contingent responsiveness, coordinated gaze and object exploration, etc.), and later outcomes. This will allow researchers to derive models depicting developmental cascades and establish which specific skills lead to specific developmental outcomes, and how these relations are moderated by the multimodal social environment. This can eventually provide a basis for appropriately targeting interventions to foundational skills.

11.8.2 Developmental Trajectories for Multisensory Attention Skills

The developmental trajectories of multisensory attention skills in typically developing children also need to be established. By characterizing the typical development of multisensory attention skills – matching synchronous sights and sounds of social or nonsocial events, quickly shifting to these events, and sustaining attention to these events in the face of distracting events – researchers will be able to identify infants and children whose skills fall outside the range of typical variability and are at risk for delays. The availability of the MAAP and IPEP allow testing of young infants as well older children using the same protocols, making it feasible to establish developmental trajectories using the same measures across ages.

11.8.3 Detecting Early Risk

In conjunction with models of developmental cascades, knowledge of typical developmental trajectories will allow researchers to determine which children are in need of intervention and which skills would be most effective for accelerating development for different outcomes. Assessing multisensory attention skills in early development will open the door to much earlier identification of risk for delays in attention skills and in the outcomes that rely on these skills than currently possible. Thus, early identification can provide opportunities for early intervention to optimize development.

11.8.4 Training Multisensory Attention Skills

Another future direction that will be needed to lay the groundwork for effective interventions is to establish successful protocols for training multisensory attention skills, including intersensory processing (synchrony detection), attention maintenance, and rapid shifting to audiovisual events. This will require exploring the effectiveness of training studies, monitoring progress on the skills in question, assessing generalization to events and contexts not trained, and assessing long-term effects of training.

11.8.5 Promoting Optimal Development

Finally, the availability of individual difference measures also makes possible a shift in the focus of developmental science from normative development versus atypical development – to one conceptualizing development along a continuum, from suboptimal to optimal (e.g., Karmiloff-Smith, 1998). This not only characterizes atypical development along a continuum with typical development, but also opens the door to a new focus on the study of optimal developmental outcomes. Given the importance of intersensory processing and attention regulation for school readiness, social competence, and academic success (Blair & Raver, 2012, 2015), it is imperative that developmental science focus research effort on how to maximize outcomes for typically developing children (alongside the focus on atypically developing children). Consistent with the recent emergence of the field of positive psychology and the discovery of its enormous benefits for health and well-being (e.g., Fredrickson, 2000; Seligman & Csikszentmihalyi, 2000; Slavich & Cole, 2012), the use of individual difference measures provides tools for developmental scientists to study factors and processes that support children – not just performing at level – but thriving. This calls for developmental scientists to focus on factors that support optimal language, social, and cognitive outcomes – outcomes that will promote overall well-being and a sense of competence in children.

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