Bahrick, L. E. (2010). Intermodal perception and selective attention to intersensory redundancy: Implications for typical social development and autism. In G. Bremner & T. D. Wachs (Eds.). Blackwell handbook of infant development: 2nd ed. (pp. 120-166), Blackwell Publishing: Oxford, England.

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Intermodal Perception and Selective Attention to Intersensory Redundancy: Implications for Typical Social Development and Autism

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Introduction

The world of objects and events floods our senses with continuously changing multimodal stimulation, but we can attend to only a small portion of this stimulation at any time. The organization of our senses plays a fundamental role in guiding and constraining what we attend to, perceive, learn, and remember from this flux of multimodal stimulation. A fundamental challenge for the infant is to develop economical skills of attentional shifting that maximize the pick-up of relevant information, coherent across time and space, and minimize the pick-up of information that is irrelevant and incoherent across time and space (E. J. Gibson, 1969). It is critical that we process multimodal stimulation from single, unitary events and follow their flow of action. For example, we must selectively attend to a single person speaking and follow the flow of dialogue, rather than attending to disconnected streams of auditory and visual stimulation from unrelated but concurrent events. How do we accomplish these challenging tasks?

In this chapter, I review what is known about how these skills emerge and develop across infancy. I argue that the overlap across unique forms of stimulation from the different senses plays a powerful role in this developmental process. This overlap provides "amodal" redundant information (such as temporal synchrony, rhythm, or intensity, common across more than one sense modality) which guides and constrains what we attend to, perceive, learn, and remember, particularly in early development when attentional resources are most limited. Detection of amodal information effectively simplifies and organizes incoming sensory stimulation and provides a basis for perceiving unitary objects and events rather than the "blooming, buzzing, confusion" postulated long ago by William James (1890, Vol. 2, p. 488).

Most perception is "intermodal" (also referred to as intersensory or multimodal) and includes perception of social and nonsocial events, the self, and stimulation from all the senses and their combinations. In order to reduce the scope of this chapter, I focused on some topics at the expense of others. I include primarily the development of auditory-visual perception (a topic of much infant research) at the expense of tactile, gustatory, and olfactory perception. I also focus on the development of intermodal perception of the self and social events, at the expense of nonsocial events, because the self in interaction with the social world provides a foundation for the majority of infant learning (see Bahrick, 2004; Kellman & Arterberry, 1998; Lewkowicz & Lickliter, 1994, for additional reviews of intermodal perception). Since research has demonstrated that even areas previously considered "unimodal", such as face discrimination, are profoundly influenced by intersensory redundancy from multimodal stimulation, this chapter has a somewhat different emphasis and scope from prior reviews of this topic. Here, I examine the effects of intersensory redundancy on the development of perception and learning about all types of event properties, both amodal and modality-specific.

Three important themes that call for the integration of research and theory across traditionally separate areas are emphasized throughout this chapter. The first highlights the need for conducting and integrating research on the nature of selective attention into developmental accounts of perception, learning, and memory. Attention provides the input for all that is perceived, learned, and remembered and these processes are inextricably interconnected, forming a system of reciprocal influences. The second theme calls for enhancing ecological validity of developmental research by integrating studies of unimodal functioning (e.g., auditory perception, visual perception) with studies of multimodal functioning (e.g., audiovisual perception). The modalities are typically studied separately yet exploratory behavior typically results in stimulation to multiple sense modalities and gives rise to important interactions not observable through studying one sense alone. Finally, the third theme emphasizes the need for cross-fertilization between basic research on typical and atypical development, particularly disorders of development such as autism. Typical and atypical development are generally studied separately, yet considerable insight into typical development can be gained though understanding how developmental processes go awry, and conversely, identifying atypical patterns of development hinges on clearly articulating the course of typical development. The present chapter provides a starting point for integration along these three critical dimensions.

Selective Attention: The Underappreciated Foundation for Perception, Learning and Memory in a Dynamic, Multimodal Environment

The natural environment provides a flux of changing, concurrent stimulation to all our senses, far more than can be attended to at any given time. However, adults are exquisitely skilled at selectively attending to unitary multimodal events, picking out information that is relevant to their needs, goals, and interests, and ignoring irrelevant stimulation from this vast array. For example, we easily pick out a friend in a crowd, follow the flow of action in a ball game, and attend to the voice of the speaker at a cocktail party in the context of competing conversations. Moreover, we long ago learned to pick out figure from ground, signal from noise, human speech from nonspeech sounds, parse continuous speech into meaningful units such as syllables and words, and ignore variations across speakers, accents, and differing intonations to identify words. Similarly, we learned to parse the visual array into coherent objects and surfaces despite variation due to lighting and shadow, and interruption of surfaces due to occlusion. These remarkable skills, easily taken for granted by experienced perceivers, develop rapidly across infancy through experience interacting with objects and events. They entail systematic changes in selective attention across time – increasing attention and economy of information pick-up for relevant aspects of the environment, honing in on useful and economical levels of analysis, and attending to meaningful variability while ignoring meaningless variability (E. J. Gibson, 1969, 1988; E. J. Gibson & Pick, 2000; Ruff & Rothbart, 1996). A great deal of research and theory has been devoted to accounts of how perception and learning develop. In contrast, little research effort has focused on the processes that guide selective attention to relevant aspects and levels of stimulation in the first place. This process itself is the result of much learning and at the same time, it provides the basis for further learning and exploratory activity. Figure 4.1 depicts the central role of selective attention in relation to processes of perception, learning, and memory.

Selective attention can be considered the gateway to information pick-up and processing (e.g., Broadbent, 1962; Neisser, 1976; Triesman, 1964). As depicted in Figure 4.1, selective attention to stimulation generated from our exploratory activity provides the basis for all that is perceived, learned, and remembered. In turn, what is perceived, learned, and remembered, influences what is attended to next, in continuous cycles of attention → perception → learning → memory → attention, and so forth. Moreover, action is tightly coupled with these processes, as exploratory activity constantly provides new stimulation for attention, perception, learning, and memory (Adolph & Berger, 2005, 2006; E. J. Gibson, 1988; E. J. Gibson & Pick, 2000; Thelen, 1995; Von Hofsten 1983, 1993). Attention entails exploratory behavior such as orienting, eye movements, and active interaction with the environment (e.g., reaching, head turning) and these ongoing behaviors in turn provide continuous and contingent feedback to multiple senses. This cycle may be characterized as a system of dynamic, interactive influences that evolve over time (see Adolph & Berger, 2006; E. J. Gibson, 1988; Thelen & Smith, 1994, for a discussion of such systems). Figure 4.1 depicts the integral role of attention in two interrelated feedback loops. One loop highlights the role of attention in the processes of perception, learning, and memory, and their reciprocal interactions. The other, highlights the role of attention in perception-action cycles, and the reciprocal interactions among these processes. Selective attention (honed and shaped by learning and memory) operates on stimulation from action, and determines what we perceive versus ignore, and in turn the nature of our next exploratory activities.

Across infancy, we develop and establish patterns for selectively attending to aspects of our environment. These patterns become increasingly more efficient with experience

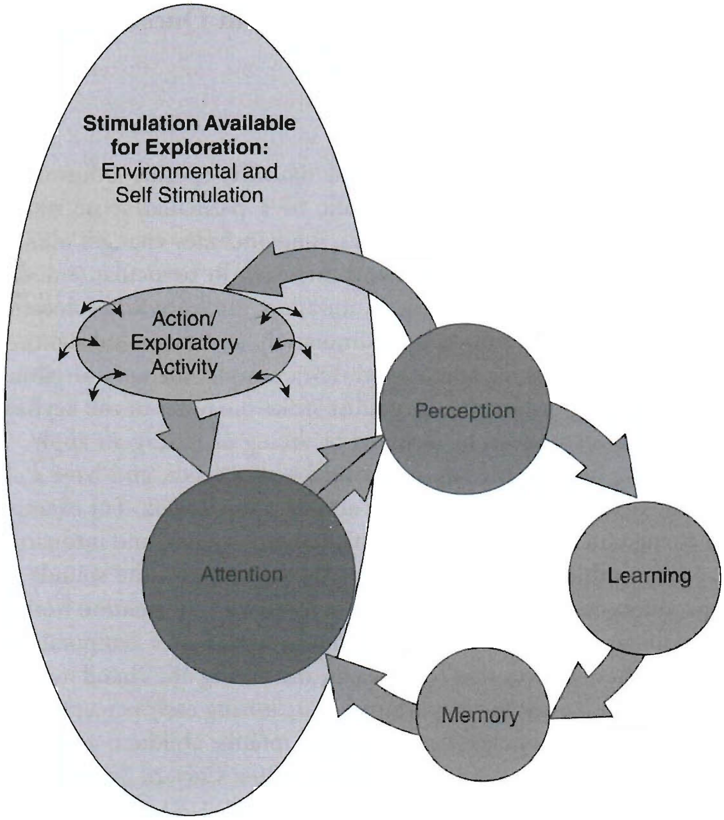

Figure 4.1 The integral role of attention in the development of perception, learning, and memory is depicted through two interrelated, concurrent, feedback loops, (a) the attention → perception → learning → memory system, and (b) the attention → perception → action system. The arrows represent the primary direction of the flow of information. Selective attention to stimulation that results from our exploratory activity provides the basis for what is perceived, what is perceived provides the basis for what is learned, and in turn what is remembered. This in turn affects what we attend to next and in subsequent encounters with similar stimulation. Perception is also tightly coupled with action via selective attention to the stimulation generated from exploratory activity in a continuous feedback loop.

and evolve into the expert patterns of adult selective attention. What rules govern this process and how does such uniformity evolve across individuals in the way adults attend to people, faces, voices, objects, and events? Little scientific effort has been devoted to the study of attentional selectivity in infancy (see Ruff & Rothbart, 1996 for a review) despite its obvious importance for providing the input for cognitive, social, perceptual, and linguistic development. In the remainder of this chapter, I address this gap by considering the fundamental role of selective attention in the development of perception and learning about multimodal events.

Intermodal Perception: Definitions, Issues, and Questions

Amodal versus modality-specific information

Objects and events provide both amodal and modality-specific information. Amodal information is information that is not specific to a particular sense modality, but is common or redundant across multiple senses. This includes changes along three basic dimensions of stimulation – time, space, and intensity. In particular, amodal properties include temporal synchrony, rhythm, tempo, duration, intensity, and colocation common across auditory, visual, and proprioceptive stimulation, and shape, substance, and texture common across visual and tactile stimulation. For example, the same rhythm and tempo can be detected by seeing or hearing the pianist strike the notes of the keyboard, and the same size, shape, and texture can be detected by seeing or feeling an apple.

Since events occur across time, are distributed across space, and have a characteristic intensity pattern, virtually all events provide amodal information. For example, speech is comprised of changes in audiovisual synchrony, tempo, rhythm, and intonation (intensity changes) that are common to the movements of the face and the sounds of the voice. Self-motion produces continuous proprioceptive feedback (information from the muscles, joints, and vestibular system) that is synchronous and shares temporal and intensity changes with the sight of self-motion (e.g., seeing and feeling one's hand move). Perception of amodal information is critically important for organizing early perceptual development and for accurate perception of everyday events, for infants, children, and adults alike (see Bahrick & Lickliter, 2002; Lewkowicz & Lickliter, 1994; Calvert, Spence, & Stein, 2004, for reviews).

All events also make modality-specific information available. Modality-specific information is information that can be specified through only one sense modality. For example, color and visual pattern can be detected only through vision, pitch and timbre can be detected only though audition, and temperature can be detected only through touch. Most events that can be seen and heard typically provide information that is specific to vision and audition. For example, perception of modality-specific information allows us to differentiate between the faces and between the voices of different individuals of the same gender, between sounds of a guitar versus a harp, between letters of the alphabet, and between a ripe versus a green apple.

Selecting relevant, cohesive, multimodal events

Because we can attend to only a small portion of the available stimulation at a time, the infant faces a significant developmental challenge: to become increasingly economical and efficient at selecting multimodal stimulation that is unitary (coherent across the senses and originating from a single event) and relevant to their needs and actions, while ignoring stimulation that is less relevant and discordant with the focus of their attention.

All events, whether enjoying a family dinner, watching television, or playing basketball, provide a continuously changing array of both modality-specific and amodal information across time. They also provide variations in incoming stimulation that are meaningful and relevant (e.g., speech sounds, goal-directed human actions) and other variations that are relatively meaningless and must be ignored or categorized as similar (differences in lighting and shadow across cohesive objects, changes in retinal size of objects across observer or object movement, variations in accent, speaker voice, or intonation across the same phoneme). What determines which information is selected and attended to and which information is ignored? In early development, it is thought, selective attention is more stimulus-driven and with experience attention becomes increasingly endogenous and modulated by top-down processes such as prior goals, plans, and expectations (see Colombo, 2001; Haith, 1980; Johnson, Posner, & Rothbart, 1991; Ruff & Rothbart, 1996, for reviews). Thus, for experienced perceivers, prior knowledge, categories, goals, plans, and expectations guide information pick-up (Bartlett, 1932; Chase & Simon, 1973; Neisser, 1976; Schank & Ableson, 1977). What we learn, know, and expect influences where we look and, in turn, what information we pick-up in present and future encounters. What guides this learning process in infants who have little prior knowledge to rely on, such that perception becomes rapidly organized and aligned with adult categories?

One important skill that fosters perception of unitary multimodal events is the infant's early coordination and calibration of audiovisual space. Typically, there is visual information about an event at the locus of its sound, such as a person speaking or an object falling and breaking. Even newborns turn their head and eyes in the direction of a sound, promoting the early coordination of audiovisual space and providing a basis for further processing of unitary multimodal events (Muir & Clifton, 1985; Wertheimer, 1961). Over time, the perception of audiovisual space is further calibrated and refined. However, in the typical environment, there are many objects and events in one's field of view and sound localization is not precise enough to specify which of many visible objects goes with the sound one is hearing. What guides this process so that attention is efficiently and reliably directed to the source of a sound and can then follow the flow of action?

Consistent with J. J. Gibson's (1966, 1979) ecological view of perception, research has revealed that detection of amodal information such as temporal synchrony, rhythm, tempo, and intensity is a cornerstone of this developmental process (see Bahrick, 2004; Bahrick & Lickliter, 2002 for reviews). J. J. Gibson proposed that the different forms of stimulation from the senses were not a problem for perception, but rather provided an important basis for perceiving unitary objects and events. Our senses, he proposed, work together as a unified perceptual system. They pick up "amodal" information that is "invariant" or common across the senses. By attending to and perceiving amodal information, there was no need to learn to integrate stimulation across the senses in order to perceive unified objects and events, as proposed by constructivist accounts of development (e.g., Piaget, 1952, 1954). Perceiving amodal relations ensures that we attend to unified multimodal events. Temporal synchrony, the most global type of amodal information, has been described as the "glue" that binds stimulation across the senses (see Bahrick & Pickens, 1994; Bahrick & Lickliter, 2002; Lewkowicz, 2000). For example, by attending to audiovisual synchrony, the sounds and sights of a single person speaking would be perceived together, as a unified event. Detecting this information prevents the accidental association of unrelated but concurrent sensory stimulation, such as a nearby conversation. The "ventriloquism effect" (Alais & Burr, 2004; Radeau & Bertelson, 1977; Warren, Welch, & McCarthy, 1981) illustrates the powerful role of this amodal information in guiding attention and perception. The ventriloquist moves the dummy's mouth and body in synchrony with his own speech sounds, thus, he creates the illusion that the dummy is speaking, despite the fact that the sound emanates from a slightly different location. Amodal information such as temporal synchrony, rhythm, tempo, and intensity changes common across the visual and acoustic stimulation promote the perception of a unitary event, the dummy speaking, and override information about the location of the sound. Infants show this effect even in the first months of life (Morrongiello, Fenwick, & Nutley, 1998). Once attention is focused on the "unitary" audiovisual event, further differentiation of the unitary event is promoted. In this way, detection of amodal information such as audiovisual synchrony then guides and constrains further information pick-up.

Increasing specificity in the development of intersensory perception: Synchrony as the gatekeeper for intermodal processing

Objects and events can be characterized as having nested or hierarchically organized properties, with global amodal information (such as temporal synchrony and collocation), nested levels of amodal structure, and more specific, "modality specific" information (E. J. Gibson, 1969). According to E. J. Gibson's theory of perceptual development, based on J. J. Gibson's ecological theory of perception, differentiation of perceptual information proceeds in order of increasing specificity. Research has demonstrated that the domain of intersensory perception is no exception. Detection of amodal relations proceeds in order of increasing specificity with infants first differentiating synchrony between an object's motions and its sounds, and later detecting more specific, embedded temporal information ("temporal microstructure") such as that specifying the object's composition or substance (Bahrick, 2000, 2001, 2004; E. J. Gibson, 1969). Further, there is a developmental lag between detecting amodal and modality-specific information in the same events (Bahrick, 1992, 1994, 2004). This lag is adaptive since knowledge of amodal relations can be meaningfully generalized across events and contexts, can constrain perception of modality-specific information, and can provide a framework for organizing more specific details. For example, when objects striking a surface are presented in synchrony with their impact sounds, synchrony promotes rapid differentiation of sound–sight relations and differentiation progresses to the specific nature of the sound, the specific appearance of the object, and the relation between them (Bahrick, 1988, 1992; Bahrick, Hernandez-Reif, & Flom, 2005). In contrast, after experiencing asynchronous impact sounds along with objects striking a surface, infants show no evidence of differentiating the sound, the appearance of the object, or learning the relations between them (Bahrick, 1988). Similarly, in the domain of speech, infants who are too young to understand that speech sounds refer to objects, detect the arbitrary relation between a verbal label and the object to which it refers when there is temporal synchrony between naming and showing the object, but not when the object is static or moved out of synchrony with naming (Gogate & Bahrick, 1998). Thus, in early development, synchrony functions as a "gatekeeper" for further processing of unitary events (see Bahrick & Lickliter, 2002; Lewkowicz, 2000; 2002). That amodal properties of multimodal stimulation are salient and detected developmentally prior to other properties is critically important for optimal perceptual development (Bahrick, 2000, 2001; Bahrick & Lickliter, 2002, Bahrick & Pickens, 1994). Sensitivity to amodal properties promotes attention to unified multimodal events in the presence of competing stimulation from other sounds and motions, and guides subsequent knowledge acquisition by allowing general perceptual information to precede and constrain the acquisition of details. What makes this important type of information so salient to infants?

Intersensory redundancy

When the same amodal information occurs together, and in synchrony across the senses, this is called "intersensory redundancy" (Bahrick & Lickliter, 2000). The argument developed here is that intersensory redundancy makes amodal information stand out with respect to other types of stimulation. "Intersensory redundancy" is provided by an event when the same amodal information (rhythm, tempo, intensity changes) is simultaneously available and temporally synchronized across two or more sense modalities. For example, when the same rhythm and tempo of speech can be perceived by looking and by listening, the rhythm and tempo are said to be redundantly specified (as illustrated by a typical speaker, or artificially created by a ventriloquist). Intersensory redundancy is highly salient to both human and animal infants (Lickliter & Bahrick, 2000, 2004). Its salience also appears to have a neural basis (see Calvert et al., 2004, for a review). It promotes heightened neural responsiveness as compared with the same information in each modality alone (Stein & Meredith, 1993) and promotes attention to and perceptual processing of the event and its redundant properties. Most naturalistic, multimodal events provide intersensory redundancy for multiple properties (e.g., tempo, rhythm, duration, intensity). By definition, only amodal properties (rather than modality-specific properties) can be redundantly specified across the senses. Typically, a given event (such as a person speaking) also provides nonredundant, modality-specific information such as the appearance of the face and clothes, and the specific quality of the voice.

What guides selective attention to these various properties of events? Research indicates that redundancy across the senses promotes attention to redundantly specified properties at the expense of other (nonredundantly specified) properties, particularly in early development, when attentional resources are most limited (e.g., Bahrick & Lickliter, 2000, 2002). Later, attention extends to less salient nonredundantly specified properties. Factors such as the length of exploratory time, complexity, familiarity, and the level of expertise of the perceiver affect the speed of progression through this salience hierarchy. The intersensory redundancy hypothesis, a model of early selective attention, provides a framework for understanding how and under what conditions attention is allocated to amodal versus modality-specific aspects of stimulation in a world providing an overabundance of concurrent, dynamic multimodal stimulation, and how this guides perceptual development.

The Intersensory Redundancy Hypothesis (IRH)

Bahrick, Lickliter, and colleagues (Bahrick & Lickliter, 2000, 2002; Bahrick, Flom & Lickliter, 2002; Lickliter, Bahrick, & Honeycutt, 2002, 2004) proposed and provided empirical support for the Intersensory Redundancy Hypothesis (IRH). The IRH consists of a fundamental set of principles that are thought to guide information pick-up. It is a model of selective attention developed to explain under what conditions perceivers attend to and process different properties of events, redundantly specified versus nonredundantly specified. The IRH provides a framework to address the question of how infants with no knowledge of the world, learn to perceive unitary events and attend to stimulation that is relevant to their needs and actions. Moreover, because environmental stimulation far exceeds our attention capacity, particularly during early development, these principles of information pick-up should have a disproportionately large effect on perception in early development when attention is most limited. Although the IRH is primarily thought of as a framework for describing the early development of attention and intermodal perception, the principles also apply across development. The IRH also integrates into a single model, perception of unimodal and multimodal events, bridging the long-standing gap in the literature between these areas.

The IRH consists of four specific predictions. Two predictions address the nature of selective attention to different properties of events and are depicted in Figure 4.2. The remaining two are developmental predictions that address implications across the life

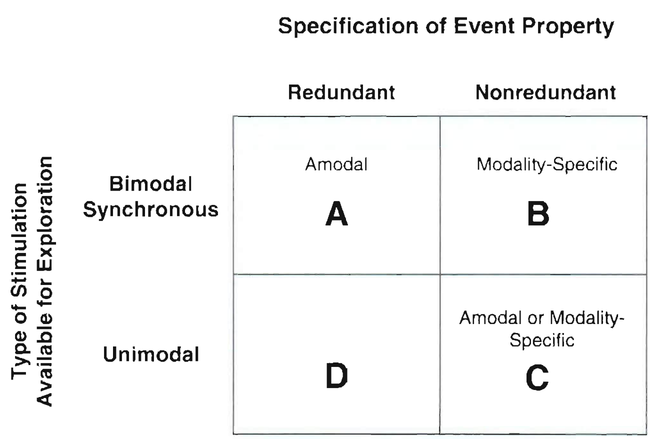

Figure 4.2 Facilitation versus attenuation of attention and perceptual processing for a given event property is a function of whether the property is redundantly versus nonredundantly specified and whether the type of stimulation available for exploration is bimodal, synchronous versus unimodal. Predictions of the IRH: Intermodal facilitation *of AM properties* (A > C): detection of a redundantly specified AM property in bimodal stimulation (A) is greater than when the same property is nonredundantly specified in unimodal stimulation (C); Unimodal facilitation *of MS properties* (C > B): detection of a nonredundantly specified MS property in unimodal stimulation (C) is greater than when the same property is nonredundantly specified in bimodal stimulation (B). Note: Quadrant D reflects *intra*sensory redundancy *not discussed here.*

span. These predictions have been supported by empirical studies with human and animal infants. Below I review the four predictions and the original research findings that support each.

Prediction 1: Intersensory facilitiation (A > C, figure 4.2)

> Redundantly specified, amodal properties are highly salient and detected more easily in bimodal synchronous, stimulation than the same amodal properties in unimodal stimulation (where they are not redundantly specified).

According to the IRH, intersensory redundancy (the synchronous alignment of stimulation from two or more senses), makes amodal properties of events such as tempo, rhythm, and intensity highly salient. Redundancy recruits infant attention to redundantly specified properties, causing them to become "foreground" and other properties to become "background". In fact, this redundancy is so salient that it allows young infants to selectively attend to one of two superimposed events while ignoring the other. When the soundtrack to one film, such as a person striking the keys of a toy xylophone, is played, 4-month-old infants can selectively follow the flow of action, even when it is superimposed with another film such as a hand-clapping game. The sound event appears to "pop out" and become attentional foreground while the silent event becomes background. Infants then treat the background event as novel in a novelty preference test (Bahrick, Walker, & Neisser, 1981). Detecting intersensory redundancy leads to early processing and learning about unitary events by focusing attention on properties that are specified in more than one sense modality concurrently. Research has demonstrated that intersensory redundancy promotes enhanced attention and perceptual processing in both human and nonhuman animal infants (Bahrick & Lickliter, 2000, 2002; Bahrick, Flom, et al., 2002; Lickliter & Bahrick, 2000; Lickliter et al., 2002, 2004).

For example, young infants detected the rhythm and tempo of a toy hammer tapping when they experienced the synchronous sights and sounds together (providing intersensory redundancy) but not when they experienced the rhythm or tempo in one sense modality alone or when the sights and sounds were out of synchrony (providing no intersensory redundancy) (Bahrick & Lickliter, 2000; Bahrick, Flom, et al., 2002). Research from other laboratories has also found support for this hypothesis. For example, 4-month-old infants detected the serial order of events in synchronous audiovisual but not unimodal auditory or unimodal visual stimulation (Lewkowicz, 2004). Seven-month-old infants detect numerical information in audiovisual sequences of faces and voices developmentally earlier than in auditory or visual sequences alone (Jordan, Suanda, & Brannon, 2008). Finally, this hypothesis has also received clear support from studies of nonhuman animal infants. Following redundant audiovisual prenatal stimulation (where synchronized lights and call were presented to embryos), quail chicks learned an individual maternal call four times faster and remembered it four times longer than when they had only heard the call alone, or when the call and light were presented out of synchrony (Lickliter et al., 2002, 2004).

Taken together these studies have shown that intersensory redundancy available in bimodal stimulation plays a critical role in organizing selective attention and, in turn, perception, learning, and memory. It facilitates attention to redundantly specified properties such as the rhythm, tempo, and temporal patterning of audible and visible stimulation, as compared with the same properties experienced in one sense modality alone. Moreover, the facilitation observed in bimodal synchronous but not bimodal asynchronous conditions (where the overall amount and type of stimulation are equated), rules out alternative hypotheses such as arousal or receiving stimulation in two different modalities as the basis for facilitation. Thus, it appears that the redundancy across the senses serves as a basis for heightened attention and processing of certain aspects of multimodal events.

Prediction 2: Unimodal facilitation (C > B, figure 4.2)

> Nonredundantly specified, modality-specific properties are more salient and detected more easily in unimodal stimulation than the same properties in bimodal, synchronous stimulation (where redundantly specified, amodal properties compete for attention).

In unimodal stimulation, where intersensory redundancy is not available, attention is selectively directed to nonredundantly specified properties such as color, pattern, pitch, or timbre, to a greater extent than in multimodal stimulation. This "unimodal facilitation" occurs in part because there is no competition for attention from salient intersensory redundancy. Particularly in early development, a given event typically provides significantly more stimulation than can be attended to at any one time, and thus redundantly and nonredundantly specified properties within the same event compete for attention. Because redundantly specified properties are more salient, they capture attention at the expense of modality-specific properties. For example, a young infant exploring a person speaking, might selectively attend to amodal properties such as the prosody of speech (composed of rhythm, tempo, and intensity patterns) at the expense of modality-specific properties such as the appearance of the person, color of their clothing, or specific nature of their voice. In contrast, when salient redundancy is unavailable, as when the person is silent, attention is free to focus on nonredundant, modality specific properties available in unimodal visual stimulation. Under these conditions we would observe unimodal facilitation and enhanced attention to the appearance of the individual. (This attentional tradeoff as a function of modality of stimulation will be elaborated further using social events as an example, in The Role of Intersensory Redundancy in Social Development below).

Consistent with this prediction, research has shown that, in early development, unimodal stimulation selectively recruits attention and promotes perceptual processing of nonredundantly specified, modality-specific properties more effectively than does redundant, audiovisual stimulation. Studies assessing infant discrimination of faces, voices, and the orientation of a toy hammer tapping (Bahrick et al., 2006; Bahrick, Lickliter, et al., 2005; Bahrick, Lickliter, Vaillant, Shuman, & Castellanos, 2004) have demonstrated that young infants discriminate these properties in unimodal visual and unimodal auditory stimulation, but not in synchronous audiovisual stimulation. For example, Bahrick et al. (2006) found that 3- and 5-month-olds discriminated a change in the orientation of a toy hammer tapping (upward against a ceiling vs. downward against a floor) when they could see the hammer tapping (unimodal visual stimulation) but not when they could see and hear the natural synchronous audiovisual stimulation from the hammer. This latter condition provided intersensory redundancy which presumably attracted attention to redundantly specified properties such as rhythm and tempo and interfered with attention to visual information such as the direction of motion or orientation of the hammer. Further, research has also shown that infants' failure to discriminate in the redundant, bimodal condition was due to competition from salient redundant properties and not to other factors such as bimodal stimulation providing a greater amount of stimulation or being more distracting than unimodal stimulation. We tested the possibility that these factors, rather than intersensory redundancy per se, drew the infant's attention away from the visual information, attenuating detection of orientation. To address this issue, an asynchronous control condition was presented which eliminated intersensory redundancy but equated overall amount and type of stimulation with the bimodal synchronous condition. Instead of impairing perception of orientation, this bimodal but asynchronous condition *enhanced* infant perception of orientation of the hammer tapping as compared with the bimodal, synchronous condition. Consistent with predictions of the IRH, asynchronous sights and sounds resulted in heightened discrimination on a par with that of the unimodal, visual condition. Thus, unimodal facilitation occurs when salient intersensory redundancy is eliminated and attention is free to focus on information conveyed by a single sense modality at a time.

Predictions 1 and 2 integrated: Attentional biases and salience hierarchies as mechanisms of developmental change

In sum, these findings reveal an attentional trade-off in early development such that in multimodal stimulation, amodal properties are more salient and modality-specific properties less salient, whereas in unimodal stimulation, modality specific properties are more salient and amodal properties less salient. Together, studies of intersensory and unimodal facilitation using the same toy hammer events (Bahrick & Lickliter, 2000; Bahrick, Flom, et al., 2002) indicate that synchronous, bimodal stimulation attenuates attention to modality-specific properties of events because salient redundancy directs attention elsewhere – to amodal, redundantly specified properties such as rhythm and tempo. Multimodal stimulation appears to impair attention to modality-specific and nonredundantly specified properties (such as orientation, pitch, timbre, color, pattern, and facial configuration) when it is synchronous and provides intersensory redundancy (as in most natural stimulation). In fact, synchronous, bimodal stimulation appears to be "unitized" (perceived as one event) by infants (e.g., Spear, Kraemer, Molina, & Smoller, 1988). This unitization simplifies the event and effectively reduces the overall amount of stimulation experienced, as infants are adept at detecting organization and pattern in stimulation.

It should be noted that testing predictions 1 and 2 of the IRH (intermodal versus unimodal facilitation) entails comparing detection of a given property of an event under conditions of redundant stimulation (bimodal, synchronous) versus conditions of nonredundant stimulation (unimodal or asynchronous). Tests of these predictions have typically not involved comparing detection of one property (e.g., amodal) versus another (e.g., modality specific), a comparison with inherent task difficulty confounds. Instead, by focusing on detection of a particular property of an event (e.g., tempo) in one modality versus another, we can hold constant the nature of the information to be detected, and can then generalize findings appropriately to the particular modalities tested (e.g., audio-visual vs unimodal visual).

Because most events are multimodal, and intersensory redundancy is highly salient to infants, on balance there is a general processing advantage for amodal over modality-specific properties in early development. This is adaptive and ensures coordinated perception by allowing infants to process visual, auditory, and tactile stimulation from unitary events. This provides a viable explanation for the "developmental lag" described above and promotes development in order of increasing specificity. Moreover, it may have a cascading effect on cognition, language, and social development, which emerge from multimodal learning contexts, by establishing initial conditions that favor processing of amodal information from unitary, multimodal events (Bahrick & Lickliter, 2002; Gogate & Bahrick, 1998; Lickliter & Bahrick, 2000).

Furthermore, the general processing advantage for amodal over modality-specific information exerts a greater influence on early development than later development for another important reason. Salience hierarchies have the greatest impact when resources are most limited, as is the case in early development. We (Bahrick, Gogate, & Ruiz, 2002; Bahrick & Lickliter, 2002; Bahrick, Lickliter, Castellanos and Vaillant-Molina, in press; Bahrick & Newell, 2008) have proposed that properties of objects and events are processed in order of attentional salience, with properties that are most salient attracting attention initially, and as exploration continues attention is then allocated to less salient properties as well. Thus, during longer bouts of exploration and with faster processing of information, the likelihood of processing the less salient modality-specific information along with the more salient amodal information increases. However, on average (across episodes of exploration), the more salient aspects of objects and events receive substantially greater attention and processing than less salient aspects. Effects of salience hierarchies are most pronounced in early development when attentional resources are most limited. In this case only the most salient aspects of stimulation are likely to be processed. For example, a given bout of exploratory activity may terminate before attention can shift to less salient aspects. In contrast, when greater attentional resources are available, processing of both the less salient and more salient aspects is promoted. For this reason, salience hierarchies should have a much greater impact on attention and processing in early development than later development. They should also exert a greater influence when tasks are difficult or attentional capacities of perceivers are taxed, for example, under conditions of high attentional and cognitive load (see Bahrick et al., 2010 for discussion). Predictions 3 and 4 build upon this logic.

Prediction 3: Developmental improvement in attention: Attenuation of facilitation effects

> Across development, infants' increasing perceptual differentiation, efficiency of processing, and flexibility of attention lead to detection of both redundantly and nonredundantly specified properties in unimodal, nonredundant and bimodal, redundant stimulation.

The IRH thus provides a basis for describing developmental change in attention and perceptual processing. Salience hierarchies exert the greatest effect on perceptual development during early infancy. As infants become older and more experienced, processing speed increases, perceptual differentiation progresses, and attention becomes more efficient and flexible (see E. J. Gibson, 1969, 1988; Ruff & Rothbart, 1996). Infants habituate more quickly to stimuli, show shorter looks, more shifting between targets, and can discriminate the same changes in objects and events with shorter processing times (e.g., Colombo, 2001, 2002; Colombo & Mitchell, 1990, 2009; Colombo, Mitchell, Coldren & Freeseman, 1991; Frick, Colombo, & Saxon, 1999; Hale, 1990; Hunter & Ames, 1988; Rose, Feldman, & Jankowski, 2001). These changes, along with experience differentiating amodal and modality-specific properties in the environment, allow infants to detect both redundantly and nonredundantly specified properties in unimodal and bimodal stimulation. As perceptual learning improves, greater attentional resources are available for detecting information from multiple levels of the salience hierarchy. Attention progresses from the most salient to increasingly less salient properties across exploratory time. Improved economy of information pick-up and increased familiarity with events and their structure through experience, frees attentional resources for processing information not detected earlier when attention was less economical and cognitive load was higher.

For example, infants show developmental shifts from detection of global to local (more detailed) information (Frick, Colombo, & Allen, 2000), from detection of actions and information about object function to more specific information about the appearance of objects (Bahrick, Gogate, et al., 2002; Bahrick & Newell, 2008; Oakes & Madole, in press; Xu, Carey, & Quint, 2004), and from detection of global, amodal audiovisual relations to more specific amodal audiovisual relations across exploration time and across development (Bahrick, 1992, 1994, 2001; Morrongiello, Fenwick, & Nutley, 1998). These examples characterize progressions in order of attentional salience both across development and during a given sustained period of exploration within a single point in development. These developmental progressions also illustrate the principle of increasing specificity proposed by E. J. Gibson (1969) as a cornerstone of perceptual development. Differentiation of information is thought to progress from abstract and global, to increasingly more specific levels of stimulation across development.

Studies testing predictions of the IRH reveal findings consistent with the developmental improvements described above. Research demonstrates that with only a few months additional experience, infants viewing the toy hammer events used in the prior studies detect both redundantly specified properties such as rhythm and tempo (Bahrick, Lickliter & Flom, 2006), and nonredundantly specified properties such as orientation (Bahrick & Lickliter, 2004) in both unimodal visual and bimodal synchronous stimulation. Thus, patterns of facilitation (described by Predictions 1 and 2 of the IRH) that were apparent in early development became less apparent in later development as infants gained experience with objects and events in their environment.

Moreover, research indicates that one avenue for developmental improvement is "education of attention" (see E. J. Gibson, 1969; Zukow-Goldring, 1997 for discussions of this concept). Multimodal stimulation elicits selective attention to amodal properties of stimulation at the expense of other properties. By focusing on amodal properties in multimodal stimulation, we can "educate" attention to those same properties in subsequent unimodal stimulation, much like transfer of training effects. Comparative studies of bobwhite quail chicks illustrate this process. Lickliter, Bahrick, & Markham (2006) found that prenatal redundant audiovisual exposure to a maternal call followed by unimodal auditory exposure (bimodal → unimodal) resulted in a significant preference for the familiar auditory maternal call 2 days after hatching, whereas the reverse sequence did not (unimodal → bimodal). Intersensory redundancy (in bimodal stimulation) apparently highlighted the temporal features of the call and then "educated attention" to these features, generalizing to the subsequent unimodal stimulation. This conclusion was also supported by additional control conditions showing that asynchronous followed by unimodal stimulation and unimodal-only stimulation were also insufficient to lead to a preference for the familiar call 2 days later. Remarkably, education of attention to amodal temporal properties was effective even after delays of 2 or 4 hours between initial bimodal stimulation and subsequent unimodal stimulation. Recent studies of human infants assessing their sensitivity to the tempo of action in the toy hammer events using combinations of redundant audiovisual, asynchronous audiovisual, and unimodal visual presentations, showed parallel findings (Castellanos, Vaillant-Molina, Lickliter, & Bahrick, 2006). Thus, education of attention appears to be a viable potential mechanism for developmental change in human infants.

Do the patterns of unimodal and intermodal facilitation of attention disappear across age as infants become more skilled perceivers? The answer depends on the nature of the task, and in particular its difficulty in relation to the skills of the perceiver. Patterns of intersensory and unimodal facilitation do become less evident across development as discrimination capabilities improve and the events presented become more familiar and relatively simple to perceive. However, attentional facilitation may depend on relative task difficulty. The simple discrimination tasks used with younger infants would not sufficiently challenge older infants and thus their performance may be at ceiling. The logic underlying the IRH suggests that if measures of discrimination were more sensitive or tasks were made sufficiently difficult to challenge older perceivers, intersensory and unimodal facilitation predicted by the IRH should be apparent across the life span. Thus, patterns of facilitation described by the IRH should not disappear across age. Rather, they should simply become less evident as perceiving the world of objects and events becomes easier with experience. Prediction 4, below, describes the rationale and conditions under which intersensory and unimodal facilitation should be most evident in later development.

Prediction 4: Facilitation across development: Task difficulty and expertise

> Intersensory and unimodal facilitation are most pronounced for tasks of relatively high difficulty in relation to the expertise of the perceiver, and are thus apparent across the lifespan.

Attentional salience is thought to lead to longer, deeper processing and greater perceptual differentiation of events and their salient properties (Adler & Rovee-Collier, 1994; Craik & Lockhart, 1972; E. J. Gibson, 1969). Continued exposure to an event promotes perceptual differentiation, likely in order of salience, such that more salient properties are differentiated first and differentiation of less salient properties requires longer processing time. Further, perceptual differentiation of event properties may, in turn, enhance efficiency and flexibility of attention by fostering more rapid detection of previously differentiated properties in subsequent encounters and more flexible attentional shifting among familiar properties (see Ruff & Rothbart, 1996). Thus, the degree of intersensory and/or unimodal facilitation observed should be, in part, a function of familiarity and task difficulty in relation to the expertise of the perceiver. In early development, perceivers are relatively naïve and events are relatively novel, and therefore perceptual processing of most events is likely rather difficult and effortful, entailing a higher cognitive load. Thus, effects of intersensory redundancy should be most pronounced in early development. However, because perceptual learning and differentiation progress throughout the lifespan, effects of intersensory facilitation should also be evident in later development, as well. Perceivers continue to develop expertise through interaction with new information or by learning to perceive finer distinctions in familiar stimuli. For example, children and adults may learn a new language, learn to play a musical instrument, or become skilled at identifying birds. Under these conditions, in early stages of learning, expertise is low in relation to task demands. Therefore, older perceivers should experience intersensory and unimodal facilitation when learning new material.

Research findings are consistent with this view. Studies in a variety of domains including motor and cognitive development, indicate that under conditions of higher cognitive load, performance of infants and children reverts to that of earlier stages of development (Adolph & Berger, 2005; Berger, 2004; Corbetta & Bojczyk, 2002). Research generated from predictions of the IRH has also directly tested this hypothesis. By the age of 5 months, infants no longer showed intersensory facilitation for discrimination of simple tempo changes, as their performance was at ceiling in both the unimodal and bimodal audiovisual conditions (Bahrick & Lickliter, 2004). However, by increasing task difficulty, we reinstated intersensory facilitation in 5-month-olds. They showed intersensory facilitation in the more difficult tempo discrimination task, comparable to that shown by 3-month-olds in a simpler version of the task (Bahrick et al., in press). Data collection with adults is currently in progress and findings thus far indicate intersensory facilitation (Bahrick et al., 2009). If findings of intersensory and unimodal facilitation hold up across studies of adults, the IRH will provide a useful framework for understanding the nature of selective attention and perceptual processing of various properties of events across development. This will have important applications, particularly when children or adults are attending to new or difficult information or when cognitive load is high.

Significance and broader implications of the IRH for development

The IRH provides a model of selective attention addressing how attention is allocated in early development to dimensions of stimulation that are fundamental for promoting veridical perception of objects and events. Because selective attention provides the basis for what is perceived, learned, and remembered, patterns of early selectivity can have longterm, organizing effects on the development of knowledge across the lifespan. Together, current findings indicate that (a) attentional trade-offs such that amodal properties are more likely to be detected in multimodal stimulation and modality-specific properties in unimodal stimulation, (b) these processing biases lead to general salience hierarchies in attentional allocation, (c) salience hierarchies exert a disproportionately large effect on early development when attentional resources are most limited and cognitive load is highest, and (d) they also exert some influence on later development when cognitive load and task difficulty are high.

Given that initial conditions have a disproportionately large effect on development, particularly because they can constrain what is learned next (Smith & Thelen, 2003; Thelen & Smith, 1994), these principles of early attention have a profound impact on the emergence of typical perceptual, cognitive, and social development. However, there has been little research on the development of selective attention in infancy (see Ruff & Rothbart, 1996) and no prior model that integrates attention to unimodal and multimodal stimulation. Given that environmental stimulation is primarily experienced multimodally, this focus is critical for making research and theory more ecologically relevant (see Lickliter & Bahrick, 2001). The IRH provides a viable starting point for this integration. By examining how detection of redundant, amodal information is coordinated with detection of nonredundant, modality-specific information across development, we can observe interactions between unimodal and multimodal functioning not otherwise accessible to scientific study. Further, an understanding of these interactions will provide a basis for specific educational applications or interventions such as more appropriate matching of learning tasks (whether they require knowledge of amodal or modality-specific properties) with their mode of presentation (multimodal vs. unimodal) to enhance learning outcomes. It will also provide an important basis for comparisons between children of typical versus atypical development.

The following sections examine the development of perception and learning about social events in a multimodal environment, using principles of the IRH as a framework for achieving a more ecological and integrated approach. First, I review what is known about the development of perception of multimodal social events in typically developing infants, and later how this developmental process might go awry in atypical development, such as autism.

The Role of Intersensory Redundancy in Social Development: Perception of Faces, Voices, Speech, and Emotion

"Social orienting" in infancy promotes typical development

Social events are arguably the most important form of stimulation for guiding and shaping infant perceptual, cognitive, social, and linguistic development. Consequently, "social orienting" or selective attention to social events on the part of infants is critically important for fostering typical developmental outcomes. It is therefore fortunate, but no accident, that the developmental requirements of the infant fit so well with the stimulation typically provided by the social environment – social events are prevalent, highly salient, and readily capture infant attention. Typically developing infants prefer faces over many other stimuli, pick out the sounds of speech even *in utero*, and orient to voices and faces in the first days of life. Social events are one of the first and most frequent events encountered by infants, and it appears that perceptual learning occurs rapidly in this domain. Indeed, even newborns can discriminate their mothers' face (Bushnell, 2001; Field, Cohen, Garcia, & Greenberg, 1984), her voice (DeCasper & Fifer, 1980), and the prosody of speech (DeCasper & Spence, 1986) in unimodal stimulation. Rather than being "innate", these early capabilities arise from a complex system of organism–environment interactions that guide and shape early social orienting (Gogate, Walker-Andrews, & Bahrick, 2001; Harrist & Waugh, 2002; Mundy & Burnette, 2005). Much infant learning takes place during face-to-face interactions with adults. Adults provide a rich source for learning about the world of objects, events, and language, as well as a forum for social interaction and for the infant's developing sense of self and other. Adults guide and direct infant attention, scaffold learning about the affordances of people, objects, and the structure of language (e.g., Gogate, Walker-Andrews, & Bahrick 2001; Moore & Dunham, 1995; Mundy & Burnette, 2005; Rochat & Striano, 1999; Zukow-Goldring, 1997). Unfortunately, in developmental disorders such as autism, young children do not respond to this structure in the same way as typically developing children, and they show social orienting impairments (e.g., Dawson, Meltzoff, Osterling, Rinaldi, & Brown, 1998; Dawson et al., 2004), paying little attention to faces, voices, speech, and people, and focusing more attention on nonsocial events. It is not known how these children develop such deficits in social attention and the resulting impairments in cognitive and communicative functioning. However, it is clear that understanding how typically developing infants come to selectively attend to social events such as faces, voices, and emotions, is critical to answering this question, as well as for constructing more viable theories of perceptual and cognitive development. What makes social events so salient to infants and why do they typically show "social orienting"?

The salience of intersensory redundancy promotes social orienting in infancy

Social events are widely known to be highly salient to infants, and there are many theories regarding the basis for their attractiveness to infants, ranging from innate mechanisms (Goren, Sarty, & Wu, 1975; Johnson & Morton, 1991; Morton & Johnson, 1991), to their contingent responsiveness (Harrist & Waugh, 2002; Watson, 1979), and to familiarity, experience, and their general perceptual qualities (Diamond & Carey, 1986; Gauthier & Tarr, 1997; Nelson, 2001). There is currently no consensus regarding which perspectives are more correct or most fundamental. The basis for social orienting and interaction clearly involves a complex system of interactive influences, and identifying more fundamental and influential components of this system is critical for understanding the mechanisms underlying typical and atypical development. Recent advances in the field of neuroscience (see Mareschal et al., 2007) have generated promising neurodevelopmental models of autism and social orienting (e.g., Akshoomoff, Pierce, & Courchesne, 2002; Brock, Brown, Boucher, & Rippon, 2002; Dawson et al., 2002; Mundy, 2003; Mundy & Burnette, 2005; Mundy & Newell, 2007). In conjunction with behavioral models such as the IRH, important strides can be made toward identifying underlying mechanisms and fundamental components of this social orienting system. Here, I propose that a fundamental basis for "social orienting", or the attentional salience of social events to infants, starting in the first months of life, is the salience of intersensory redundancy (see Bahrick & Lickliter, 2002; Flom & Bahrick, 2007 for discussions).

Social events, in particular, provide a great deal of rapidly changing, amodal, redundant stimulation. For example, audiovisual speech is rich with intersensory redundancy uniting the tempo, rhythm, and intensity shifts across faces and voices. Social agents are also contingently responsive, providing cycles of reciprocal communicative exchanges with infants characterized by distinctive amodal temporal and intensity patterning common across auditory, visual, and tactile stimulation. These important forms of multimodal and redundant stimulation can serve as a basis for social orienting in early development by attracting and maintaining selective attention to faces, voices and audiovisual speech. Because detection of intersensory redundancy focuses and maintains attention on social events and their amodal properties such as temporal synchrony, rhythm, and intensity, this promotes perception of integrated multimodal social events and serves as the gatekeeper to further perceptual processing of cohesive social events. Prolonged attention leads to detection of modality-specific information, in order of increasing specificity. Detection of amodal information is particularly important in social contexts, where multiple individuals speak and interact concurrently, and one must selectively attend to the sights and sounds of a particular individual and separate them from those of other individuals. Communication involves engaging in reciprocal, well-synchronized social interaction involving coordination of gaze, vocalization, movement, and touch with a social partner. Thus, detection of intersensory redundancy for amodal temporal and spatial information in social exchanges plays an important role in parsing the stream of social stimulation into meaningful social events, initiating and maintaining infant attention to these events, and regulating interaction with a social partner.

The IRH provides a framework for exploring the development of infant perception of social events ranging from detection of specific faces and voices (based on modality specific information) to emotion and the prosody of speech (based on amodal information), in both unimodal and multimodal dynamic social stimulation. What do infants abstract from this diverse array of changing stimulation? As highlighted in the sections above, all aspects of events, be they social or nonsocial, are not equally salient, and in the context of limited attentional resources, differences in attentional salience have a pronounced effect on what is attended to and perceived from a single event, such as a person speaking. When and under what conditions do infants attend to different properties of social events, from discrimination of faces and voices, to selectively attending to a single speaker in the context of concurrent speech, and perceiving and recognizing emotional expressions?

Intersensory redundancy: A foundation for typical social development

It is clear that to foster optimal social development, young infants must look at faces, listen to voices, coordinate what they see with what they hear, and engage in reciprocal social interactions with adults. Developmental disorders such as autism highlight that these basic processes, often taken for granted in typical development, sometimes go awry. This presents a clear challenge to developmental psychologists: How and under what conditions do young infants come to perceive different aspects of this social stimulation as salient? What is the typical course of development of interest in faces, voices, speech, and emotion in multimodal everyday events and on what basis does it emerge? Developmental science is making progress in addressing these important questions, but it is far from providing a complete picture of these developmental processes. This is due, in part, to a lack of research focus on development in a multimodal, dynamic environment as well as a scarcity of studies assessing developmental change across a number of ages under uniform conditions; methods, measures, and research questions have differed widely across studies. For all of these reasons it is difficult to piece together an integrated developmental account of each of these skills. However, a more complete and integrated account of these developmental processes is central to developmental theories of attention, perception, learning, and memory as well as being critically important for identifying atypical developmental patterns for the early detection of children at risk for developmental delay and autism. The IRH provides a framework that can guide this process and suggests that an important mechanism for promoting typical social development is detection of intersensory redundancy which promotes attention to some aspects of stimulation (amodal) and attenuates attention to other aspects (modality-specific) in early development. The sections below review what is known about social development and orienting to social events across the first half year of life and the role of interersensory redundancy in this developmental process.

Prenatal origins of intersensory responsiveness. Prenatal development has a profound effect on postnatal behavioral organization (see Fifer & Moon, 1995; Gottlieb, 1997; Lickliter, 2005; Smotherman & Robinson, 1990, for reviews). Although little is known about the development of intersensory functioning during the prenatal period, it is clear that fetuses are exposed to intersensory redundancy across a wide range of stimulation to auditory, vestibular, and tactile senses. During fetal development, the functioning of the senses emerges in an invariant sequence (common across mammals and birds), with tactile/vestibular functioning emerging first, the chemical senses of smell and taste next, followed by auditory functioning early in the third trimester, and finally visual functioning becomes available at birth (Gottlieb, 1971). The successive emergence of sensory function raises the important question of how the senses and their respective stimulation histories influence one another during the prenatal period. Turkewitz & Kenny (1982) proposed that sensory limitations during early development both reduce overall stimulation and mediate the timing of the introduction of stimulation, thereby reducing the amount of competition between sensory systems. Thus, auditory perception typically develops without competition from visual stimulation during fetal development, and provides a context for the emergence of visual functioning at birth.

The developing fetus is likely to experience a diverse array of redundancy across the senses, particularly accompanying self-movement and the sounds of the mother's voice. Moving one's body produces proprioceptive feedback that is correlated with tactile and vestibular consequences of the motion. Thus, sucking, kicking, and turning produce patterns of proprioceptive, tactile, vestibular, and even auditory stimulation that covary and share amodal temporal, spatial, and intensity patterning. This activity and the multimodal stimulation it generates in turn affect neural development in a continuous and complex pattern of mutual influence. Altering the amount and/or timing of stimulation to one sense modality affects responsiveness and neural development in other modalities (Lickliter, 2005; Gottlieb, 1997). Neural development is activity-dependent, in the sense that it is continuously shaped by the nature of our actions and the stimulation we experience across development (see Edelman, 1987; Mareschal et al., 2007, for reviews). The prenatal period is one of strikingly rapid neural development (some 250,000 new neurons are generated each minute during some stages) and thus the activity of the fetus has a particularly large effect on neural development. Fetal activity and the multimodal stimulation it generates foster the development of neural architecture which supports further development of intersensory perception.

Auditory stimulation from sources such as the mother's voice is detected beginning in the 6th month of fetal development (see Fifer, Monk, & Grose-Fifer, 2001 for a review). Stimulation from the mother's voice is the loudest and most frequently heard sound (Fifer & Moon, 1995) and is also likely to be accompanied by a range of stimulation to various senses, providing a rich source of intersensory redundancy during the fetal period. For example, the mother's voice produces vibrations of her spinal column, synchronous movements of her diaphragm, and is often accompanied by movements of her body, as well as physiological changes (Abrams, Gerhardt & Peters, 1995; Fifer & Moon, 1995; Mastropieri & Turkewitz, 1999; Turkewitz, 1994). This multimodal synchrony may be detected by the fetus, causing the temporal patterning and prosody of the mother's voice to become particularly salient. This is likely to provide an important basis for the neonate's preference for the mother's voice and the prosody of her speech (DeCasper & Fifer, 1980; DeCasper & Spence, 1986; Moon & Fifer, 2000), as well as her face (Sai, 2005) shortly after birth.

Sai (2005) found evidence that newborns' preference for their mother's face results from intermodal perception and familiarity with her voice during prenatal development. Neonates' preference for their mother's face over that of a female stranger disappeared if they were prevented from hearing their mother's voice while observing her face from birth until the time of testing. Preferences for the mother's face were shown only by neonates who received postnatal experience with the mother's face and voice together. This remarkable finding suggests that the newborn's preference for the mother's face is a product of intermodal perception, probably due to experiencing her face moving in synchrony and collocated with her voice, a highly familiar stimulus which, itself, has been accompanied by intersensory redundancy. This provides a viable developmental explanation for an early preference that has puzzled scientists for decades.

Animal models of intersensory development have provided direct evidence of intersensory functioning during prenatal development and the links between sensory experience and neural development. These studies can manipulate the experience of the embryo by augmenting or decreasing typical sensory stimulation, or substituting one type of sensory stimulation for another (see Lickliter, 2005 for a review). Research indicates that altering stimulation to one sense modality can result in changes in other senses, affecting both behavioral and neural development. For example, studies with bobwhite quail embryos have shown that unusually early visual experience interferes with typical auditory responsiveness following hatching (Lickliter, 1990). Moreover, providing avian embryos with augmented auditory stimulation while the visual system is developing (rather than just before or after) results in impaired visual responsiveness and modified neural development in multimodal areas of the brain (Markham, Shimuzu, & Lickliter, 2008). Further, there is clear evidence that intersensory redundancy experienced *in ovo* can promote learning and memory for temporal properties of events in quail embryos, just as it does in human infants (Lickliter et al., 2002, 2004). For example, chicks who received redundant audiovisual exposure to a maternal call learned the call with one fourth of the exposure time and remembered it four times longer than chicks who received unimodal auditory exposure, and chicks who received asynchronous exposure showed no learning at all. The convergence of findings across species highlighting the important role of intersensory redundancy in directing learning and memory suggests that this is a fundamental process shaping fetal development across species. A direct test of human fetal sensitivity to intersensory redundancy awaits future research.

Intermodal proprioceptive-visual information and self-perception. Self-exploration results in one of the earliest and most potent sources of intersensory redundancy (see Rochat, 1995; Rochat & Striano, 1999). Infants engage in active intermodal exploration of the self, starting during fetal development and increasing dramatically after birth and across the first months of life (Butterworth & Hopkins, 1988; Rochat, 1993; Van der Meer, Van der Weel, & Lee, 1995). At birth, vision becomes functional and provides a new, and particularly powerful, channel for detecting amodal, redundant stimulation, both about events in the world, and also about the self. Visual stimulation specifying self-motion is continuously available, and provides redundancy across auditory, tactile, and proprioceptive stimulation. Infants experience continuous and ongoing proprioceptive feedback from their muscles, joints, and vestibular system resulting from their own motion. For example, when the infant observes his own hand move, he experiences congruent information across vision and proprioception for self-motion. This amodal, proporioceptive-visual information is temporally synchronous, perfectly contingent, and characterized by common patterns of temporal, spatial, and intensity variation across the senses. Similarly, when the infant vocalizes, he experiences the covariation between his sounds and the feedback from his articulatory movements. This multimodal self-exploration provides infants with access to a great deal of controllable intersensory redundancy and contributes to the early emergence of the "ecological" self (Neisser, 1991; Rochat 1995) – the infant's sense of self as a separate entity and an agent of action.

Research demonstrates that infants of 3 to 5 months detect intersensory redundancy across visual and proprioceptive feedback from their own motions and can differentiate self from social stimulation in the first months of life (Bahrick & Watson, 1985; Rochat & Morgan, 1995; Schmuckler, 1996). Bahrick & Watson (1985) developed a procedure to directly assess infants' ability to perceive intersensory redundancy from self-motion. Infants were presented with a live video image of their own legs kicking (which provides perfect contingency or intersensory redundancy between felt and seen motions), along side that of another infant's legs kicking, or a prerecorded video of their own legs kicking (which provides only accidental contingency or intersensory redundancy). Results indicated that 5-month-old infants detected the intersensory redundancy provided by the live video feedback and preferred to watch the nonredundant videos of the peer's legs and their own prerecorded legs. Because only stimulation from the self is perfectly redundant with proprioceptive feedback, we proposed this perfect redundancy or contingency provided an early basis for distinguishing self from social stimulation. Five-month-olds prefer the social stimulation from a peer over the perfectly contingent and redundant stimulation from the self. At 3 months, however, infants showed bimodally distributed preferences, suggesting they were in transition from a preference for self to social stimulation. Subsequent studies have replicated the preference for noncontingent social stimulation over the perfectly redundant stimulation from the self and extended these findings across a variety of contexts (e.g., Rochat & Morgan, 1995; Schmuckler, 1996: Schmuckler & Fairhall, 2001). Taken together with other findings reviewed in this chapter, there appears to be a shift in early development, around the age of 3 months, from attention to self and the perfect intersensory redundancy it provides, to greater attention to social partners and the partially contingent, turn-taking structure of social interaction. In other words, there is a transition to greater "social orienting" in early infancy. Interestingly, a recent study using Bahrick & Watson's (1985) task to compare children with autism and mental age-matched children of typical development (Bahrick, Castellanos, et al., 2008) found that 2- to 5-year-old children with autism had not made this important transition. It is not yet clear whether these children failed to detect the redundancy across proprioceptive stimulation and the visual display of their own motion or whether they had no preference for social stimulation over self generated stimulation.

Further evidence of this transition comes from data showing that young infants also discriminate a video image of their own face from that of another infant, based on its visual appearance (Bahrick et al., 1996). Here, too, infants show a preference for the social partner over the self, and consistent with findings above, this appears to emerge between 2- and 3-months of age (Bahrick, 1995; Bahrick et al. 1996). Parents of children in this study reported that their infants received regular mirror exposure. Most likely, this allowed them to detect the correspondence between visual transformations and proprioceptive feedback, making their own facial images not only familiar, but distinct from other facial images.

Infants also detect intermodal relations between self-motion and external events, allowing them to discover the effects of their own behavior on the environment, promoting a sense of competence and self-efficacy (e.g., Watson, 1972, 1979). Infants who discover that they control the movements of an overhead crib mobile though detecting proprioceptive-visual contingency show positive affect and social behaviors such as smiling and cooing (Watson, 1972). Infants also remember the contingency between their own motion and the movement of a crib mobile even after delays of 24 hours or more (Bhatt & Rovee-Collier, 1994; Greco, Rovee-Collier, Hayne, Griesler, & Earley, 1986; Rovee-Collier & Barr, 2001). Even newborns show evidence of early intermodal coordination and self-perception. They appear to distinguish between the self and other objects by showing a rooting response to touch from objects but not to self touch (Rochat & Hespos, 1997; Rochat & Striano, 2000). This is likely to have its roots in prenatal intersensory exploration. Neonates are also able to imitate facial expressions (Meltzoff & Moore, 1977, 1983). In order to do this, they must relate their own production of the expression with the visual appearance of the adult model. This is most likely guided by proprioceptive feedback and shows evidence of active intermodal mapping (Meltzoff & Moore, 1983, 1994). Meltzoff (2007) argues that detection of self–other equivalence is a starting point for social cognition and through self-perception infants come to understand the actions of others.

Intermodal coordination of self-motion with external visual information is also evident by the rapid development of posture control and "visually guided reaching" across the first year of life (see Bertenthal, 1996; Butterworth, 1992; von Hofsten, 1993 for reviews). Visually guided reaching involves the prospective control of motion, and is present even in newborns (von Hofsten, 1980, 1993). Young infants can adapt the trajectory of their reach to contact a moving target and this involves continuous adjustments in reaching as a function of visual input about the size, shape, and position of the object (von Hofsten, 1983, 1993). Infants, like adults, also use visual feedback to maintain an upright posture and adapt their posture to changes in the environment (e.g., Bertenthal, Rose, & Bai, 1997; Butterworth & Hicks, 1977; Lee & Aronson, 1974). Older infants show prospective control of locomotion, adapting their posture, locomotion, and exploratory behavior to visual information about the slant and solidity of the surface (see Adolph & Berger, 2006 for a review).

Infants also detect auditory-proprioceptive/vestibular patterns. Bouncing to a rhythm results in listening preferences for rhythmic patterns that match the infant's own movement patterns (Phillips-Silver & Trainor, 2005). Even neonatal learning benefits from self-contingent stimulation. Infants receiving audiovisual stimulation contingent upon their looking behavior learned an arbitrary sound-sight relation, whereas those who received noncontingent stimulation did not (Slater, Quinn, Brown, & Hayes, 1999). This illustrates the principle of increasing specificity and the powerful role of intersensory redundancy in guiding attention to contingent events and promoting further processing of those events.

Identifying speakers, differentiating speech, and learning words: The critical role of intersensory redundancy. Infant sensitivity to intersensory redundancy is critically important for the development of speech perception and language. As discussed earlier, intersensory redundancy attracts and maintains attention to the face of a speaker, allowing the infant to perceive coordinated visual and vocal stimulation emanating from a unitary multimodal event – audiovisual speech. When adults speak to infants, it is well known that they use a special form of speech (infant-directed speech, or "motherese"; see Fernald, 1984, 1989) which exaggerates the amodal information and intersensory redundancy across face, voice, and gesture, providing one of the most important bases for social orienting (see Perceiving Emotion and Prosody below for more detail).

What about perception of speech in the natural environment, which is often "noisy", providing a dynamic flux of concurrent events and multiple speakers? Like adults, infants make extensive use of intersensory redundancy in order to localize speakers and follow the flow of speech (e.g., Gogate et al., 2001; Hollich, Newman, & Jusczyk, 2005). Young infants prefer to look at faces that are synchronized with speech sounds as compared with those that are not (Lewkowicz, 1996) and they match faces and voices on the basis of speech sounds. For example, 2-month-olds can determine which woman is producing an /a/ sound and which is producing an /i/ sound, when both are articulating in synchrony, by relating the shape of the mouth and its movement with the "shape" of the sound (Kuhl & Meltzoff, 1982, 1984).

Moreover, like adults, infants rely on intersensory redundancy between auditory and visual speech to separate two concurrent speech streams (as in the "cocktail party phenomenon," Cherry, 1953). Hollich et al., (2005) found that infants were able to use face–voice synchrony to separate a target speech stream from concurrent background speech of equal intensity. This allowed infants to identify individual words (segment the speech stream) in the target speech. Even a synchronized oscilloscope pattern was equally effective, demonstrating the critical role of intersensory redundancy. In a similar study, providing infants with the synchronized face of one woman speaking against concurrent speech of another woman, allowed infants to selectively attend to the synchronized voice, ignore the nonsynchronized voice, and discriminate between the two voices (Bahrick, Shuman, et al., 2008). These findings illustrate how intersensory redundancy in the form of synchronous audiovisual stimulation, serves as a basis for localizing speakers in noise, selectively attending to one voice while ignoring another, and differentiating individual words in continuous speech in the context of concurrent events.

Infants also learn speech sound–object relations on the basis of intersensory redundancy. In contrast to nativist views of language development (e.g. Chomsky, 1980; Fodor, 1983) research on intersensory perception indicates that general perceptual processes rather than language-specific mechanisms account for early word–object mapping (see Gogate et al., 2001). For example, infants as young as 7 months can detect the relation between a speech sound and an object, only when the sound is temporally synchronized with a movement of the object (such as lifting and showing the object) and not when it is spoken while the object is still, or when the object is moved out of synchrony with the speech sound (Gogate & Bahrick, 1998). Detection of temporal synchrony fosters coordinated perception of word–object relations, highlighting which of many visible objects is the referent of the sound, eventually contributing to the understanding that sounds refer to things, and that a particular sound refers to a particular object (see Gogate et al., 2001). This learning is embedded in a mutually contingent social interaction between the infant and caregiver, described in more detail in the section below.

Intermodal dyadic synchrony and social development. Successful social and communicative development also depends on engaging in reciprocal social interactions that are temporally and spatially intercoordinated. Detection of amodal information and intersensory redundancy is the foundation for this process and infants quickly become skilled at this exchange. For example, in the first months of life, infants learn to participate in reciprocal exchanges and turn-taking interactions with their adult caretakers – their movements and vocal rhythms are intercoordinated with the temporal patterning of adult communication and this relies on intermodal perception of proprioceptive-visual-auditory relations (Beebe et al., 2010; Jaffe et al., 2001; Sander, 1977; Stern, 1985; Trevarthen, 1993; Tronick, 1989). Dyadic synchrony (the continuous, bidirectional, temporal, intensity, and spatial coordination of gaze, touch, vocalization, and affect) has been found to promote a wide range of fundamental developmental processes, including the early regulation of arousal and internal rhythms, as well as fostering caregiver–infant affective attunement and later attachment, joint attention, communicative competence, and a sense of self-efficacy (see Harrist & Waugh, 2002; Tarabulsy, Tessier, & Kappas, 1996, for reviews).

Dyadic synchrony between caregivers and infants functions as part of a well-honed intermodal developmental system that promotes cognitive, social, and communicative development (see Thelen & Smith, 1994, for discussion). For example, when teaching infants novel names for objects, mothers embed words in multimodal events and tailor their use of temporal synchrony between naming and showing an object to their infants' level of lexical development (Gogate, Bahrick, & Watson, 2000). Temporal synchrony attracts and maintains attention to the object-referent relations, and mothers make most use of synchrony for infants in early stages of lexical development, when they can most benefit from it. Infant phonological development is also the product of bidirectional, multimodal, mother–infant interactions. The development of babbling and the production of more canonical speech sounds is shaped by the contingent responsiveness of the mother/caregiver (Goldstein, King, & West, 2003). Similarly, birdsong of juvenile males is also shaped by interactive, reciprocal exchanges with adult females who selectively reinforce more adult forms with behaviors such as wing strokes (West & King, 1988). These mutually contingent, social interactions involve a host of complex, multimodal skills. The infant must selectively attend to amodal, redundant, temporal, spatial, and intensity patterns from continuously changing multimodal social stimulation, discriminate and track visual, proprioceptive, and auditory stimulation generated by the self as distinct from that of the social partner, and intercoordinate their multimodal behaviors with those of the adult. This complex dance provides a cornerstone for social and communicative functioning in typical development.

Perceiving emotion and prosody: The critical role of intersensory redundancy. Intersensory redundancy between audible and visible speech makes emotion and prosody particularly salient in communicative exchanges. Detection of emotion and prosody of speech is primarily supported by amodal information and is thus promoted in synchronous stimulation from face, voice, and gesture. Emotion is conveyed by a complex combination of amodal properties including changes in tempo, temporal patterning, and intensity of facial and vocal stimulation (see Walker-Andrews, 1997, for a review). Prosody of speech provides information about communicative intent (such as prohibition, comfort, or approval) and is conveyed by amodal information such as rhythm, tempo, and intensity shifts (see Cooper & Aslin, 1990; Fernald, 1984).

Adults typically speak to infants using infant-directed speech and this stimulation is highly attractive to infants and preferred over adult-directed speech (Cooper & Aslin, 1990, Fernald, 1984, 1989; Nazzi, Bertonicini, & Mehler 1998, Werker & McLeod, 1989; see Cooper, 1997 for a review). Natural infant-directed speech contains a great deal of intersensory redundancy such as exaggerated prosody (rhythm, tempo, and intensity shifts), longer pauses, more repetition, and wider pitch excursions (Fernald, 1984, 1989) that can be experienced in the sounds of speech as well as the facial movements and gestures (see Gogate, Walker-Andrews & Bahrick, 2001). The salience of redundant, amodal stimulation appears to underlie the well-established infant preference for infant-directed speech over adult-directed speech. Infant-directed speech also conveys information about language identity, communicative intent such as comfort versus prohibition, and helps infants parse and detect meaning-bearing parts of the speech stream (Cooper, 1997; Cooper & Aslin, 1990; Moon, Cooper, & Fifer, 1993; Nazzi et al., 1998; Spence & Moore, 2003).

Consistent with predictions of the IRH, research has found that detection of prosody in speech is facilitated by intersensory redundancy. For example, infants of 4 and 6 months were habituated to a woman reciting phrases using prosodic patterns conveying approval versus prohibition in unimodal auditory speech, synchronous audiovisual speech, or asynchronous audiovisual speech. Infants discriminated a change in prosody only in the synchronous audiovisual speech condition at 4 months of age. By 6 months, they discriminated the change in unimodal auditory speech as well (Castellanos, Shuman, & Bahrick, 2004). These findings demonstrated that prosody specifying approval versus prohibition is initially perceived by detecting amodal information in the multimodal stimulation from faces and voices, and a few months later, detection of prosody is extended to unimodal auditory and visual speech. Moreover, intersensory redundancy in audiovisual speech was also found to educate attention to prosodic changes specifying approval and prohibition in the unimodal auditory speech that followed, for infants as young as 4 months. This provides a potential basis for the developmental improvement observed between 4 and 6 months (Castellanos et al., 2006).

Perception and discrimination of emotion follow a similar developmental trajectory. Infants become skilled at discriminating emotional expressions such as happy, sad, and angry, under a variety of conditions between the ages of 3 and 7 months (see Walker-Andrews 1997 for a review). Discrimination of emotions appears to emerge prior to matching faces and voices on the basis of emotion (Walker-Andrews, 1997). The ability to match facial and vocal expressions of emotion in unfamiliar individuals appears to develop between the ages of 5 and 7 months, whereas detection of emotion in familiar individuals, such as the mother, appears to emerge earlier, by the age of 3 months (Montague, & Walker-Andrews, 2002). From an extensive review of the literature, Walker-Andrews (1997) concluded that emotion is perceived and discriminated in multimodal, naturalistic stimulation early in development and later in development is extended to unimodal stimulation from vocal expressions and from facial expressions alone.

We recently tested this hypothesis directly. Flom and Bahrick (2007) habituated infants of 3, 4, 5, and 8 months with films of a woman speaking in a happy, angry, or sad manner, under a variety of conditions, and then assessed discrimination of the woman displaying a different emotion. Consistent with predictions of the IRH, infants discriminated the emotion in multimodal stimulation (synchronous audiovisual speech) by 4 months of age; however, discrimination in unimodal stimulation was not evident until later. By 5 months of age, infants discriminated the emotions in unimodal auditory speech, and by 8 months, discrimination was extended to unimodal visual speech. This trend from multimodal emotion perception, to unimodal auditory, to unimodal visual emotion perception parallels that found by Walker-Andrews (1997) from her survey of the literature and reflects the critical role of intersensory redundancy in guiding and organizing perceptual development.

Discriminating faces and voices relies on detection of modality-specific information. The need for more ecologically relevant research is particularly apparent in the domain of face and voice perception. Face perception has become a "hot topic" of investigation and debate regarding origins of knowledge in infancy in recent years. It has been described by some scientists as "special" in the sense that faces are thought to be innately preferred over other stimuli by young infants, and mediated by special-purpose mechanisms rather than general perceptual processes (Bruyer et al, 1983; Farah, Wilson, Drain, & Tanaka, 1995; Goren et al., 1975; Johnson & Morton, 1991; Morton & Johnson, 1991). Others argue that although face processing is "special", it differs in degree, not kind, from processing of complex nonsocial objects (Diamond & Carey, 1986; Farah Wilson, Drain, & Tanaka, 1998; Gauthier & Tarr, 1997; Gauthier & Nelson, 2001; Nelson, 2001; Turati, 2004). From this view, the development of expertise through experience with faces underlies our remarkable ability to perceive faces. This expertise view is most compatible with predictions of the IRH and with research findings generated from ecological, multimodal face events.

In contrast to the development of skills reviewed earlier such as detection of prosody, emotion, dyadic synchrony, and localization of speakers, which all rely on detection of amodal information in multimodal stimulation, discriminating faces and voices relies primarily on detection of modality-specific information in unimodal stimulation, and is thus impaired by intersensory redundancy (see Figure 1: Prediction 2 of the IRH, Bahrick & Lickliter, 2002; Bahrick, Lickliter, & Flom, 2004). Voice recognition is primarily based on sensitivity to pitch and timbre (although individuals also show distinctive prosodic patterns), whereas face recognition is primarily based on detection of facial features and their configuration. Thus, although not yet widely appreciated, face and voice perception are enhanced in unimodal face or voice presentations and impaired in multimodal presentations, particularly in early development. This is evident in studies directly comparing face perception in unimodal versus multimodal conditions. Given that the vast majority of face discrimination studies have been conducted using unimodal visual facial stimuli where infant attention is drawn to facial features, findings of these studies are likely to present an exaggerated view of the salience of faces to infants in the typical dynamic, multimodal environment where faces and voices occur as a unified multimodal event and individuals speak in synchrony with facial movement. In fact, research has found that everyday actions, such as brushing hair or teeth, are much more salient, discriminable, and memorable to infants than the faces of the women engaging in these activities (Bahrick, Gogate, & Ruiz, 2002; Bahrick & Newell, 2008; Walker-Andrews & Bahrick, 2001). That being said, the vast proliferation of studies of unimodal visual face perception (where there is no competition from intersensory redundancy) have shown adept face processing skills in the first half year of life.

For example, newborns show recognition of the mother's face in visual displays within hours of birth (Bushnell, 2001; Bushnell, Sai, & Mullin, 1989; Field et al., 1984; Sai, 2005; Slater & Quinn, 2001) and by 1-month, they show recognition of her face when external features such as the hair have been masked (Pascalis, de Schonen, Morton, Dereulle, & Fabre-Grenet, 1995). Infants of 2 to 5 months also differentiate faces of strangers in unimodal static visual conditions (Cohen & Strauss, 1979; Cornell, 1974; de Haan, Johnson, Maurer, & Perrett, 2001; Fagan, 1972; 1976). Between 3 and 6 months infants differentiate between their own face and that of an age-matched peer in static and dynamic conditions, and discriminate somewhat better in dynamic displays (Bahrick et al., 1996). However, it cannot be determined how these excellent face processing skills in unimodal visual events compare with those of multimodal events. Direct comparisons are needed.

Much less research has focused on perception and discrimination of individual voices in infancy. However, it is clear that following a history of fetal experience with voices, infants discriminate the mother's voice from that of a female stranger and the father's voice from a male stranger, and even between the voices of two strangers shortly after birth (DeCasper & Fifer, 1980; DeCasper & Prescott, 1984; Floccia, Nazzi, & Bertoncini, 2000). Further, studies of intermodal face–voice matching demonstrate that following synchronous audio-visual exposure, by 4 months of age infants can discriminate adult female faces, voices, and match the women's faces with their voices (Bahrick, Hernandez-Reif, et al., 2005). Between 4 and 6 months, infants also match faces and voices on the basis of amodal properties such as those specifying gender (Walker-Andrews, Bahrick, Raglioni, & Diaz, 1991) and age (Bahrick, Netto, & Hernandez-Reif, 1998), and classify voices on the basis of gender (Miller, 1983; Miller, Younger & Morse, 1982).

The superiority of face and voice perception in unimodal stimulation over multimodal stimulation has been tested in a few studies to date. Bahrick, Hernandez-Reif, et al. (2005) found that 2-month-olds could discriminate the faces and voices of two unfamiliar women in unimodal visual and unimodal auditory speech, respectively. However, it was only by 4 months of age that infants could discriminate the faces and voices and detect a relation between them in natural, audiovisual speech, where intersensory redundancy was available and most likely competed for attention. More direct tests of the interfering effects of intersensory redundancy and the resulting superiority of face perception in unimodal stimulation as compared with multimodal stimulation have also been conducted (Bahrick, Lickliter, Vaillant, et al., 2004; Vaillant-Molina, Newell, Castellanos, Bahrick, & Lickliter, 2006). Two- and 3-month-old infants were habituated with faces of unfamiliar women speaking in unimodal visual, audiovisual synchronous, and audiovisual asynchronous speech, and were then tested for discrimination of the familiar from a novel face. Consistent with predictions of unimodal facilitation (Prediction 2 of the IRH), at 2 months, infants discriminated the faces in unimodal visual but not bimodal synchronous, audiovisual speech where intersensory redundancy apparently interfered with face discrimination. They also discriminated the faces in an asynchronous audiovisual speech control condition. This condition eliminated intersensory redundancy but the amount and type of stimulation was equal to that of synchronous audiovisual speech. Only by 3 months of age, did infants discriminate the faces in the context of intersensory redundancy from natural, synchronous audiovisual speech. Thus, discrimination of faces appears to emerge first in unimodal visual stimulation (where there is no competition from intersensory redundancy and attention is free to focus on visual properties) and later in development it extends to multimodal contexts where there is attentional competition from redundantly specified properties. A parallel study of voice perception also revealed a similar developmental pattern (Bahrick, Lickliter, et al., 2005). Discrimination among voices of unfamiliar women emerged first in unimodal auditory stimulation at 3 months, and was later extended to bimodal, audiovisual speech at 4 months of age.

Thus, the developmental progression for discriminating faces and voices is consistent with predictions of the IRH and parallels the pattern found for nonredundantly specified aspects of nonsocial events described earlier (e.g., Bahrick et al., 2006, orientation of motion). This developmental shift from detection of visual and acoustic information in nonredundant, unimodal stimulation to detection of this same information in the context of competition from redundant audiovisual stimulation becomes possible as infants increase their speed and efficiency of information processing, gain attentional flexibility, and gain experience with similar classes of events. This allows them to detect both the most salient and somewhat less salient aspects of stimulation in an episode of exploration. This developmental progression appears to occur more rapidly in the social domain (across a period of only 1 month for face and voice perception) than the nonsocial domain. This may be due to the high frequency of exposure, salience, and degree of familiarity with faces and voices.

These findings thus support the view that the development of face perception is governed by general perceptual processes as a result of perceptual experience and contrast with the position that face perception is the result of specialized face processing mechanisms that function differently from object processing. From the present view, faces become especially salient to infants because they are frequently encountered and typically the source of a great deal of intersensory redundancy. Their attentional salience would promote rapid processing and perceptual learning in order of salience and increasing specificity (Bahrick, 2001; E. J. Gibson, 1969), first facilitating detection of amodal properties such as prosody, affect, rhythm, and tempo of audiovisual speech in multimodal stimualtion. Later, with further exploration, more specific properties such as the configuration and specific facial features and the pitch and timbre of voices would be promoted. In contrast, in unimodal stimulation, visual features of the face become especially salient, consistent with newborn recognition of the mother's face in silent unimodal conditions (e.g., Field et al, 1984; Bushnell, 2001) and this promotes the development of face expertise. Similarly, voice perception, is promoted by unimodal auditory exploration where vocal qualities such as pitch and timbre are more easily differentiated. Converging findings across the literature (Bahrick, Hernandez-Reif, et al., 2005; see Walker-Andrews, 1997 for a review) show improvement in face and voice processing across early infancy, with detection in unimodal contexts and for familiar individuals emerging first, and sensitivity to specific faces and voices in bimodal contexts emerging somewhat later, and finally, intermodal matching of faces and voices, and memory for these relations emerging later.

Lessons from Atypical Development

Social orienting impairments in autism

In contrast to typical development, in atypical development characterizing autism spectrum disorder, children show a "social orienting impairment" (Dawson et al, 1998, 2004; Landry and Bryson, 2004; Mundy & Burnette, 2005). They exhibit reduced attention and orienting to social as compared with nonsocial events, avoid interaction and eye contact with others, and fail to respond to their own name. Because autism is a disorder that appears to emerge and worsen across early development, affecting a wide variety of areas, including social, communicative, and cognitive functioning, it is generally agreed that identifying developmental precursors or symptoms that are "primary" and have the potential for explaining a range of later developing symptoms is critical to early diagnosis, theory, and intervention (e.g., Volkmar, Lord, Bailey, Schultz, & Klin, 2004; Sigman, Dijamco, Gratier, & Rozga, 2004). This poses a challenge for researchers for a number of reasons. First, we cannot reliably identify which infants will develop autism and its relatively low incidence, occurring in approximately one in 150–200 individuals (Frombonne, 2005), makes longitudinal or prospective studies difficult and impractical. Second, although there is a major emphasis on the need for early diagnosis, autism is not typically diagnosed until 18 to 24 months of age, when significant delays in social and communicative functioning have become apparent and entrenched. Thus scientists have had to rely on indirect methods such as using home videos and questionnaires to learn about the infant behaviors of children who were later diagnosed with autism (e.g., Maestro et al, 2002; Osterling & Dawson, 1994). We now have more promising prospective methods including studies of siblings of children with autism who tend to have a higher incidence of either developing autism or showing symptoms of the "broad phenotype", symptoms that fall along the spectrum of behaviors associated with autism (e.g., Cassel, Messinger, Ibanez, Haltigan, Acosta & Buchman, 2007; Yirmiya et al., 2006). Finally, autism presents a wide variety of symptoms with a great deal of individual variability, so no one pattern fits all cases.

Given recent research indicating that neurodevelopmental anomalies occur even in prenatal development (see Akshoomoff et al., 2002, for a review), it is clear that research should focus on early developing skills, particularly those that emerge within the first 6 months of life. Early disturbances of attention such as the "social orienting impairment" (Dawson et al., 1998, 2004) are excellent candidates for the study of potential primary symptoms. The neurodevelopment of attention is shaped during prenatal development, attention develops rapidly across the first 6 months of life, and social orienting is seen in typical development even at birth (Bushnell, 2001; DeCasper & Fifer, 1980; Mondloch et al., 1999; Sai, 2005; Simion, Valenza, & Umilta, 1998). Further, the development of attention has been the subject of well-controlled studies in early infancy (as reviewed in this chapter; see Bahrick & Lickliter, 2002; Ruff and Rothbart, 1996 for reviews). Given that attention provides the input for all that is perceived, learned, and remembered it provides the foundation for the rapid development of a wide range of skills, both social and cognitive, in infancy and childhood.

In particular, the early disturbance of attention to social events may contribute to impairments in a host of other skills that depend on heightened attention to social events, including joint visual attention (sharing attention by coordinating eye gaze with a social partner on an object of mutual interest), face recognition, the development of reciprocal interactions, responding to emotional signals, and language development (Dawson et al., 1998; Mundy & Burnette, 2005; Mundy, 1995; Volkmar, Chawarska, and Klin, 2005). The development of autism has been described as a developmental cascade where impairments in early systems such as joint attention, reciprocal interactions, and social orienting, lead to increasing social, communicative, and neurological disturbance (Mundy & Burnette, 2005). Symptoms become evident and worsen across development, in part because deficits in basic building blocks of social and communicative functioning in infancy lead to further amplification of disturbances in more complex, derivative skills and associated neurodevelopment (Akshoomoff et al, 2002; Dawson et al., 2002 Mundy & Burnette, 2005). Thus, a failure of social stimulation to become salient and preferentially attended over other stimulation in early infancy would lead to a drastic decrease in the flow of social information that provides the input and interaction necessary for typical developmental gains in cognitive, social, emotional, and linguistic development. It seems reasonable that even a small deficit in social orienting could lead to an ever widening gap between typical and atypical development.

In this light, I have made a case (see *The salience of intersensory redundancy promotes social orienting in infancy*) hat a fundamental basis for social orienting in typical infant development is the salience of intersensory redundancy. As reviewed in this chapter, social events are multimodal and provide an extraordinary amount of rapidly changing intersensory information which infants rely on for differentiating self from other, identifying speakers in noisy environments, differentiating speech from nonspeech, learning words, perceiving emotion and communicative intent, and engaging in reciprocal communicative exchanges. The salience of intersensory redundancy is a primary mechanism for promoting social orienting and for guiding and constraining acquisition of knowledge about the social world. Impairment to this system would lead to a wide range of atypical developmental outcomes.

Intersensory processing impairment: An hypothesis for autism

In light of the above logic and the growing literature on intersensory impairments in autism, I propose that a fundamental basis for the development of social-communicative and cognitive impairments characterizing autism is an "intersensory processing impairment", in particular, a reduced sensitivity to amodal information in the context of intersensory redundancy (see also Bebko, Weiss, Demark, & Gomez, 2006; Brock et al., 2002; Iarocci & McDonald, 2005; Mundy & Burnette, 2005). A slight deficit in intersensory functioning, evident in infancy, could lead to early social orienting impairments and, in turn, promote a cascade of impairments to social, cognitive, and communicative functioning, typical of autism spectrum disorders.

Moreover, the Intersensory Redundancy Hypothesis (Bahrick & Lickliter, 2000, 2002) can provide a new perspective regarding the nature and basis of impairments in autism. In particular, if intersensory processing is impaired, in addition to reduced attention to social events, the typical salience hierarchies and critical balance between attention to amodal versus modality-specific properties of events as a function of type of stimulation (unimodal vs. multimodal, see Figure 4.2) would be disrupted. This disruption of salience hierarchies would alter the typical developmental pattern where amodal properties guide and constrain the detection of modality-specific details, in order of increasing specificity. This, in turn, could result in more piecemeal information processing, a greater emphasis on local than global information, processing modality-specific information prior to perceiving unitary multimodal events, heightened attention to visual and acoustic detail disconnected from context, and less generalization of learning across domains, all characteristics of individuals with autism. Future research will be needed to map the nature of intersensory processing impairments in autism by evaluating each of the four predictions of the IRH in children with autism and those of typical development. If intersensory processing is intact but somewhat reduced, interventions may build on existing intersensory skills to train attention, rebuild intersensory processing, and promote typical attentional salience hierarchies.

Evidence of impaired intersensory processing in autism is now mounting, supporting "intersensory processing impairment" as a hypothesis for autism. Individuals with autism show impaired intersensory integration of audiovisual speech (Smith & Bennetto, 2007; Magnee, de Gelder, van Engeland, & Kemner, 2008). Smith & Bennetto (2007) demonstrated that adolescents with autism showed less benefit from visual information in identifying speech in noise than do typically developing adolescents (matched for IQ), and this impairment could not be explained by auditory or visual processing deficits alone. Both adults and children show a reduced susceptibility to the McGurk effect, an index of audiovisual speech integration (de Gelder, Vroomen, & van der Heide, 1991; Mongillo et al., 2008; Williams, Massaro, Peel, Bosseler, & Suddendorf, 2004). Moreover, even young children with autism show impaired intersensory processing of audiovisual temporal synchrony in simple and complex audiovisual speech events, but no evidence of impairment in nonsocial events (Bebko et al., 2006). The mirror neuron system (Williams, Whiten, Suddendorf, & Perrett, 2001), an intersensory system thought to show similar neural activity to both observed and performed actions, is also thought to be compromised in autism, contributing to impaired empathy, imitation, and speech perception (e.g., Dapretto et al., 2006; Oberman et al., 2005; Oberman & Ramachandran, 2008). However, there is still debate as to the nature and basis of intersensory impairments in autism (e.g., Hamilton, Brindley, & Frith, 2007; van der Smagt, van Engeland, & Kemner, 2007). Some studies find no evidence of impairment to specific intersensory skills (Haviland, Walker-Andrews, Huffman, Toci, & Alton, 1996; van der Smagt et al., 2007), some find impairments are related to cognitive ability (e.g., Loveland et al., 1997), others find intersensory processing is limited by unimodal sensory impairments, particularly to social stimuli (e.g., Boucher, Lewis, & Collis, 1998; Williams et al., 2004), whereas others find intersensory impairments independent of these factors (e.g., Bebko et al., 2006; de Gelder et al., 1991; Smith & Benetto, 2007). Nevertheless, it appears that intersensory impairments are most pronounced for social and speech events, which are relatively complex and provide a particularly high level of intersensory redundancy. These findings suggest that the IRH and proposed intersensory processing impairment may provide a viable hypothesis for guiding future investigations of impairments in autism.

Benefits of integrating basic research across typical and atypical development

It is clear that a more profound understanding of the nature and basis of social orienting in typical development, at both the behavioral and neural levels, will have important pay-offs in terms of earlier and more accurate identification of atypical patterns of social development and the development of interventions. Moreover, understanding patterns of atypical development also has important benefits for the study of typical development. The challenge of understanding the developmental cascades that characterize the emergence of autism spectrum disorders highlights a critical lack of knowledge about typical development. Scientists have yet to clearly identify basic building blocks of social and communicative functioning in typical infant development, identify primary versus derivative skills, and articulate the nature of developmental cascades that lead to optimal developmental patterns. Studying the critical role of intersensory redundancy for guiding and shaping social attention and social interaction, outlined in this chapter, is one clear starting point for this endeavor. Understanding the nature of attentional biases is critical to understanding the typical and atypical emergence of social orienting and the host of other skills that emerge from attention to social stimulation. The cross-fertilization of typical and atypical developmental perspectives will provide significant benefits to developmental science for understanding the typical trajectories, mechanisms, and bases for developmental processes.

Conclusions and Future Directions: Toward a More Integrated, Ecologically Relevant Model of Perceptual Development

This chapter has highlighted three themes, each stressing the benefits of greater integration across typically separate areas of inquiry in developmental science. The first theme emphasizes the need to integrate selective attention with studies of perception, learning, and memory, as attention provides the foundation for what is perceived, learned, and remembered. This review illustrated the benefits of such an approach for developmental science by applying the Intersensory Redundancy Hypothesis, a theory of selective attention, to understanding perceptual development. The second theme emphasizes the importance of integrating the study of both multimodal (e.g., audiovisual) and unimodal (visual or auditory) functioning in understanding what drives development and in making our investigations more ecologically relevant. This chapter thus highlighted how the attentional salience of intersensory redundancy, available in multimodal but not unimodal stimulation, promotes perceptual processing of some properties of events at the expense of others, creating general salience hierarchies that can impact development across the life span. In multimodal stimulation, attention is selectively focused on redundantly specified amodal properties such as synchrony, rhythm, tempo, and intensity, which support perception of emotion, prosody, and localization of speakers. Development of these skills emerges in multimodal stimulation and is later extended to unimodal contexts. In contrast, in unimodal (visual or auditory) stimulation, selective attention focuses first on modality-specific properties of events such as visual pattern, form, color, or auditory pitch and timbre, supporting perception of individual faces and voices and the appearance of objects and the specific nature of their sounds. Development of these skills emerges in unimodal contexts and later extends to multimodal contexts. Since most events are multimodal, these attentional biases promote general salience hierarchies for amodal over modality specific properties of events, and thus can have a profound effect on development, particularly when there is competition for attentional resources and processing capacity is most limited, as in early development.

Just as sensory limitations in prenatal development are adaptive for promoting healthy differentiation of the senses in an environment of competition for developmental resources, sensory limitations in early postnatal development may be adaptive for promoting optimal perceptual and cognitive development in an environment of competition for attentional resources. Salience hierarchies, like sensory limitations of the fetus, limit the amount and type of incoming stimulation during a time when development is particularly plastic and the system is particularly vulnerable to outside influence (Turkewitz & Kenny, 1982). Thus, the salience of intersensory redundancy in combination with sensory limitations limits the amount of modality-specific detail that can be processed in early development. This effectively buffers the young infant against a flood of disorganized and specific information until a more general organizational framework has begun to emerge. These early emerging patterns of perceiving the world of objects and events in turn support later developing skills such as joint attention, language, and social interaction patterns, promoting subsequent social and cognitive developmental cascades. It is likely that even a relatively slight modification of the typical salience hierarchy could result in an ever widening gap between typical and atypical development, such as that observed in the neurodevelopmental disorder of autism. Although salience hierarchies are likely to have their most profound effects on early development when attentional resources are most limited, they also appear to persist across development and affect performance primarily in tasks that are difficult.

Future research should assess the implications of these and other attentional biases for promoting developmental change, in an atmosphere of competition for attentional resources, for both typical and atypical perceptual development. Attentional biases are likely to affect processing across exploratory time as well as across age and cumulative experience. A relatively unexplored hypothesis is that perceptual processing proceeds in order of attentional salience across exploratory time (similar to a levels of processing view, e.g., Craik & Lockhart, 1972), with processing of the most salient aspects of events first, and later progressing to the less salient aspects. Cumulative experience from such a processing hierarchy in turn may provide a basis for the developmental progressions in order of attentional salience reported here.

The third theme of this chapter stressed integration across studies of typical and atypical development, highlighting the benefits of cross-fertilization for each. Not only does knowledge of typical development provide a foundation for understanding and identifying atypical development such as autism, but developmental disorders such as autism also have a great deal to teach us about typical development. For example, appreciating the importance of identifying developmental precursors to later emerging abilities and understanding the nature of developmental cascades in autism highlights both the relative lack of knowledge and the value of understanding these processes in typical development. There is a critical need for systematic studies of developmental change across multiple ages, under uniform conditions, in the study of typical perceptual development.

In particular, this review highlighted the need for articulating the developmental processes that lead to social orienting in typical infants and toddlers. This seemingly simple phenomenon turns out to be quite rich, complex, and multiply determined, with factors ranging from prenatal determinants, infant-directed speech, dyadic synchrony, and emotional communication playing fundamental roles. The present review suggests that a common denominator across these varied contexts that attracts and maintains attention to social events is the high degree of intersensory redundancy they provide, coupled with the salience of intersensory redundancy to young infants. An intersensory processing impairment in autism was proposed as a basis for social orienting impairment and the resulting cascade of disturbance to social and communicative functioning.

In this chapter, we have seen how significant processes that shape the nature and direction of development originate from the interaction of our limited capacity attentional system and the overabundance of dynamic, multimodal stimulation provided by the environment. It is strikingly clear that the "messiness" of natural, dynamic, multimodal stimulation, in combination with attentional competition from overlapping multimodal events is a key to the typical development of perception, learning, and memory. An important conclusion of this review is the need for developmental science to take seriously the rich and complex structure and conditions of the natural environment for fostering development. Thus, the study of the emergence of skills, whether they be face perception, speech perception, categorization, or language should be conducted in both *unimodal and multimodal* contexts, and in the *dynamic stimulation* of naturalistic events. This effort will promote more integrated, ecologically relevant theories of development, and bring us closer to solving critical applied issues such as the early identification of atypical patterns of development in disorders such as autism.

Acknowledgments

The research and theory development reported here were supported by NIH grants RO1 HD 053776, RO1 MH 62226, and RO3 HD052602, NSF grant SBE 0350201, and Autism Speaks grant #1906. Correspondence should be addressed to Lorraine E. Bahrick, Department of Psychology, Florida International University, Miami, FL 33199, bahrick@fiu.edu.

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