Chapter 8

The role of intersensory redundancy in early perceptual, cognitive, and social development

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> In the simplest of terms, attention refers to a selectivity of response. Man or animal is continuously responding to some events in the environment and not to others that could be responded to (or noticed) just as well.
> *(Donald Hebb 1949, p. 4)*

8.1 **Introduction**

The natural environment provides a flux of concurrent stimulation to all our senses, far more than can be attended to at any given moment in time. Adults are exquisitely skilled at selectively attending to specific features or aspects of objects and events, picking out information that is relevant to their needs, goals, and interests, and ignoring irrelevant stimulation. 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. We long ago learned to pick out human speech from non-speech sounds and parse continuous speech into meaningful words by ignoring variations across speakers, accents, and intonation. Similarly, we have 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 as a result of ongoing experience with objects and events (Kellman and Arterberry 1998; Lewkowicz and Lickliter 1994). This rapid perceptual development entails improving attentional allocation and economy of information pick-up for relevant aspects of the environment by attending to meaningful variability while ignoring meaningless variability (E.J. Gibson 1969, 1988; E.J. Gibson and Pick 2000; Ruff and Rothbart 1996).

A great deal of research and theory has been devoted to understanding how perception and learning develop across the first years of life. In contrast, little developmental research has focused on the processes that guide selective attention to relevant aspects and levels of stimulation in the first place (see Driver 2001; Pashler 1998; Spence and Driver 2004, for useful reviews of adult-based research). Like perceptual development, the progressive honing of selective attention is also the result of ongoing experience with objects and events and provides the basis for further perceptual learning and exploratory activity. In contrast with later development, the early

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development of attentional selectivity is thought to be more influenced by the infant's sensitivity to salient properties of stimulation such as contrast, movement, intensity (e.g. Kellman and Arterberry 1998; Lewkowicz and Turkewitz 1980), and intersensory redundancy (overlapping information across auditory, visual, tactile, and/or proprioceptive stimulation for properties of objects and events; see Bahrick 2010; Bahrick and Lickliter 2002). In this chapter, we explore the powerful role of intersensory redundancy in guiding and shaping early selective attention and, in turn, perception and learning. We review recent empirical and theoretical efforts to better understand what guides the allocation of selective attention during early development and we briefly discuss the implications of early selective attention for perceptual, cognitive, and social development.

8.2 **Perceiving unitary multisensory events in infancy: a basic bootstrapping problem**

The newborn infant faces a significant developmental challenge following birth: how to become increasingly economical and efficient at attending to multisensory 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. This is a particularly challenging task, as the environment provides far more stimulation from multiple objects and events than can be attended to at any given time, each providing stimulation to multiple sense modalities concurrently. The infant must attend to variations in incoming stimulation that are meaningful, relevant, and coherent (e.g. coordinated changes in the face and voice of a single speaker amidst unrelated changes in other objects, people, and events nearby; goal-directed human actions amidst irrelevant movements of people, objects, and events) and ignore other variations that are relatively meaningless (differences in lighting and shadow across cohesive objects, variations in speaker voice or intonation across the same phoneme). What factors might determine which information is selected and attended to by young infants and which information is typically ignored during early development?

Evidence accumulated over several decades of infancy research suggests that selective attention is more stimulus-driven during early postnatal development and with experience becomes increasingly endogenous and modulated by top-down processes, including the individual's goals, plans, and expectations (see Colombo 2001; Haith 1980; Johnson *et al.* 1991; Ruff and Rothbart 1996). Thus, for experienced perceivers, prior knowledge, categories, goals, plans, and expectations typically guide information pick-up (e.g. Bartlett 1932; Chase and Simon 1973; Neisser 1976; Schank and Ableson 1977). What we know and what we expect to happen influence where we allocate our attention and what information we pick up in the present as well as in future encounters. What guides this process in young infants, who have little prior knowledge or experience to rely on in the first months of postnatal life?

8.3 **The salience of amodal information during early development**

Amodal information is information that is not specific to a particular sense modality. Rather, it is information that can be conveyed redundantly across multiple senses, including fundamental aspects of stimulation such as time, space, and intensity. A large body of research has indicated that the detection of amodal information such as temporal synchrony, rhythm, tempo, and intensity is a cornerstone of early perceptual development (see Bahrick 2004, in press; Bahrick and

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Lickliter 2002; Lewkowicz 2000; Lewkowicz and Lickliter 1994). The finding that infants are adept at perceiving amodal information is consistent with J.J. Gibson's (1966, 1979) ecological view of perception, which proposed that the different forms of stimulation available to the senses are not a problem for perception, but rather provide an important basis for perceiving unitary objects and events, such as a person speaking or a ball bouncing. Gibson proposed that our senses work together as a unified perceptual system. For example, by attending to and perceiving amodal information, there is no need to learn to integrate stimulation across the senses in order to perceive unified objects and events, as proposed by constructivist accounts of early perceptual and cognitive development (e.g. Piaget 1952, 1954). Perceiving amodal relations, combined with an increasing sensitivity to the statistical regularities of the environment, effectively ensures that young inexperienced perceivers preferentially attend to unified multimodal events, such as people speaking, dogs barking, or keys jingling.

Temporal synchrony is the most fundamental type of amodal information. Temporal synchrony refers to the simultaneous co-occurrence of stimulation across the senses (e.g. audiovisual) with respect to onset, offset, and duration of sensory patterning. It is a higher-order, global amodal property, in that it can be detected only by abstracting information across different sense modalities (e.g. audible and visual changes) over time. Thus, it is inherently relational and abstract. Furthermore, it facilitates the detection of nested amodal properties such as rhythm, tempo, and duration across the senses (Bahrick 1992, 1994, 2001; E.J. Gibson 1969). Temporal synchrony has been proposed as the 'glue' that effectively binds stimulation across the senses (see Bahrick and Lickliter 2002; Bahrick and Pickens 1994; Lewkowicz 2000). For example, by attending to audiovisual synchrony, the sounds and sights of a single person speaking will be perceived together as a unified event. Detecting this synchronous information can prevent the accidental association of unrelated but concurrent sensory stimulation, such as nearby conversations. The 'ventriloquism effect' (Alais and Burr 2004; Radeau and Bertelson 1977; Warren *et al.* 1981) illustrates the powerful role of synchronous amodal information in guiding perception. Because the ventriloquist moves the dummy's mouth and body in synchrony with his own speech sounds, he or she creates amodal information, which promotes the illusion that the dummy is speaking even though the sound actually emanates from the ventriloquist's mouth. Amodal information (audiovisual temporal synchrony, rhythm, tempo, and intensity changes common to the dummy's movements and the sounds of speech) promotes the perception of a unitary event—the dummy speaking—and effectively overrides information about the source or location of the sound. Young infants show similar sensitivity to synchronous amodal information, even in the first months of life (e.g. Bahrick 1988; Lewkowicz 1996; Morrongiello *et al.* 1998). Importantly, once infant attention is focused on a 'unitary' audiovisual event, further perceptual differentiation of the unitary event can then be promoted. This sequence sets the stage for coherent perceptual processing and in turn provides a foundation for early cognitive and social development.

8.4 **Selective attention: the foundation for perception, learning, and memory**

Attention entails exploratory behaviour such as orienting, eye movements, and active interaction with the environment (e.g. reaching, head turning). These behaviours, provide continuous and contingent feedback to our multiple senses. An obvious but nonetheless important insight is that selective attention to stimulation generated from exploratory activity provides the basis for what is perceived, learned, and remembered. In turn, what is perceived, learned, and remembered, influence what is attended to in subsequent bouts of exploration, in continuous cycles of

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attention → perception → learning → memory → attention, and so on. Figure 8.1 illustrates this dynamic system of influences and the fundamental role of selective attention for perception, learning, and memory. Moreover, action is tightly coupled with these processes, as exploratory activity provides new stimulation for attention, perception, learning, and memory across continuous feedback loops (see Fig. 8.1; Adolph and Berger 2005; E.J. Gibson 1988; E.J. Gibson and Pick 2000; von Hofsten 1983, 1993). This cycle can be characterized as a system of dynamic, interactive influences that evolve over time, with concurrent changes in neurodevelopment that go hand-in-hand with perception and action (see Adolph and Berger 2006; E.J. Gibson 1988; Thelen and Smith 1994, for discussion of such systems).

Surprisingly little scientific effort has been devoted to the study of attentional selectivity in infancy (see Colombo 2001; Ruff and Rothbart 1996 for overviews), despite its obvious importance for perceptual, cognitive, social, and linguistic development. However, in recent years investigators working at the neural, physiological, and behavioural levels of analysis have begun to provide new insights into the nature and processes that guide attentional allocation to unimodal and multimodal stimulation during early development (e.g. Hollich *et al.* 2005; Hyde *et al.*

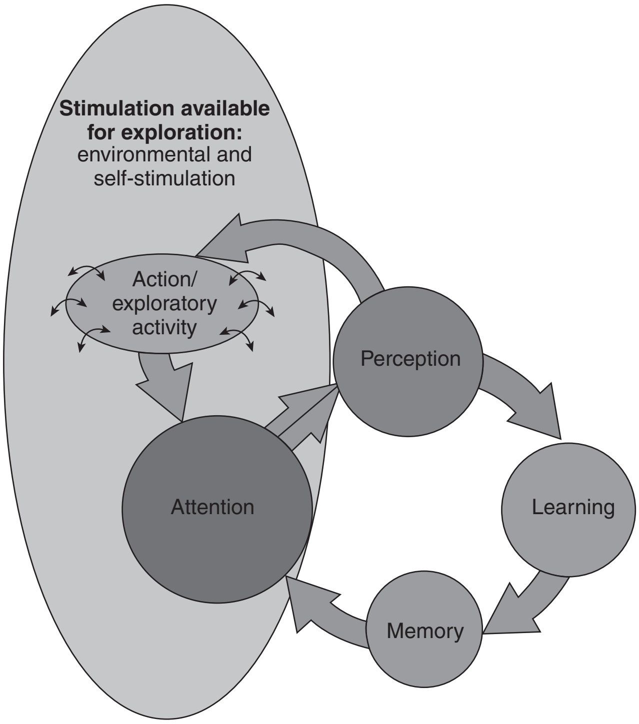

Fig. 8.1 The critical role of selective attention in the development of perception, learning and memory is depicted in two interrelated, concurrent feedback loops: (a) the attention–perception–learning–memory system, and (b) the attention–perception–action system. The arrows represent the primary direction of the flow of information. Selective attention to stimulation that results from 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 sequence in turn affects what is attended to next and in subsequent encounters with similar stimulation. Perception is tightly coupled with action via selective attention to the stimulation generated from exploratory activity in a continuous feedback loop. (Reproduced from Theories of Infant Development, Bremner, and A. Slater, The development of perception in a multimodal environment, Bahrick, L.E., pp. pp. 90–120 © 2004, John Wiley & Sons, Ltd., with permission.)

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2009; Reynolds *et al.* 2010; Richards *et al.* 2010). This work emphasizes the salience of multimodal stimulation for early attention allocation. It is clear that infants quickly establish efficient patterns for selectively attending to relevant and coherent aspects of the environment, and these patterns become increasingly efficient with experience, eventually evolving into the expert patterns of adult selective attention. A central issue for developmental science is to uncover what principles govern this process. We have proposed and provided support for the intersensory redundancy hypothesis (IRH), a framework describing four general principles that we think guide this developmental process (Bahrick 2010; Bahrick and Lickliter 2000, 2002; Bahrick *et al.* 2004a; Lickliter and Bahrick 2004). These principles are all an outcome of infants' sensitivity to intersensory redundancy in attentional allocation, perceptual processing, and learning and memory during the first months of postnatal life. A large body of research indicates that intersensory redundancy promotes attention and perceptual processing of some properties of stimulation at the expense of others, particularly in early development when attentional resources are most limited. We have argued that this has a profound effect on the nature and trajectory of early development (Bahrick and Lickliter 2002).

8.5 The intersensory redundancy hypothesis: a framework for early perceptual development

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 rhythm and tempo of speech can be perceived by looking and by listening, the rhythm and tempo are redundantly specified. Most naturalistic, multimodal events provide intersensory redundancy for multiple properties (e.g. tempo, rhythm, duration, intensity). By definition, only amodal properties (as opposed to modality-specific properties) can be redundantly specified across the senses. Typically, a given event (such as a person speaking) also provides non-redundant modality-specific information, such as the appearance of the face, the colour of clothing, and the specific acoustic qualities of the voice. What guides selective attention to these various properties of events during bouts of exploration? Infant-based research consistently indicates that redundancy across the senses (both global and nested amodal properties) promotes attention to redundantly specified properties of objects and events at the expense of other (non-redundantly specified) stimulus properties, particularly in early development when attentional resources are most limited (e.g. Bahrick and Lickliter 2000, 2002; Bahrick *et al.* 2010; Lewkowicz 2000; Lickliter and Bahrick 2004). Later in development, attention is extended to less salient, non-redundantly specified properties. Factors such as complexity, familiarity, the length of exploratory time, and the level of expertise of the perceiver can affect the speed of progression through this salience hierarchy.

The IRH (Bahrick and Lickliter 2000, 2002) is a model of how selective attention guides early perceptual development. It provides a framework for understanding how and under what conditions attention is allocated to amodal versus modality-specific aspects of stimulation. The IRH addresses how young infants, with no prior knowledge of the world, rapidly come to perceive unitary events and attend to stimulation that is relevant to their needs and actions. Although the IRH is primarily a framework for describing the early development of attention and intermodal perception, the principles can also apply across the lifespan, particularly when attentional resources are limited (for example, for difficult tasks or conditions of high cognitive load).

The IRH consists of four specific predictions. Two predictions address the nature of selective attention to different properties of objects and events. The remaining two are developmental predictions that address implications of the IRH across the life span. The first prediction describes

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the salience of redundantly specified amodal properties in multimodal synchronous stimulation (intersensory facilitation). The second describes the salience of non-redundantly specified, modality-specific properties in unimodal stimulation (unimodal facilitation). The third prediction holds that across development infants become more efficient and flexible processors, leading to detection of both redundantly and non-redundantly specified properties in unimodal and multimodal stimulation. The fourth prediction holds that intersensory and unimodal facilitation are most pronounced for tasks of relatively high difficulty in relation to the expertise of the perceiver, and thus are likely apparent under some conditions across the lifespan.

These four predictions have been supported by empirical studies with both human and non-human animal infants and across non-social and social domains. Below we describe the four predictions of the IRH in more detail and briefly review the research findings that support each prediction. Table 8.1 provides a summary of the convergent research findings from our labs that have supported each of the four predictions to date.

8.5.1 **Prediction 1: intersensory facilitation**

> Redundantly specified, amodal properties are highly salient and detected more easily in bimodal synchronous stimulation than are the same amodal properties in unimodal stimulation.

According to the first and most fundamental prediction of the IRH, intersensory redundancy (the synchronous alignment of stimulation across two or more senses) recruits infant attention to redundantly-specified properties of events (amodal properties such as tempo, rhythm, duration, and intensity), effectively causing them to become 'foreground' and other stimulus properties to become 'background' in a given bout of exploration. For example, intersensory redundancy has been shown to be 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 (e.g. a hand striking the keys of a toy xylophone) is presented to 4-month-old infants, they can selectively follow the flow of action even when the film is superimposed on another film (e.g. a toy slinky or a hand-clapping game). In other words, the sound-synchronized film appears to 'pop out' and become foreground while the silent film becomes background, indicated by the fact that infants respond to the background film as novel when given a novelty preference test (Bahrick *et al.* 1981).

Research from our respective labs (see Table 8.1) has demonstrated that intersensory redundancy promotes enhanced attention and perceptual discrimination and learning in human and non-human animal infants (Bahrick and Lickliter 2000, 2002; Bahrick *et al.* 2002a; Flom and Bahrick 2007, 2010; Lickliter *et al.* 2002, 2004). For example, in the domain of non-social events, human infants detect the rhythm and tempo of a toy hammer tapping when they experience the synchronous sights and sounds together (providing intersensory redundancy), but not when they experience the rhythm or tempo in one sense modality alone or when the sights and sounds are presented out of synchrony (providing no intersensory redundancy, see Bahrick and Lickliter 2000; Bahrick *et al.* 2002a). In particular, our habituation studies demonstrate that infants show visual recovery to a change in tempo or a change in rhythm only in the context of redundant stimulation (i.e. when they can see and hear the hammer tapping in synchrony). In contrast, they show no visual recovery to this change in tempo or rhythm in the context of non-redundant stimulation (i.e., unimodal visual or asynchronous audiovisual hammer tapping). Our data also suggest evidence of intersensory facilitation for detection of tempo changes in adult participants (Bahrick *et al.* 2009a). Research from other laboratories has also provided support for intersensory facilitation. For example, four-month-old infants have been shown to detect the serial order of events in synchronous audiovisual but not unimodal auditory or unimodal visual stimulation (Lewkowicz 2004). Seven-month-old infants can detect numerical information in audiovisual

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Table 8.1 Studies providing support for the intersensory redundancy hypothesis. Most studies listed under 'Developmental change' also include specific age groups which provide support for 'Intersensory facilitation' or 'Unimodal facilitation' as well. Thus these studies are entered again under the respective categories. Under findings, type of stimulation is defined as: A, unimodal auditory (soundtrack accompanied by static image); V, unimodal visual (dynamic visual, no soundtrack); AV, bimodal dynamic audiovisual; Sync, synchronous (soundtrack temporally aligned with video); Async, asynchronous (sound unsystematically out of phase with video). All infant studies were conducted using infant-control habituation procedures, and some also included two-choice preference phases. Discrimination is inferred from visual recovery to a change in infant-control habituation procedures, as well as from preference data. All studies testing bobwhite quail were conducted using two-choice preference procedures. Studies testing children and adults were conducted using forced-choice judgments. Recognition memory is inferred from two-choice novelty preference data and forced-choice judgments

Prediction	Study	Event property	Domains assessed	Stimuli	Subjects	Findings
1. Intersensory facilitation	Bahrick and Lickliter (2000)	Rhythm	Discrimination	Non-social (hammer tapping)	Infants: 5 months	Discriminate rhythm change in AV-sync but not V, A, or AV-async
	Bahrick *et al.* (2002a)	Tempo	Discrimination	Non-social (hammer tapping fast vs slow)	Infants: 3 months	Discriminate tempo change in AV-sync but not V or A
	Lickliter *et al.* (2002)	Multiple temporal properties	Discrimination, recognition memory	Social (maternal call A vs B)	Quail embryos and chicks	Learn and remember call in AV-sync but not A or AV-async across prenatal to postnatal life
	Lickliter *et al.* (2004)	Multiple temporal properties	Discrimination, long-term recognition memory	Social (maternal call A vs B)	Quail embryos and chicks	Learn and remember AV-sync but not A across 4 days
	Lickliter *et al.* (2006)	Multiple temporal properties	Discrimination, recognition memory, educating attention	Social (maternal call A vs B)	Quail embryos and chicks	Discriminate a maternal call with AV-sync→A exposure, but not with A→AV-sync exposure or AV-async →A exposure
	Castellanos *et al.* (2006)	Tempo	Discrimination, educating attention	Non-social (hammer tapping fast vs slow)	Infants: 2 months	Discriminate tempo in V habituation following AV-sync but not V pre-exposure
	Flom and Bahrick (2007)	Affect	Discrimination	Social (women speaking- happy, sad, angry)	Infants: 3, 4, 5, 7 months	3 months, no discrimination 4 months, discriminate AV-sync 5 months, discriminate AV-sync, A 7 months, discriminate AV-sync, A, V

(*Continued*)

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Table 8.1 (continued) Studies providing support for the intersensory redundancy hypothesis

Prediction	Study	Event property	Domains assessed	Stimuli	Subjects	Findings
	Bahrick, Todd *et al.* (2009)	Tempo	Discrimination, recognition memory	Non-social (hammer tapping, four tempos)	Adults	More correct responses (same/different judgments) for AV-sync than V; main effect of task difficulty
	Jaime *et al.* (2010)	Synchrony	Discrimination, educating attention	Social (maternal call A vs B)	Quail embryos and chicks	Onset AV-sync sufficient to enhance learning of maternal call
	Bahrick *et al.* (submitted)	Prosody of speech	Discrimination; categorization	Social (women speaking: approval vs prohibition)	Infants: 4 months	Discriminate approval vs prohibition in AV-sync but not A or AV-async
	Vaillant-Molina and Bahrick (submitted)	Object-affect relations	Discrimination, recognition memory	Social (contingent robot vs pony)	Infants: 5.5 months	Social referencing: discriminate affective expressions and the object to which they refer in AV-sync but not V; prefer to touch objects paired with happy expression
	Castellanos and Bahrick (2008)	Prosody of speech	Discrimination, educating attention	Social (women speaking -approval vs prohibition)	Infants: 3 months	Discriminate prosody in A habituation following AV-sync but not A or AV-async pre-exposure
2. Unimodal facilitation	Bahrick *et al.* (2005)	Pitch of voice	Discrimination	Social (women speaking)	3, 4 months	3 months, discriminate voice in A but not AV-sync 4 months, discriminate voice in A and AV-sync
	Bahrick *et al.* (2006)	Orientation	Discrimination	Nonsocial (hammer tapping up vs down)	Infants: 3,5, 8 months	3 months and 5 months, discriminate orientation in V but not AV-sync 8 months, discriminate in V and AV-sync 3 months, controls discriminate in AV-async
	Vaillant *et al.* (2009)	Pitch	Discrimination	Social (maternal call pitch A vs B)	Quail embryos and chicks	Detect a change in pitch following A but not AV-sync exposure
	Bahrick, Krogh-Jesperson, *et al.* (submitted)	Facial configuration	Discrimination, recognition memory	Social (women speaking)	Children: 4 yrs	Face discrimination and memory in V and AV-async but not AV-sync

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	Flom and Bahrick (2010)	Orientation	Discrimination, long-term memory	Non-social (hammer tapping up vs down)	Infants:3, 5, 9 months	Memory across a 1-month delay for V but not AV-sync at 5 months
3. Developmental change	Bahrick and Lickliter (2004)	Rhythm and tempo	Discrimination	Nonsocial (hammer tapping)	Infants: 3, 5, 8 months	Older infants discriminate tempo and rhythm change in AV-sync and V; younger infants discriminate in AV-sync but not V
	Bahrick *et al.* (2005)	Pitch of voice	Discrimination	Social (women speaking)	Infants: 3, 4 months	3 months, discriminate voice in A but not AV-sync 4 months, discriminate voice in A and AV-sync
	Bahrick *et al.* (2006)	Orientation	Discrimination	Non-social (hammer tapping up vs down)	Infants: 3, 5, 8 months	3 months and 5 months, discriminate V but not AV-sync 8 months, discriminate V and AV-sync 3 months, controls discriminate AV-async
	Flom and Bahrick (2007)	Affect	Discrimination	Social (women speaking-happy, sad, angry)	Infants: 3, 4, 5, 7 months	3 months, no discrimination 4 months, discriminate AV-sync 5 months, discriminate AV-sync, A 7 months, discriminate AV-sync, A, V
	Flom and Bahrick (2010)	Orientation	Discrimination, long-term memory	Non-social (hammer tapping up vs down)	Infants: 3, 5, 9, months	Memory across a 1-month delay emerged by 5 months for V (but not AV-sync) and by 9 months for V and AV-sync; memory was expressed as shifting preference (novelty-null-familiarity) across retention time
4. Task difficulty and expertise	Bahrick *et al.* (2010)	Tempo	Discrimination	Non-social (hammer tapping fast vs slow)	Infants: 5 months	For difficult tasks, older infants discriminate tempo in AV-sync but not V; for easy tasks older infants discriminate tempo in AV-sync and V
	Bahrick, Todd *et al.* (2009)	Tempo	Discrimination, recognition memory	Non-social (hammer tapping 4 tempos)	Adults	More correct responses (same/different judgments) for AV-sync than V; main effect of task difficulty

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sequences of faces and voices developmentally earlier than in auditory or visual sequences alone (Jordan *et al.* 2008).

Similar effects are also found for perception of social events. Detection of emotion and prosody of speech is primarily supported by amodal information, including changes in tempo, temporal patterning, and intensity of facial and vocal stimulation. Four-month-old infants can detect a change in prosody (from approval to prohibition, or vice versa) in bimodally synchronous audiovisual speech, but not in unimodal auditory or asynchronous audiovisual speech (Bahrick, Castellanos, *et al.* submitted). Similarly, four-month-old infants can detect a change in the affect of a woman speaking (happy, sad, angry) in synchronous audiovisual speech, but not in unimodal visual or asynchronous audiovisual speech (Flom and Bahrick 2007). Moreover, social referencing appears to emerge in the context of intersensory redundancy. Infants of 5.5 months can detect the relation between a woman's emotional expression (happy versus fearful) and the object to which it refers when presented with audiovisual redundancy (synchronous audiovisual speech) speech, but not in the absence of redundancy (unimodal visual speech). They also preferentially touch the three-dimensional object previously paired with the happy expression (Vaillant-Molina and Bahrick, 2012). Taken together, these findings demonstrate the powerful role of intersensory redundancy in directing infant selective attention and perceptual processing to amodal properties in both social and non-social events. These parallel findings across social and non-social events indicate that attention and perceptual processing in both the social and non-social domains is governed by the same domain general processes, arguing against the view that perception of social events is a function of domain-specific mechanisms (see Bahrick and Todd, in press).

Studies of non-human animals have also found support for intersensory facilitation, even during the prenatal period of development. Following redundant audiovisual prenatal stimulation (where a synchronized light and a maternal call were presented to embryos), quail embryos learned an individual maternal call four times faster and remembered the individual call four times longer into postnatal development than when they heard the maternal call alone or when the call and light were presented out of synchrony (Lickliter *et al.* 2002, 2004). As can be seen from Tab. 8.1, Prediction 1 of the IRH (intersensory facilitation) has received empirical support across diverse participants (human infants, children, and adults; animal embryos and neonates) and stimulus properties, including tempo, rhythm, affect, prosody, and temporal patterning in both social and non-social events.

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

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2 or 4 hours between initial bimodal stimulation and subsequent unimodal stimulation (Lickliter *et al.* 2006).

A recent study investigated the role of educating attention in perceptual learning at a more fine-grained level of analysis. Jaime *et al.* (2010) found that audiovisual temporal synchrony occurring only at the onset (first note) of the five-note bobwhite maternal call was sufficient to facilitate enhanced perceptual learning of the call when compared to unimodal exposure. Indeed, onset synchrony (the visual stimulus is present only with the first note and not subsequent notes in the call burst) was just as effective as full synchrony across all five notes of the call in facilitating prenatal learning in quail embryos. Apparently, intersensory redundancy created by a single flash synchronized with the first note of the maternal call effectively educated attention to the temporal patterning of the entire call that followed. In contrast, embryos that received alternating auditory and visual stimulation (rather than synchronous exposure) showed no perceptual learning following hatching (Jaime *et al.* 2010).

Studies of human infants have shown parallel findings. Four month-old infants detect a change in the tempo of the toy hammer tapping in unimodal visual stimulation only if they had received a brief pre-exposure to redundant (synchronous audiovisual), but not to non-redundant (unimodal visual or asynchronous audiovisual) stimulation from the hammer tapping (Castellanos *et al.* 2006). Similar results were found for infant detection of prosody in speech (Castellanos and Bahrick 2008). Thus, attention can be 'educated' to amodal properties of events in unimodal stimulation by pre-exposing infants to salient intersensory redundancy, which serves to highlight amodal properties. It appears that infants continue to detect those same amodal properties in familiarized events, even when redundancy is eliminated. Educating attention and shifting exploration from multimodal to unimodal and vice versa is a fundamental and practical process, important for attention allocation in the natural environment. For example, as the mother speaks, her synchronous face and voice may be visible to her infant, but when she turns away while speaking, only her voice is audible. This process of 'educating attention' likely serves as a central means by which infants extend their detection of amodal properties from multimodal to unimodal events.

Taken together, our results from human and animal infants indicate that the intersensory redundancy available in bimodal stimulation plays a key role in organizing early selective attention, and in turn in directing early perception, learning, and memory. In particular, the evidence indicates that redundancy can facilitate attention to amodal properties such as the rhythm, tempo, and temporal patterning of audible and visible stimulation when compared with the same properties experienced in only one sense modality. Moreover, the finding that intersensory facilitation is observed in bimodal *synchronous* but not bimodal *asynchronous* conditions (where the overall amount and type of stimulation are equated) effectively rules out alternative hypotheses: that increased levels of overall arousal or simply receiving stimulation in two different modalities could be the basis for demonstrations of intersensory facilitation.

It is important to emphasize that our findings supporting intersensory facilitation do not suggest that intersensory redundancy is always better for perception or learning than unimodal stimulation nor that, as some studies suggest (e.g. Shams and Seitz 2008), it is superior for perception of all stimulus properties. Rather, intersensory redundancy promotes attention to certain properties of stimulation (amodal) at the expense of other properties (modality specific). Given that the environment provides far too much stimulation to attend to at any given time and that intersensory redundancy is high on the infant's salience hierarchy, it can play a powerful role in regulating and constraining which aspects of stimulation are attended to, particularly early in development when attention resources are most limited. However, in bouts of exploration of the natural environment, intersensory redundancy is not always available. Prediction 2 of the IRH

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describes which properties of events are attended to when intersensory redundancy does not compete for attention—in unimodal stimulation.

8.5.2 **Prediction 2: unimodal facilitation**

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

According to the second prediction of the intersensory redundancy hypothesis, in conditions of unimodal stimulation attention is selectively directed to non-redundantly specified properties such as colour, pattern, timbre, or pitch 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 non-redundantly specified properties within the same event compete for an infant's attention. Because redundantly specified properties are more salient, they typically 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 (comprised of rhythm, tempo, and intensity patterns) at the expense of modality-specific properties such as the appearance of the person, the colour of their clothing, or the specific nature of their voice. In contrast, when salient redundancy is unavailable, as when the person is silent, attention is free to focus on non-redundant, modality specific properties available in unimodal visual stimulation. Under these conditions we would expect to observe unimodal facilitation and enhanced attention to the appearance of the individual.

Consistent with this second prediction of the IRH, research has shown that in early development unimodal stimulation selectively recruits attention and promotes the perceptual processing of non-redundantly specified, modality-specific properties more effectively than does redundant, audiovisual stimulation. The findings of our studies to date supporting this prediction are summarized in Table 8.1 (Prediction 2). For example, Bahrick *et al.* (2006) found that 3- and 5-month olds can discriminate a change in the orientation of a toy hammer tapping against a surface (upward versus downward) when they could see the hammer tapping (unimodal visual) but not when they could see and hear the natural synchronous audiovisual stimulation. This latter condition provided intersensory redundancy, which presumably attracted attention to redundantly specified amodal properties such as rhythm and tempo and interfered with attention to visual information such as the direction of motion or orientation of the hammer. An asynchronous control condition eliminated intersensory redundancy but equated overall amount and type of stimulation with the bimodal synchronous condition. Instead of impairing perception of orientation, asynchronous bimodal stimulation *enhanced* infant perception of orientation when compared with synchronous bimodal stimulation (Bahrick *et al.* 2006). Consistent with the predictions of the IRH, asynchronous sights and sounds resulted in heightened discrimination on a par with that of unimodal visual stimulation. Studies assessing infant discrimination of faces and voices have found similar results (see Table 8.1; Bahrick *et al.* 2004b; Bahrick *et al.* 2005). Young infants discriminated between faces in unimodal visual stimulation and voices in unimodal auditory stimulation, but did not discriminate these stimuli in synchronous audiovisual stimulation. These findings of unimodal facilitation have also been extended to memory for faces in 4-year-old children (Bahrick, Krogh-Jesperson, *et al.* submitted). Unimodal facilitation is thus seen in human infants and children and for both social and non-social events.

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Parallel studies with bobwhite quail have also demonstrated unimodal facilitation for detection of modality-specific properties of stimulation (Vaillant *et al.* 2009). Quail embryos were exposed to an individual maternal call either unimodally (auditory only) or bimodally (redundant light and call) on the day prior to hatching. Following hatching, chicks were tested between the familiar version of the maternal call that was presented prenatally versus the same maternal call with a pitch alteration (raised by one and a half notes, with all other acoustic features held constant). Results revealed that only chicks that had received unimodal exposure to the maternal call as embryos preferred the familiar call over the acoustically modified call following hatching. Chicks that received redundant audiovisual exposure as embryos failed to discriminate the change in pitch, showing no preference between the normal and modified versions of the maternal call during postnatal testing. These results provide evidence that unimodal facilitation for modality-specific properties of stimulation is promoted when salient intersensory redundancy is eliminated and attention is free to focus on the information conveyed by a single sense modality. As summarized in Table 8.1, unimodal facilitation appears to be a general principle of early attention and perceptual processing, applicable across species (human and avian), domains of stimulation (social and non-social), and developmental periods (prenatal, infancy, and childhood).

8.5.3 **Prediction 3: developmental improvement in selective attention**

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

As infants become older and more experienced, their processing speed increases, perceptual differentiation progresses, and attention becomes more efficient and flexible (see E.J. Gibson 1969, 1988; Ruff and Rothbart 1996). For example, older infants habituate more quickly to stimuli, produce shorter looks, more shifting between targets, and can discriminate changes in objects and events with shorter processing times (e.g. Colombo 2001, 2002; Colombo and Mitchell 1990; Colombo *et al.* 1991; Frick *et al.* 1999; Hale 1990; Hunter and Ames 1988; Rose *et al.* 2001). These changes, along with the accumulation of experience differentiating amodal and modality-specific properties in the environment, promote older infants' ability to detect both redundantly and non-redundantly specified properties in unimodal *and* bimodal stimulation within an episode of exploration. Furthermore, attention typically progresses from the most salient to increasingly less salient properties across exploratory time (see Bahrick 2010; Bahrick *et al.* 2002a; Craik and Lockhart 1972). Therefore, as perceptual learning and economy of information pick-up improve, more attentional resources are available for detecting information from multiple levels of the salience hierarchy, progressing from more to less salient. This pattern is consistent with the principle of increasing specificity, originally proposed by E.J. Gibson (1969) as a cornerstone of perceptual development. The principle of increasing specificity proposes that differentiation progresses from abstract and global information to increasingly more specific information across development.

For example, infants show shifts from detection of global (general) to more local (detailed) information (Frick *et al.* 2000), from detection of actions and information about object function to more specific information about the appearance of objects (Bahrick *et al.* 2002b; Bahrick and Newell 2008; Oakes and Madole 2008; Xu *et al.* 2004), and from the detection of more global (general) amodal audiovisual relations to more specific amodal audiovisual relations across exploratory time. Given that patterns of attentional selectivity across exploratory time provide the foundation for infant perceptual and cognitive development, parallel shifts from detection of

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global to specific information are evident across exploratory time *and* across developmental time (see Bahrick 1992, 1994, 2001; Morrongiello *et al.* 1998).

Studies testing predictions of the IRH have provided findings consistent with this progression for both social and non-social events. These studies are summarized in Table 8.1 (Prediction 3). For example, with only a few months' additional experience, infants viewing the toy hammer events described earlier detect redundantly specified properties such as rhythm and tempo (Bahrick *et al.* 2006) *and* non-redundantly specified properties such as orientation (Bahrick and Lickliter 2004) presented via both unimodal visual and bimodal synchronous stimulation. Moreover, evidence indicates that the developmental progression for unimodal facilitation extends to the domain of memory. For example, we found that at 5 months of age, infants could detect and remember the orientation of the toy hammer in unimodal visual presentations (but not in bimodal audiovisual presentations) following a one month retention interval. By the age of 9 months, infants could detect and remember the orientation after a 1-month retention interval in both unimodal visual and bimodal audiovisual presentations (Flom and Bahrick 2010). Thus, attention becomes more flexible across development and, consistent with our view that selective attention provides a foundation for perception, learning, and memory (see Fig. 8.1), effects of unimodal facilitation of attention extend across the domains of perception, learning, and memory and persist across considerable retention intervals (at least 1 month in young infants).

Parallel developmental progressions have been found in the social domain. Although 4-month-old infants can detect affect only in synchronous audiovisual speech, by 5 months of age they detect affect in synchronous audiovisual speech as well as unimodal auditory speech. By the age of 7 months, infants can detect affect in synchronous audiovisual speech, unimodal auditory, and unimodal visual speech (Flom and Bahrick 2007). Thus, patterns of intersensory facilitation and unimodal facilitation (described by Prediction 1 and Prediction 2 of the IRH) that are apparent in early development become less apparent in later development as infants accumulate additional experience with objects and events and their attention becomes more flexible and efficient. As discussed earlier, research with both human and animal infants suggests that one avenue for this developmental improvement is the 'education of attention' (see E.J. Gibson 1969; Zukow-Goldring 1997, for further discussion of this concept.)

The third prediction of the IRH proposes that patterns of intersensory facilitation and unimodal facilitation become less evident across development as discrimination capabilities improve and events become more familiar. However, if tasks are made sufficiently difficult to challenge older perceivers, then the patterns of intersensory facilitation and unimodal facilitation predicted by the IRH should also be apparent. In other words, if task difficulty or cognitive load is increased, we predict that the patterns of facilitation described by the IRH would not disappear across age. Instead, facilitation effects would simply become less evident as individuals become more efficient and skilled at perceiving objects and events with experience. Prediction 4 of the IRH, the most recent prediction, describes the rationale and conditions under which intersensory facilitation and unimodal facilitation should be most evident in later stages of development.

8.5.4 **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 thus should be apparent across the lifespan.

As discussed earlier, we have proposed that continued exposure to an event promotes perceptual differentiation, likely in order of salience, such that more salient properties are differentiated first

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and the differentiation of less salient properties requires longer processing time. Furthermore, 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 and Rothbart 1996). Thus, the degree of intersensory and/or unimodal facilitation observed for an individual should in large part be a function of exposure/familiarization time (which promotes perceptual learning) and task difficulty (defined in measurable units such as differences in intensity, size, or temporal parameters) in relation to the expertise (i.e. cognitive and perceptual skills developed through cumulative experience) of the perceiver. (Note that in early development, expertise roughly covaries with infant age, particularly for general perceptual skills resulting from attention to ordinary events.) Early development is a period during which task demands are typically high. Infants are relatively naïve perceivers of events, and therefore the perceptual processing of most events is likely rather difficult and effortful. Consequently, the effects of intersensory redundancy should be most pronounced in early development. However, because perceptual learning and differentiation occur across the lifespan, intersensory facilitation should also be evident in later development when the task demands are high. Children and adults continue to develop expertise, acquiring new information and learning to perceive finer distinctions such as learning a new language, playing a new musical instrument, or becoming skilled at identifying birds, dinosaurs, or aeroplanes. In early stages of learning, expertise is low in relation to task difficulty, and consequently task demands are high. The IRH predicts that when task demands are high, and attention therefore progresses more slowly along the salience hierarchy, children and even adults should experience intersensory facilitation and unimodal facilitation. Thus, when learning new material that challenges their skill level, intersensory and unimodal facilitation should be observed. Similarly, when cognitive load is high and attentional resources are taxed, such as under conditions of divided attention ('multi-tasking'), conditions that require greater self-regulation, executive function, or higher effort, unimodal and intersensory facilitation should also be apparent in older perceivers.

Research findings, including studies of adult perception (e.g. Kaplan and Berman 2010; Lavie 1995, 2005) are consistent with this view. Studies with infants and children across a variety of domains, including motor and cognitive development, indicate that under conditions of higher task difficulty and cognitive load, performance often reverts to that of earlier stages of development (e.g. Adolph and Berger 2005; Berger 2004; Corbetta and Bojczyk 2002). For example, Berger (2004) found that on a locomotor A-not-B task, 13-month-olds regressed when cognitive load was increased, demonstrating perseverative behaviours characteristic of younger infants. Research generated from predictions of the IRH has directly tested this hypothesis (see Table 8.1, Prediction 4, for a summary). We found that by the age of 5 months, infants no longer show intersensory facilitation for discrimination of simple tempo changes, as their performance was apparently at a ceiling for both unimodal and bimodal audiovisual presentations (Bahrick and Lickliter 2004). However, by increasing task difficulty (requiring finer tempo discriminations), we were able to reinstate intersensory facilitation. Specifically, in the more difficult tempo discrimination task, 5-month-olds showed intersensory facilitation comparable to that shown by 3-month-olds in the simpler discrimination task (Bahrick *et al.* 2010). Data collection with adults is currently underway on this topic and findings thus far indicate intersensory facilitation in adult perceivers under conditions of high task difficulty (Bahrick *et al.* 2009a). Similar research with adults has also demonstrated that bimodal cues capture spatial attention more effectively than unimodal cues under conditions of perceptual load (Santangelo *et al.* 2008; Santangelo and Spence 2007; Spence 2010), again suggesting that multimodal information plays a key role in directing attention in demanding events or situations.

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If findings of intersensory facilitation and unimodal facilitation hold up across studies of adults, this would suggest important applications to educational theory, particularly when children or adults are attending to new or difficult information or when cognitive load is high.

8.6 **Mechanisms of perceptual development: attentional biases, salience hierarchies and developmental change**

Taken together, the findings reviewed in this chapter reveal an attentional trade-off during early development such that under conditions of multimodal stimulation amodal properties are more salient and modality-specific properties less so, whereas in unimodal stimulation, modality-specific properties are more salient and amodal properties are less salient. Because most events are multimodal and because intersensory redundancy is highly salient to young infants, there is a general processing advantage for amodal over modality-specific properties in early development. This processing priority for amodal over modality-specific properties is likely the case both in a given bout of exploration as well as across development.

We have proposed and provided evidence for the notion of attentional salience hierarchies. Selective attention to various properties of stimulation is allocated *in order of attentional salience.* The most salient properties are attended to first, and as exploration continues, attention is then allocated to increasingly less salient properties (Bahrick 2010; Bahrick *et al.* 2002a; Bahrick and Lickliter 2002; Bahrick and Newell 2008). Thus, in the context of a given episode of multimodal exploration, selective attention is likely first allocated to the most salient amodal properties of stimulation, followed later by less salient modality-specific properties. Given limited attentional resources in early infancy, exploration may often be interrupted before attention progresses to less salient properties of stimulation. As processing becomes more efficient with age and experience, attention progresses down the hierarchy more rapidly, and less salient properties can be attended to with increasing frequency and duration. This results in an attentional salience hierarchy across development that parallels the hierarchy observed across individual episodes of exploration. On balance, in early development, attention to salient amodal properties will have a history of greater frequency, duration, and earlier processing across episodes of exploration, as compared with attention to less salient modality-specific properties. Research documenting earlier detection of amodal than modality-specific properties across age, and detection of amodal but not modality-specific properties within age, supports these developmental predictions (Bahrick 1988, 1992, 1994, 2001; Gogate and Bahrick 1998; Hernandez-Reif and Bahrick 2001). However, research has yet to document perceptual processing sequences illustrating attentional salience for amodal followed by modality-specific properties *within* an episode of exploration.

This salience hierarchy, where amodal properties are detected prior to modality-specific properties, fosters coordinated perception by allowing infants to process visual, auditory, and tactile stimulation from unitary events. Moreover, this salience hierarchy serves to guide and constrain perceptual development in order of increasing specificity. Perception of amodal relations (synchrony, rhythm, tempo, duration) constrains attention to unitary multimodal events and in turn promotes further processing of modality-specific detail, providing a coherent event context for organizing detail. For example, in a crowded room, by first processing synchronous, amodal stimulation, the infant is able to differentiate and perceive the sights and sounds of a single individual speaking while ignoring the voices and movements of other objects and individuals nearby. Once attention is focused on multimodal stimulation from a single individual, the infant can then meaningfully process other aspects of the individual such as the quality of her voice, the configuration of her face, and the colour and arrangement of her clothing (while ignoring other voices, faces, and objects). Such selective attention thereby promotes efficient learning about a single

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individual, in order of increasing specificity. Thus, sensitivity to amodal properties promotes attention to unified events and guides subsequent knowledge acquisition by highlighting general perceptual information and constraining the acquisition of specific detail. Without such constraints effectively guiding attention to multimodal events during early development, processing would often be piecemeal and unintegrated. For example, sounds of one individual might be differentiated along with the movements or colours of other individuals or objects nearby, and in turn this would promote further processing of unrelated patterns of stimulation. Thus perceptual salience and processing priority for redundant amodal properties would seem critical for promoting optimal perceptual development and typical developmental outcomes. Furthermore, early salience hierarchies likely have a cascading effect on cognition, language, and social development (which emerge in multimodal learning contexts) by establishing initial conditions which favour processing unitary, multimodal events early in perceptual processing sequences (e.g. Bahrick and Lickliter 2002; Gogate and Bahrick 1998; Lickliter and Bahrick 2000). Importantly, a disturbance of this salience hierarchy, where modality-specific details are acquired prior to or without the context of unitary multimodal events, could potentially contribute to the piecemeal processing and social-orienting impairments observed in children with autism (Dawson *et al.* 1998, 2004; Mundy and Burnette 2005; see Bahrick 2010, for further discussion).

8.7 **Summary and directions for future research**

The studies reviewed in this chapter were generated from a convergent-operations research program designed to address parallel questions across human and non-human animal participants. Our convergent animal-human work has identified several principles of early perceptual development that appear to be common across human and animal infants, including the salience of intersensory redundancy, the importance of amodal information in guiding early perceptual development, and the benefits of educating attention for facilitating learning and memory. Our findings (summarized in Table 8.1) were obtained across species, developmental periods, stimulus event types (social and non-social), and methods of inquiry. As such, they provide evidence for principles of perceptual development that should be generalizable across a wide range of contexts and developmental systems. Our converging results consistently emphasize the importance of selective attention in guiding and constraining development across the interrelated domains of perception, learning, and memory. The rich bidirectional traffic between these interconnected processes (depicted in Figure 8.1) highlights the need for more integrative theories applicable to real world, multimodal settings.

As the various chapters of this volume make clear, there is a growing appreciation of the importance of intersensory perception to social, emotional, cognitive, and language development. Recent findings from neural, physiological, and behavioural levels of analysis have provided evidence that intersensory rendundancy plays a key role in guiding and constraining the course of early perceptual responsiveness. This insight has provided a framework for advancing our understanding of the emergence and maintenance of a number of perceptual and cognitive skills observed during infancy, including affect discrimination (Flom and Bahrick 2007), face discrimination (Bahrick and Newell 2008), rhythm and tempo discrimination (Barhick *et al.* 2010), numerical discrimination (Farzin *et al.* 2009; Jordan *et al.* 2008), sequence detection (Lewkowicz 2004), abstract rule learning (Frank *et al.* 2009), and word comprehension and segmentation (Gogate and Bahrick 2001; Hollich *et al.* 2005). A number of important questions remain to be explored. For example, what accounts for the initial salience of intersensory redundancy and its effects on perceptual processing? Does intersensory redundancy foster longer attentional engagement, deeper processing, or both, and under what conditions?

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Work in embodied and developmental robotics (e.g. Arsenio and Fitzpatrick 2005; Fitzpatrick *et al.* 2008; Lungarella *et al.* 2003; Weng 2004) is advancing our understanding of how sensitivity to intersensory redundancy (particularly audiovisual synchrony) can guide and constrain perceptual, motor, cognitive, and social skills during early development. Developmental robots 'develop' their perceptual, cognitive, and behavioural skills incrementally through real-time explorations and interactions with their environment (Weng 2004). For example, Lungarella and colleagues (2003) note that repetitive actions similar to those often displayed by human infants provide developmental robots a large amount of synchronous multimodal information, which can be used to bootstrap early motor and cognitive processes. In a similar vein, Fitzpatrick and colleagues (2006) have demonstrated the importance of repetition and redundancy to robot perception and recognition of multimodal events. They have provided examples of how binding vision, audition, and proprioception can highlight temporal information and thereby enhance the development of robot perception and recognition of objects and events. Advances in developmental robotics (based in large part on our increasing knowledge of infant development) will likely make a significant contribution to more integrative theories of human perceptual as well cognitive and social development (see Smith and Breazeal 2007).

Studies of atypical development, including autism and autism spectrum disorders (ASD) are also providing evidence that points to the critical role of multimodal stimulation and intersensory processing in promoting typical perceptual, cognitive, and social development (see Bahrick and Todd in press, for a review). Research indicates intersensory processing impairments in ASD, including deficits in intersensory binding, audiovisual speech processing, and matching synchronous sights and sounds, particularly for social events. We have proposed that social events provide exaggerated amounts of intersensory redundancy relative to non-social events, and that infant sensitivity to intersensory redundancy underlies the typical emergence of preferential attention to social events. In ASD, there is a disturbance of intersensory processing, contributing to social-orienting impairments and in turn, affecting language development and contributing to the repetitive behaviours characteristic of ASD (see Bahrick 2010; Bahrick and Todd in press). Making sense of developmental impairments in intersensory processing will undoubtedly contribute to a deeper understanding of the typical development of intersensory processing.

Studies of the neural underpinnings of intersensory processing during early development will also help address important questions about the mechanism underlying the salience of intersensory redundancy. There is a growing body of research on the neural architecture and neural processes involved in intersensory functioning (for overviews see Chapter 14 by Wallace *et al.*; Calvert *et al.* 2004; Stein and Meredith 1993), but little of this research has had a developmental focus (but see Brainard and Knudsen 1993; King and Carlile 1993; Wallace and Stein 2007) and only a few studies have assessed the effects of redundant versus non-redundant stimulation on patterns of neural responsiveness to bimodal events during infancy (e.g. Hyde *et al.* 2009; Reynolds *et al.* 2010). Additional work in developmental cognitive neuroscience focusing on the links between selective attention and intersensory perception is needed to advance our understanding of the neural mechanisms that contribute to how young infants become economical and efficient at attending to multimodal stimulation that is unitary and relevant to their needs and actions.

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