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Intersensory Redundancy Processing in Adults with and without SLI

A dissertation submitted in partial satisfaction
of the requirements for the degree Doctor of Philosophy

in

Language and Communicative Disorders

by

Hanna Michelle Gelfand

Committee in charge:

    San Diego State University

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2015

The Dissertation of Hanna Michelle Gelfand is approved, and it is acceptable in

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Co-Chair

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Chair

University of California, San Diego

San Diego State University

2015

DEDICATION

For my wonderful, inspiring, and incredibly supportive family –
my parents, Gilbert and Candace, and my sister Jenna –
this could not have been done without you.

EPIGRAPH

The most exciting phrase to hear in science,
the one that heralds new discoveries,
is not 'Eureka!' but
'That's funny…'

Isaac Asimov

Energy and persistence conquer all things.

Benjamin Franklin

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ACKNOWLEDGMENTS

I owe the completion of this dissertation to the unwavering encouragement, support, advice and generosity of many wonderful people. Though words never quite seem to be enough, I would like to attempt to express my immense gratitude to those of you who have helped to make the impossible seem possible.

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To my committee members – Jeff Elman, Henrike Blumenfeld, Gedeon Deák, and Robert Kluender – thank you. Jeff, your support, reassurance and guidance over the last couple of years have been truly invaluable to me. Your generosity in offering your lab space afforded me the opportunity to learn about eye tracking and pilot my dissertation research. Your advice about research design was critical to the success of this dissertation. I am so thankful to have had the opportunity to work with you. Henrike, simply put, I am indebted to you. I am not sure how this dissertation would have come together without your selflessness in opening up your lab to me, sharing your participant pool with me, and helping me recruit subjects. I cannot adequately express how much I appreciate the time you have given to me to talk through my ideas and research, to help me troubleshoot, to offer me advice and encouragement,

or simply to just check in with me. Thank you for keeping the research fun. Working with you has been a joy and a privilege. Gedeon, you have been such a source of knowledge and advice for me over the last six years. Thank you for always making yourself available to talk through research ideas and design and thank you for encouraging me to pursue my own research interests. Your feedback has been essential to the quality of this project. Robert, your graduate seminar course has been my most memorable course throughout my graduate training. As a teacher, a researcher, and a mentor you have been such an inspiring role model for me. I am honored and grateful to have you as a member of my committee.

I would like to thank all members of the JDP, whom I have come to know over the years. In particular, I would like to thank Dorothy Yang and Kristen Secora. Your friendship has meant so much to me. Some of my fondest memories of grad school (coffee shop dates, game nights, rides to the airport – Dorothy, late night study sessions – Kristen) have been with you ladies and this journey has been easier because of you. I am so grateful to my labmates, Marisa Sizemore and Erica Ellis. Erica, your constant support, friendship, and encouragement over the years have kept me going. Thank you for showing me the way and for showing me that it could be done. A special thank you to Carly Lemcke for helping me collect my dissertation data.

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ABSTRACT OF THE DISSERTATION

Intersensory Redundancy Processing in Adults with and without SLI

by

Hanna Michelle Gelfand

Doctor of Philosophy in Language and Communicative Disorders

University of California, San Diego, 2015
San Diego State University, 2015

Professor Julia L. Evans, Chair
Professor Jeffrey L. Elman, Co-Chair

A substantial and still growing body of literature has consistently shown that sensitivity to the relationship between auditory and visual information plays an important role in developing language abilities (Kushnerenko et al., 2013; Soto-Faraco et al., 2012). Emerging evidence suggests that audiovisual processing may be impaired in specific language impairment (SLI) (e.g., Norrix, Plante, Vance & Boliek, 2007). The persistence of this finding in SLI over a wide age range has not yet been investigated.

Importantly, typical audiovisual processing follows a protracted developmental trajectory, such that audiovisual processing abilities change with age, and do not reach full maturity until adolescence (Hillock, Powers, & Wallace, 2011; Massaro,

Thompson, Barron, & Laren, 1986; McGurk & MacDonald, 1976). Furthermore, research characterizing these abilities in childhood and adolescence is relatively sparse, compared to research available in adults. Thus, the nature of audiovisual processing abilities in children is less stable and less well understood. Investigating audiovisual processing abilities in SLI in adulthood, when these abilities are more stable, may be more informative about the persistence and pervasiveness of a deficit.

While research on audiovisual processing in adults is much more extensive than in children, findings span disparate fields and research paradigms and, thus, are somewhat disunified (Calvert, Spence, & Stein, 2004). In order to constrain our investigation, we looked at audiovisual processing abilities under the predictions of the intersensory redundancy hypothesis (IRH) (Bahrick & Lickliter, 2012), which makes specific predictions about how multisensory processing (i.e., audiovisual processing) affects behavior in adults. Since this particular hypothesis is relatively understudied in adults, the research in this dissertation necessarily began by investigating the predictions made by the IRH in typical adults, prior to investigating these same predictions in adults with SLI.

This dissertation utilized eye-tracking and behavioral measures to investigate intersensory processing in adults with and without SLI. Chapter 1 provides an overview of the research motivating the questions addressed in this dissertation. Chapters 2-4 present the studies included in this dissertation. Specifically, in Chapter 2, in a group of typical adults (N = 30) accuracy and reaction time in a go/no-go task were compared in audiovisual, auditory-only, and visual-only conditions. In Chapter 3, in a group of typical adults (N = 30) accuracy, reaction time and looking behavior were compared in a go/no-go task, in synchronous and asynchronous audiovisual

conditions, in three different experiments, in which timing, predictive cue value, and signal quality were manipulated. In Chapter 4, normal language adults (N = 12) and adults with SLI (N = 12) were compared on accuracy, reaction time, and looking behavior in a go/no-go task, in three different experiments, which looked at performance in an audiovisual condition versus performance in several comparison conditions. Finally, Chapter 5 discusses the implications the current findings for future research in typical and language disordered populations and for clinical practice.

CHAPTER 1: MULTISENSORY PROCESSING AND LANGUAGE ACQUISITION: CONSIDERATIONS FOR SLI

INTRODUCTION

The constant availability of diverse sensory input makes humans' experience of the surrounding world inherently multisensory. As such, adaptive mechanisms must exist to facilitate perception when multiple streams of sensory information are available. Adaptive mechanisms seem particularly necessary, given that the mere presence of sensory information in the environment does not automatically dictate: a) which information is most relevant at any given time and b) which sensory signals stem from a shared event. In recent years, researchers have become more interested in ecologically valid approaches to the study of cognitive processes, which shifts the focus from the cognitive process to the underlying perception and perceptual knowledge that support the particular cognitive process. This ecological approach to cognitive processes calls for investigations of the relationship among multiple sensory systems rather than investigations of isolated senses. As a result, growing body of work investigating multisensory processes now exists. This body of work has identified basic principles of multisensory processing, provided insight into mechanisms that guide multisensory processing, explored the adaptive value of multisensory processing, and begun to characterize the developmental trajectory of it. Nevertheless, a number of questions remain about the nature of multisensory processing and, in particular, the impact that impaired multisensory processing may have on development.

In this chapter, I review relevant findings of basic principles and mechanisms of multisensory processing in adults. I also review the contributions of multisensory processing to language development. I will then discuss the possible implications of

deficits in multisensory processing for atypical language development, specifically as it may relate to children with specific language impairment (SLI). I conclude with a description of the goals and related studies that are included in this dissertation.

MULTISENSORY PROCESSING IN ADULTS

Terminology

Given the breadth of cognitive processes covered under the umbrella term *multisensory processing,* it is important to briefly discuss the relevant nomenclature. Broadly, *multisensory* or *multisensory processing* refers to conditions where inputs from multiple sensory sources are involved (e.g., auditory input and visual input). *Unisensory* or *unisensory processing* refers to conditions where input from only one sensory source is involved (e.g., only auditory input). For the purposes of this chapter and the dissertation as a whole, it is important to define and make a distinction between two multisensory processes in particular: *multisensory integration* and *cross-modal matching*.

The term *multisensory integration* is used widely throughout the multisensory literature to refer to a variety of different cognitive processes that rely on multiple sensory streams. As a result, the term is not consistently used to describe the *same* dynamic or relationship between different senses during processing (Stein et al., 2010). Therefore, when the term multisensory integration is used, it is not always clear if authors are intending to refer to phenomena where input from multiple senses is *integrated* as apposed to merely *additive*. In this dissertation, multisensory integration will be used to describe a process during which information from more than one sense is combined in such a manner that processing of both senses is qualitatively different from processing of each sense in isolation, resulting in a unique

percept. This usage of the term multisensory integration is consistent with how Stein et al. (2010) define multisensory integration as "the neural process by which unisensory signals are combined to form a new product. It is operationally defined as a multisensory response (neural or behavioral) that is significantly different from the responses evoked by the modality-specific component stimuli" (p. 1719). Multisensory illusion tasks, such as the McGurk task, are examples of multisensory integration. During the McGurk task an auditory speech token (e.g., "ba") is dubbed onto a visually articulated speech token (e.g., "ga"). When processed together, these two sensory signals are integrated and perceived instead as a unique percept (e.g., "da").

Cross-modal matching describes a process during which information from various senses is evaluated to determine if a relationship exists among the various sensory inputs. Again, this definition is consistent with how Stein et al. (2010) define cross-modal matching as "a process by which stimuli from different modalities are compared to estimate their equivalence" (p. 1719). Unlike multisensory integration, cross-modal matching requires "the preservation of the characteristics of the stimulation in each modality" (Stein et al., 2010, p. 1717). In contrast to multisensory integration, with cross-modal matching inputs are not integrated to form a new unique percept. Examples of cross-modal matching can be found in infant studies using preferential-looking paradigms. Many of these studies present infants with auditory and visual stimuli to determine if infants perceive and understand a relationship between the stimuli (e.g., matching an auditory speech token to a visual articulation of that speech token) (Stein et al., 2010). Intersensory redundancy processing, which will be defined and discussed later in this chapter, is also an example of cross-modal matching.

A useful way to delineate 'multisensory integration' from 'cross-modal matching' is to consider the resulting percept. During multisensory integration, information from different sensory sources is combined in some manner to form a new and unique percept (e.g., "da" during the McGurk effect). During cross-modal matching, the resulting percept maintains the characteristics of the input signals (e.g., matching the auditory speech token "dog" to a visual articulation of "dog" still results in the perception of the word "dog"). Rather than integrating information, during cross-modal matching, sensory information is instead evaluated to determine whether or not the information from various sensory sources is related in some capacity. Stein et al. (2010) suggest that cross-modal matching is really a test of whether or not an association exists between the sources of information. In describing what they mean by association, Stein et al. (2010) say the following:

> This association may occur with any two arbitrary correlated features, or through a common amodal variable. Computationally, if two sensory features are cues to the same amodal variable (e.g. gender, intensity, motion etc.), these features are statistically dependent and thus associated. (p. 1717).

While association is also necessary for multisensory integration, association alone is not sufficient to constitute multisensory integration (Stein et al., 2010). Integration and cross-modal matching are the two most commonly studied multisensory processes. The focus of this dissertation is on cross-modal matching and related research.

Basic Findings

Certain fundamental findings appear to govern multisensory processing in particularly important and relevant ways (see Calvert, Spence, & Stein, 2004; Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010, for reviews). Broadly, these findings dictate the allocation of processing resources among various sensory inputs during

real-time multisensory processing (Talsma et al., 2010). Given that this dissertation focuses on audiovisual cross-modal matching, those aspects of the findings on multisensory processing that relate specifically to instances where auditory and visual signals are available will be reviewed here.

Attention Capture

To begin, a general finding in the literature is that temporally synchronous multisensory stimuli are more likely to capture attention than temporally asynchronous multisensory stimuli (Cunillera, Càmara, Laine, & Rodríguez-Fornells, 2010; Dodd, 1977; 1979). Along the same lines, spatially congruent multisensory stimuli are also more likely to capture attention than are spatially discordant multisensory stimuli (Talsma et al., 2010).

Modality Appropriateness Hypothesis

Another fundamental finding in multisensory processing is that, during a multisensory event, perception is most influenced by the sensory system that is more reliable or capable within the context of a given task (see Shams, Kamitani, & Shimojo, 2004; Talsma et al., 2010, for reviews; Welch & Warren, 1980). This is referred to as the *modality appropriateness hypothesis*. This hypothesis suggests that because vision has higher spatial resolution, visual input will have a greater influence on spatial perception than auditory input (Battaglia, Jacobs, & Aslin, 2003). Similarly, audition will have a greater influence on temporal perception because audition has higher temporal resolution than visual input (Hirsh & Sherrick, 1961; Shams et al., 2004; Talsma et al., 2010).

Multisensory Facilitation

Compared to unisensory information, multisensory information has been shown to consistently facilitate behavioral performance. Evidence for facilitation effects have predominately come from investigations of reaction times to multisensory stimuli versus unisensory stimuli. Reaction times are typically faster to multisensory stimuli as compared to unisensory stimuli (Gielen et al., 1983; Hershenson, 1962; Rowe, 1999). This finding holds for both bimodal and trimodal combinations of auditory, visual and tactile input (Diederich & Colonius, 2004). Though more limited in number and scope, there is also evidence showing facilitation effects in accuracy performance when presented with multisensory stimuli as compared to unisensory stimuli (Frassinetti et al., 2002; Lovelace et al., 2003; Watkins & Feehrer, 1965). Investigations of detection under multisensory and unisensory conditions have largely focused on facilitation effects using auditory and visual inputs.

Multisensory facilitation effects have also been shown for more elaborate cognitive processes, including learning and memory (see Shams & Seitz, 2008; Shams, Wozny, Kim, & Seitz, 2011; Talsma et al., 2010, for reviews). For example, Seitz, Kim, & Shams (2006) trained adults on a challenging visual motion perception task using either audiovisual stimuli or visual-only stimuli. Results from the study indicated that adults trained with audiovisual stimuli learned significantly faster than adults trained with only visual stimuli. Recognition memory also improves when items are presented audiovisually as compared to just visually (Lehmann & Murray, 2005). For example, von Kriegstein & Giraud (2006) found that recognition memory for voices improved after initial multisensory exposure (i.e., voice and face), as compared to initial unisensory exposure (i.e., voice only).

Multisensory Facilitation & Temporal Synchrony

While research has shown that temporally synchronous multisensory input is more likely to capture attention than temporally asynchronous multisensory input (Cunillera et al., 2010; Dodd, 1977; 1979), interestingly, perfectly synchronous multisensory input is not necessary in order for performance to evidence facilitation effects. Reaction times to multisensory stimuli continue to evidence facilitation effects even when a visual stimulus precedes an auditory stimulus by as much as 120 ms (Bernstein, Clark, & Edelstein, 1969; Miller, 1986; Morrell, 1968; Nickerson, 1970). To some extent, this is also true for cases where the auditory stimulus precedes the visual stimulus; however, effects are less robust and the asynchrony range that can be tolerated is much more limited (Miller, 1986; Morrell, 1968; Nickerson, 1970). At the cortical level, auditory signals are processed faster than visual signals (see Schroeder & Foxe, 2004, for a review), a finding which has been used to explain why multisensory facilitation effects persist despite temporal asynchronies created by a preceding visual stimulus (Morrell, 1968; Miller, 1986). In general, for asynchronies up to 200 ms, sensory signals are considered to be within reasonable temporal proximity for multisensory processing (see Laurienti & Hugenschmidt, 2012, for a review). However, the size of this time window does vary with age (Diederich, Colonius, & Schomburg, 2008; Laurienti & Hugenschmidt, 2012).

Multisensory Facilitation & Language

The evidence for multisensory facilitation effects that has been discussed thus far has come from investigations of behavioral performance during nonlinguistic tasks. However, evidence for multisensory facilitation effects is not limited to the nonlinguistic domain. Speech perception is a profoundly multisensory process (see

Fowler, 2004; Massaro, 2004; Munhall & Vatikiotis-Bateson, 2004; Soto-Faraco, Calabresi, Navarra, Werker, & Lewkowicz, 2012, for reviews). Thus, it is not surprising that speech perception is amenable to the facilitation effects of multisensory input. For example, perception of a speech signal is more accurate when a listener has access to audiovisual speech (i.e., both the acoustic signal and visual cues from the speaker's face are available) as compared to just having access to auditory or just visual speech information (see Massaro, 2004, for a review; Massaro & Cohen, 1995).

The perceptual benefit of access to both the auditory and visual speech signals is especially salient in instances where the acoustic signal is degraded in some way. For example, speech perception improves with access to audiovisual speech when the auditory signal is degraded by background noise (Dodd, 1977; Sumby & Pollack, 1954). Improved intelligibility for speech in noise with access to visual speech cues has been shown in children (Barutchu et al., 2010; Erber, 1971), adolescents (Dodd, 1977) and adults (Sumby & Pollack, 1954). Eye-tracking studies indicate that the duration of fixations to the nose and mouth increase during speech in noise tasks, providing further evidence that individuals use visual speech cues to support speech perception (Buchan, Paré, & Munhall, 2008). Access to audiovisual speech also facilitates perception of hard to perceive perceptual features, like non-native phonemic contrasts (Navarra & Soto-Faraco, 2007), such that production of and memory for foreign language phrases also improve (Davis & Kim, 2001). Audiovisual speech has also been shown to improve the intelligibility of speech produced by speakers with foreign accents (Arnold & Hill, 2001; Reisberg, Mclean, & Goldfield, 1987; Veinott, Olson, Olson, & Fu, 1997).

While not specific to speech perception, additional findings in the adult multisensory processing literature suggest that language and language related processing benefit from multisensory information. For example, adults' ability to segment words from a continuous speech stream is facilitated by simultaneously presented visual information (Cunillera et al., 2010). Peripherally related to language processing, identification of communicative mechanisms, like emotional expression, also improves with access to auditory and visual cues (Collignon et al., 2008). The literature on multisensory contributions to language, above and beyond speech perception, is comparatively sparse in adults; however, a more substantial developmental literature exists both on multisensory contributions to speech perception and on multisensory contributions to language more generally.

MULTISENSORY CONTRIBUTIONS TO LANGUAGE DEVELOPMENT

Theorists have suggested that multisensory processing is fundamental to cognitive development (Edelman, 1987; Gibson, 1969; Sheya & Smith, 2010; Smith & Gasser, 2005; Thelen & Smith, 1994). Information that is conveyed redundantly or through the coherence of multiple modalities plays a critical role in infants' ability to learn from the mass of information present in the environment (see Bremner, Lewkowicz, & Spence, 2012, for a review; Lewkowicz, 2004; 2000). The fact that infants are able to integrate and/or bind multisensory information within the chaotic medley of sensory signals and noise in the environment, suggests that cognitive mechanisms must exist that provide infants the ability to perceptually navigate their sensory environment. In this section, I will primarily focus the discussion on multisensory contributions to speech perception, since this has been the most studied area of multisensory processing contributions to language development. In particular I

will focus on two aspects of the speech perception literature: (a) early sensitivity to audiovisual speech and (b) the facilitative role of sensitivity to audiovisual speech for other language abilities. I will then discuss an established theoretical account, which describes how multisensory perception operates and contributes to development.

Early Sensitivity: Audiovisual Temporal Alignment in Speech

Previous research has demonstrated that beginning very early on in the course of development, infants are sensitive in a number of ways to both the acoustic and visual cues present when viewing a talking face. These previous studies have demonstrated early sensitivity during both multisensory integration and cross-modal matching forms of multisensory processing. For example, Dodd (1979) showed that 10-16 week old infants were significantly more attentive to stimuli depicting a woman speaking in synchrony with an auditory speech signal as compared to stimuli depicting a woman speaking out of synchrony with an auditory speech signal. This is an example of cross-modal matching. Infants are able to evaluate auditory and visual speech signals for temporal associations. Since Dodd (1979), a number of additional studies have confirmed that infants are sensitive to the temporal relationship between the acoustic speech signal and visual speech cues (Hollich & Prince, 2009; Soto-Faraco et al., 2012).

Early Sensitivity: Audiovisual Congruence in Speech

Beyond sensitivity to the temporal relationship between auditory and visual speech signals, infants also appear to be sensitive to the congruence of information conveyed in auditory and visual speech signals. In a set of landmark studies by Kuhl & Meltzoff (1982; 1984), infants demonstrated preferences for videos of a woman articulating a vowel that matched the accompanying acoustic speech signal as

compared to videos of a woman articulating a vowel that did not match the accompanying acoustic signal. This preference for matching information in the auditory and visual speech signals indicates that infants are sensitive to the relationship between an acoustic speech signal and the articulatory movements that generate that speech signal. These studies demonstrate another example of cross-modal matching in infancy because infants are demonstrating an ability to evaluate the acoustic and visual signals for equivalent speech information. Infants' ability to match auditory and visual signals based on congruency of the speech information has been replicated by a number of additional studies (Pons, Lewkowicz, Soto-Faraco, & Sebastián-Gallés, 2009; Soto-Faraco et al., 2012).

The McGurk Effect in Infants

In addition to sensitivity to congruence of auditory and visual speech signals, studies have looked at sensitivity to incongruence of auditory and visual speech signals. This has been tested using a very well documented phenomenon known as the McGurk effect. The McGurk effect, which is an example of multisensory integration, rather than cross-modal matching, occurs when auditory and visual speech signals conflict in a very specific way (see Green, 1996, for a review; McGurk & MacDonald, 1976) . The canonical example of the McGurk effect occurs when the acoustic signal /ba/ is dubbed on to a video of a person articulating /ga/ and participants report hearing the intermediary or illusory phoneme /da/. Researchers often suggest that the McGurk effect occurs because the brain is attempting to integrate the conflicting auditory and visual signals. It is worth considering the underlying premise of that suggestion: the brain would likely not attempt to integrate these two signals if it were not accustomed to processing auditory and visual speech

signals together. Nevertheless, the McGurk effect is a robust finding in adults (see Soto-Faraco & Alsius, 2009 , for a review). In the original study, McGurk & MacDonald (1976) found that 98% of adult responses to the canonical McGurk paradigm described above were consistent with an illusory percept.

A handful of developmental studies have attempted to determine if the McGurk effect is present in infancy. Burnham & Dodd (2004) tested 4.5-month-old infants using a habituation paradigm and stimuli consistent with the canonical McGurk task. Based on differences in looking times, results from Burnham & Dodd (2004) suggested that 4.5-month-old infants showed evidence of perceiving the McGurk effect. Rosenblum, Schmuckler, & Johnson (1997) tested 5-month-old infants also using a habituation paradigm but the stimuli were not consistent with the canonical McGurk task. Rosenblum et al. (1997), based on looking time data, also suggested that 5-month-old infants showed evidence of perceiving a McGurk effect. However, due to the fact that findings were based on looking-time data rather than verbal responses, a necessity for infant research, it is not clear from this research what exactly the infants were perceiving and if they did, in fact, experience a McGurk effect. What can be concluded from these studies is that infants are sensitive to incongruent audiovisual stimuli in a way, similar to adults, that may alter their perception. Furthermore, these studies provide more evidence that, from a very early age, infants are privy to the synergistic relationship between auditory and visual speech cues.

Multisensory Facilitation & Language Acquisition

Attending to Speech

From an evolutionary standpoint, early sensitivity to the relationship between auditory and visual speech signals must have adaptive value. Indeed, evidence suggests that this sensitivity in infancy may facilitate language acquisition in specific ways. For example, Hollich, Newman, & Jusczyk (2005) found that 7.5-month-old infants were able to attend to a target speech stream in the presence of a concurrent distractor speech stream, but only when dynamic and synchronized visual speech cues accompanied the target speech stream (i.e., video of the speaker matching the target auditory speech stream). In the two experiments where infants succeeded at this task, both the target and distractor passages were played auditorily while infants watched either a synchronized video of a woman reciting the target passage or a synchronized video of an oscilloscope pattern matching the target passage. Infants failed at this task in two additional experiments during which they were presented with both the target and distractor speech streams auditorily, while either an unrelated video of a woman reciting a passage (not the target passage) played on the screen or a static image of a female face appeared on the screen. Taken together, these results do suggest, as Hollich et al. (2005) posit, that infants may rely on visual cues, when the auditory environment is noisy, to select one speech stream from another.

Phonetic Discrimination

Furthermore, research suggests that visual speech cues may facilitate phonetic discrimination in infants. Teinonen, Aslin, Alku, and Csibra (2008) found that infants who were auditorily habituated to synthetic speech stimuli on a /ba/-/da/

continuum, paired with a matching video of a woman articulating either /ba/ or /da/[1], showed evidence of discriminating auditory-only tokens of /ba/ and /da/ at test. In comparison, infants who were habituated to the auditory synthetic speech stimuli on a /ba/-/da/ continuum paired *either* with a video of a woman articulating /ba/ *or* with a video of a woman articulating /da/ did not show evidence of discriminating auditory-only tokens of /ba/ and /da/ at test. Thus, visual speech information heavily influences phonetic discrimination of speech tokens. What makes this finding perhaps more interesting and pertinent to the language acquisition process is the predictive power of phonetic discrimination abilities at 6 months for later language abilities. Tsao, Liu, & Kuhl (2004) found that performance measured at 6 months of age on an auditory only phonetic discrimination task significantly predicated language abilities at 13, 16, and 24 months. Furthermore, Kushnerenko et al. (2013) found a relationship between looking behavior during congruent and incongruent speech at 6-9 months, and later language abilities measured at 14-16 months.

Speech Production

Speech production attempts, an important developmental milestone, represent another stage of language development during which infants may rely on the support of visual speech cues. Speech production attempts begin with canonical babbling at around 6 months of age. Around this time, specifically between the ages of 4 months and 8 months, infants shift their focus of attention from primarily gazing at a speaker's eyes to gazing at the speaker's mouth (Lewkowicz & Hansen-Tift, 2012). Around 12 months of age, when perceptual narrowing has set in and infants are very experienced with the acoustic nature and visual speech cues of their native language,

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[1] Matching was based on the phoneme boundary determined by adult ratings of the /ba/-/da/ stimuli.

attention once again shifts from the mouth back to the eyes. Importantly, this shift that occurs around 12 months of age is not seen when infants are presented with non-native audiovisual speech, suggesting that, much like adults, when the acoustic signal is less familiar, infants continue to rely on visual speech cues to facilitate perception (Lewkowicz & Hansen-Tift, 2012).

MECHANISMS OF MULTISENSORY PROCESSING

In order to develop sensitivity to audiovisual speech perception, infants must be able to simultaneously process and link information across multiple modalities. How does the infant do this? Research suggests that *intersensory redundancies* may act as cues to relevant signals (Bahrick, 2010). Bahrick (2010) defines *intersensory redundancy* as the *simultaneous* co-occurrence of amodal information across two or more sensory modalities.

Naturally occurring phenomena provide both modality-specific information and modality general, also known as amodal, information. Amodal information is information that exists in multiple modalities (e.g., duration) and therefore is not unique to one particular modality (e.g., color, which is uniquely perceived by the visual modality). Thus, amodal information can be perceived either from unisensory stimuli or from multisensory stimuli. Bahrick (2010) suggests that amodal information can exist in three dimensions: time, space and intensity. She further clarifies that temporal synchrony, rhythm, tempo, duration, intensity and spatial colocation are amodal properties typically expressed through auditory, visual and proprioceptive stimuli or phenomena. For example, the same information about tempo is perceived by watching a metronome or by hearing a metronome. Shape, substance and texture are amodal properties more exclusively expressed through visual and tactile stimuli or

phenomena. For example, the same information about shape is perceived by looking at a baseball or by feeling a baseball.

Modality-specific information is, as it sounds, information that is specific to or unique to one modality. Barhick (2010) offers several examples of what constitutes modality-specific information in a variety of modalities: color and pattern are specific to the visual modality, pitch and timber are specific to the auditory modality, and temperature is specific to the tactile modality.

The developmental literature provides a number of examples of the salience and utility of intersensory redundancies in infancy, particularly with respect to audiovisual speech perception, as discussed in the previous section (Kuhl & Meltzoff, 1984; Rosenblum et al., 1997; see Soto-Faraco et al., 2012, for a review). Research has also shown that intersensory redundancies play an important role in infants' ability to learn paired associations (i.e. linking a label to an object). For example, infants are able to learn object-label pairs when redundancy is present through the synchronous movement and labeling of objects; however, when objects remain static or when movement and naming are temporally asynchronous, conditions during which redundancy is not present, infants are not able to learn object-label pairs (Gogate & Bahrick, 1998). Much like adults, infants are especially tuned to intersensory redundancies when the information presented is unfamiliar. Recall the recently discussed study, which investigated infants' gaze patterns to a dynamic talking face and found that as infants grew older and their language skills advanced, less time was spent looking at the speaker's mouth (which presented visually redundant information for the auditory signal) unless the speaker was speaking a foreign language (Lewkowicz & Hansen-Tift, 2012). Results from this study suggest

that infants rely more on redundantly presented information (i.e. audiovisual speech) when they are unfamiliar with or perhaps have under-established representations for the information being presented.

The contributions of intersensory redundancies to development have been formalized in a theory known as the *intersensory redundancy hypothesis (IRH)*, which will be discussed in detail in the following section (Bahrick, 2010; Bahrick & Lickliter, 2000; Bahrick, Lickliter, & Flom, 2004)

The Intersensory Redundancy Hypothesis (IRH)

At its core, Bahrick & Lickliter (2012) suggest, "the IRH is a model of how selective attention guides early perceptual development" (p. 187). Essentially, the model outlines a dynamic and cyclic process by which the sensory information present in the environment differentially influences how selective attention is deployed and, importantly, selective attention determines which information is perceived, learned and remembered. Perceiving, learning, and remembering information equates to experience and expertise, which then also influences what is subsequently attended to in the environment (see Figure 1.1; Bahrick, 2010). Thus, intersensory redundancy is a naturally occurring phenomenon that helps to guide selective attention, which, in turn, determines what experience and expertise the infant will gain about the environment. To reiterate, the cyclical nature of the model suggests that this experience and expertise will then influence which information infants attend to in the future. As such, intersensory redundancy plays an influential and important role in how infants experience and learn from their environment.
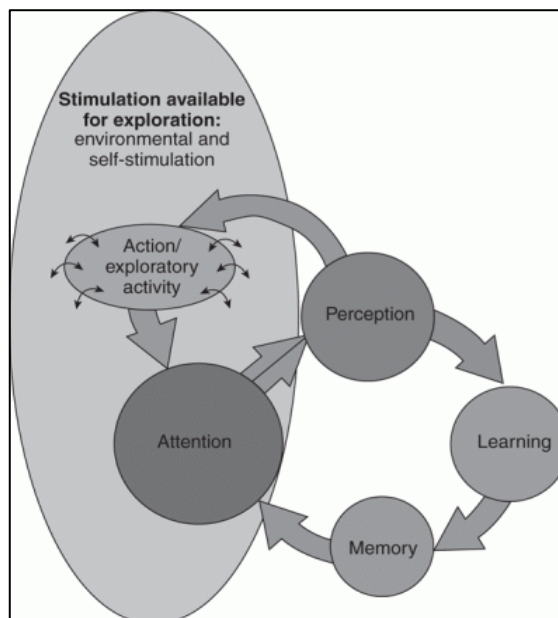
Figure 1.1 Development in a multisensory environment

The specific predictions made by the IRH describe parameters that determine when amodal characteristics of stimuli in the environment are attended to as compared to when modality-specific characteristics of stimuli in the environment are attended to. The goal of the IRH is to explain how the infant learns to associate multisensory information into unitary events. The IRH framework is based on four main predictions. The first prediction of the IRH describes the parameters under which selective attention is guided towards amodal information. The second prediction of the IRH describes the parameters under which selective attention is guided towards modality-specific information. The third prediction of the IRH suggests that selective attention becomes more efficient and flexible over the course of development such that both amodal and modality-specific information can be attended to simultaneously, even when only unisensory information is available to the infant. Finally, the fourth prediction of the IRH suggests that the parameters under

which multisensory or unisensory stimuli show a facilitative effect on perception depend upon the difficulty of the task and the experience of the perceiver. Consequently, the IRH does not limit itself to infancy and instead suggests that facilitative effects may be evident across the lifespan. In short, through these four predictions, the IRH lays out a hierarchy of processing priority based on: (1) the availability of multisensory information, (2) the availability of unisensory information (3) the experience or expertise of the perceiver and (4) the difficulty of the task. The following sections will further explain the predictions of the IRH and review relevant research and evidence for these predictions.

  The Intersensory Redundancy Hypothesis: Prediction 1. The first prediction, referred to as "intersensory facilitation," is fundamental to the IRH (Bahrick & Lickliter, 2012, p. 188). This prediction is stated as follows: "redundantly specified, amodal properties are highly salient and detected more easily in bimodal synchronous stimulation than are the same amodal properties in unimodal stimulation" (Bahrick & Lickliter, 2012, p. 188). According to Bahrick and Lickliter (2012), amodal information conveyed redundantly in the environment is especially salient to infants. In order for amodal information to be conveyed *redundantly*, it must be presented in more than one sensory modality. Thus, the prediction further specifies that amodal information is most salient when presented in a synchronous multisensory context as compared to a unisensory context. To put this prediction in the context of the processing mechanism described by the IRH (see Figure 1.1), when synchronous multisensory information is present in the environment, infants' attention is recruited to processing the amodal information that is redundantly

specified through synchronous sensory inputs, which facilitates perception and learning of this amodal information.

A number of studies have demonstrated the facilitative effects of intersensory redundancies on perception and learning of amodal information (see Bahrick 2010, 2012, for reviews; Bahrick et al., 2004; (Lewkowicz, 2000). For example, Bahrick and Lickliter (2000) found that 5-month-old infants were able to detect a change in the tapping tempo of a toy hammer only when the event was presented audiovisually and in temporal synchrony. Under auditory-only or visual-only unisensory conditions or when the event was presented audiovisually but asynchronously, 5-month-old infants were not able to detect a change in tempo. Bahrick, Flom, and Lickliter (2002) replicated this finding in 3-month-old infants; however, an audiovisual asynchrony condition was not run in this study. Furthermore, studies investigating infants' ability to identify emotions, a property of human communication that can be expressed across multiple modalities, suggest that infants initially need multisensory input in order to identify an emotion (Walker-Andrews, 1997) or detect a change in prosody associated with specific emotions (see Bahrick, 2010, 2012, for reviews).

This first prediction is not meant to suggest an omnipotent strategy for learning in infancy. It is merely a useful tool that provides infants with a way to navigate a very noisy and unfamiliar environment. This is the first building block in the hierarchy laid out by the IRH, which states very specifically how and why infants may rely on intersensory redundancies.

The Intersensory Redundancy Hypothesis: Prediction 2. The second prediction is stated as follows: "non-redundantly specified, modality specific

properties are more salient and detected more easily in unimodal[2] stimulation than are the same properties in bimodal, synchronous stimulation (where redundantly specified amodal properties compete for attention)" (Bahrick & Lickliter, 2012, p. 194). According to the second prediction of the IRH, referred to as "unimodal facilitation," modality-specific characteristics of stimuli in the environment are most salient in a unisensory context (e.g., information from only one sensory modality is available) (Bahrick & Lickliter, 2012, p.194). Bahrick (2010) further clarifies that the reason modality-specific properties are more easily detected in unisensory contexts is because, in multisensory contexts, amodal properties will compete for and are more likely to recruit selective attention. This line of reasoning follows directly from prediction one of the IRH and is also supported by a number of developmental studies. For example, research consistent with this prediction found that 3-month-old infants and 5-month-old infants were able to detect a change in orientation of a tapping hammer only when first habituated to a video of the tapping hammer in a visual-only unisensory context as compared to when they were habituated to the audio and video of the tapping hammer in an audiovisual multisensory context (Bahrick, Lickliter, & Flom, 2006). The orientation of the tapping hammer, which is a property specific to the visual modality, was manipulated by having the hammer tap out a rhythm on a wooden surface above the hammer (upward orientation) or on a wooden surface below the hammer (downward orientation).

Within the IRH framework, unisensory stimulation is discussed as an event where only one kind of sensory information is present. This is not an especially ecologically valid approach for thinking about and studying perceptual development,

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[2] Unimodal and unisensory are synonymous terms.

given that the natural environment rarely, if ever, provides only one kind of sensory information at any point in time. Perhaps a more realistic way to conceptualize a unisensory context is to consider an event where streams of information from multiple sensory sources are available but none of these steams are redundant or temporally synchronous. The IRH does not specify how infants select which stream to attend to in this sort of scenario, but once infants select a stream of information, the IRH would predict that infants would attend to the modality-specific components of the information stream. Research on prediction 2 of the IRH has not considered more ecologically valid unisensory contexts and further consideration of prediction 2 and related unisensory environments is beyond the scope of this dissertation. Suffice it to say, additional research is needed in this area.

The Intersensory Redundancy Hypothesis: Prediction 3. Bahrick & Lickliter refer to this third prediction as "developmental improvement in selective attention" (Bahrick & Lickliter, 2012, p.195). The third prediction is stated as follows: "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" (Bahrick & Lickliter, 2012, p. 195). According to this third prediction, development, which implies more experience and expertise, influences attention, which in turn influences perception and mediates how efficiently information is processed. The third prediction suggests that experience allows for more "flexibility" (Bahrick et al., 2004, p. 101) in selective attention, such that in multisensory and unisensory contexts both amodal and modality-specific information can be selectively attended to, perceived, and processed (Bahrick 2010).

Developmental research offers support for this third prediction. In the Bahrick et al. (2006) study, mentioned in the previous section as support for prediction 2, a third group of infants was tested, in addition to the 3-month-old infants and 5-month-old infants. This third group included 8-month-old infants. Unlike the 3- and 5-month-old infants, 8-month-old infants were able to detect a change in the orientation of a tapping hammer both when they were habituated to the video of the tapping hammer in a visual-only unisensory context and when they were habituated to the audio and video of the tapping hammer in an audiovisual multisensory context. This study demonstrates precisely the developmental improvement in selective attention predicted by prediction 3 of the IRH: as infants develop and become more experienced, they are able to detect both amodal and modality-specific information in both unisensory and multisensory contexts.

It was mentioned earlier that in order to identify emotions, a property of human communication that can be expressed across multiple modalities, infants initially need information from multiple modalities. However, as development progresses infants are able to glean emotion information just from the voice and eventually information about facial expression alone is sufficient (Walker-Andrews, 1997). Again, this reflects the trajectory of learning described in prediction 3: initially amodal information must be redundantly specified and then, after experience and expertise is gained, the same amodal information is also detectable in a unisensory context.

The Intersensory Redundancy Hypothesis: Prediction 4. Bahrick & Lickliter refer to this last prediction as "facilitation across development: task difficulty and expertise" (Bahrick & Lickliter, 2012, p.196). The fourth prediction is stated as follows: "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" (Bahrick & Lickliter, 2012, p. 196). Prediction four places additional parameters (i.e., task difficulty and perceiver expertise) on the facilitative effects defined by predictions 1 and 2 and, in doing so, suggests that these facilitative effects are still evident across the life span. These additional parameters predict that the facilitation defined by prediction 1 in multisensory contexts, and the facilitation defined by prediction 2 in unisensory contexts, will continue to be seen across the life span for tasks that increase cognitive load, tax attention and are difficult given the perceiver's level of expertise. Bahrick and Lickliter (2012) provide examples of the kinds of tasks that increase cognitive load and tax attention and where intersensory and unimodal facilitation may be seen across the lifespan (i.e., in adults). These examples include tasks that require novel learning, divided attention, increased self-regulation, increased executive function, or higher effort.

Bahrick, Lickliter, Castellanos, & Vaillant-Molina (2010) provide evidence for this prediction in infants. In this study, 5-month-old infants were tested on their ability to discriminate tempos at three difficulty levels: low, moderate and high. At the low and moderate levels, 5-month-old infants were able to detect a change in tempo after habituation to a unisensory visual-only video of a hammer tapping at a particular tempo or after habituation to the audio and video of a hammer tapping at a particular tempo. However, at the high level of difficulty, where an increase in discrimination expertise was required, 5-month-old infants were only able to detect a change in tempo after habituation to both the audio and video of the hammer tapping at a particular tempo. Tempo is an amodal property, which, according to prediction 1 is most salient in a redundantly specified multisensory context. 5-month-olds were able

to attend to and perceive this amodal property from unisensory stimulation at the low and moderate levels of difficulty, but needed multisensory stimulation at the high level of difficulty. These finds are in line with the fourth prediction of the IRH.

Support for this prediction in the adult literature is limited despite the studies reviewed in this chapter detailing multisensory facilitation effects in adults. The majority of the studies previously reviewed in this chapter have found facilitation effects during simple detection tasks and/or when stimuli were not presented in temporal synchrony; thus, these studies do not adhere to the parameters of prediction 4 of the IRH. However, the literature on adults' attention and learning in multisensory and unisensory contexts does provide some evidence for prediction 4 (Shams & Seitz, 2008; Talsma et al., 2010). For example, the Seitz et al. (2006) study, previously discussed as evidence of multisensory facilitation in adults, demonstrated improvements in learning efficiency for a difficult visual motion task when adults were trained with audiovisual stimuli. During audiovisual training, the auditory stimuli provided spatial/motion information that was congruent with the visual stimuli (i.e., amplitude varied linearly from the left speaker to the right speaker to match the left to right motion of the visual stimuli). Thus, for the group of adults who received audiovisual training and subsequently learned faster, the spatial information, perception of which was critical to task performance, was redundantly specified. Bahrick et al. (2009) assessed intersensory facilitation effects on perception of changes in tempo and found that adults' accuracy scores were better when tempo was presented audiovisually as compared to just visually.

Taken together, these studies suggest, per prediction 4 of the IRH, that across the life span, during cognitively demanding and/or unfamiliar tasks, the effects of

intersensory facilitation persist. However, the paucity of literature directly testing prediction 4 of the IRH, coupled with an existing literature demonstrating intersensory facilitation effects in adults under conditions that directly oppose the parameters of the IRH, suggest that a more thorough investigation of prediction 4 is warranted to both provide evidence for and further outline the criterion of prediction 4.

As a whole, the IRH describes a powerful learning mechanism that is driven by the kind of sensory information that is present in the environment. Consequently, difficulty processing sensory information, unisensory or multisensory, could pervasively impact perceptual development and subsequent learning. The bulk of this dissertation is concerned with the extension of prediction 4 to intersensory facilitation effects in adults, including in cases where sensory perception may be impaired.

Applications of the IRH

The most relevant application of the IRH to the current work is related to the process of word learning. The contributions to word learning of the principles described by the IRH, and in particular intersensory facilitation (prediction 1), are supported by a number of research studies (see Gogate, Walker Andrews, & Bahrick, 2001, for a review). For example, Gogate and Bahrick (1998) found that 7-month-old infants were able to detect an arbitrary relationship between the vowel sound /a/ or /i/ and an object, only when the auditory signal for the vowel was presented in synchrony with a video of the object moving back and forth. The 7-month-old infants were not able to detect this relationship when the auditory signal and vowel sound were presented asynchronously or when the object appeared on the screen as a static image in conjunction with the auditory signal. However, by 14 months, infants can detect these arbitrary relationships, even when the auditory and visual stimuli are

temporally asynchronous, as long as the visual stimuli are not static (Werker, Cohen, Lloyd, Casasola, & Stager, 1998). These findings support the predictions of the IRH: intersensory redundancies facilitate attention to amodal properties, such as temporal synchrony, which in turn facilitates the learning of arbitrary relationships between words and objects. Further, these findings suggest that over the course of development, experience mitigates the need for intersensory redundancies, again predicted by the IRH.

Research on joint attention has also provided evidence for the contributions of intersensory redundancy to cognitive and language development (see Gogate et al., 2001, for a review). For example, 10-month-olds and 14-month-olds during play look longer at objects that have previously been both pointed at and labeled by adults, as compared to objects that have previously just been pointed at (Baldwin & Markman, 1989). Additionally, 13-month-olds are better able to remember objects that are labeled while they are attending to the object (Woodward, Markman, & Fitzsimmons, 1994).

The IRH only begins to explain how multisensory processing is a mechanism for language acquisition through the basic linking of auditory and visual information. At a higher level, multisensory processing is a mechanism for detecting redundancy across multisensory input, which then allows the infant to establish rich representations. Smith & Gasser (2005) propose that Edelman's (1987) concepts of *degeneracy and reentry* can explain how multisensory processing is a mechanism for establishing rich representations. There are two ideas that underlie the concept of *degeneracy*. The first idea explains that any given function may arise from a number of different neural signal constellations. The second idea explains that constellations

of neural signals may play a role in a number of different functions. As a whole, the concept of degeneracy implies redundancy in the system, such that function is not lost just because a component of the system stops working. The development of spatial cognition provides a good example of how degeneracy is actually manifested in the brain. Space is a dimension of the environment that can be detected through vision, audition and proprioceptive processes (i.e., movement or touch). If any one of these systems becomes unavailable, the concept of space is not also suddenly unavailable, because that information can be perceived through other modalities and other constellations of neurons.

Reentry essentially is multisensory integration. Representations established simultaneously in individual modalities become associated and form a much richer representation. For example, imagine the experience a person has when eating a chocolate chip cookie. A visual representation is established, which includes information about the size and shape of the cookie, its coloring, whether the population of chocolate chips is sparse or abundant and perhaps even if the cookie looks burnt and hard or gooey and soft. All of that information just exists in the visual domain, but smell, texture, taste and weight are all components of the representation of a chocolate chip cookie that cannot be accessed through the visual domain. Touch, taste and smell will provide individual modality specific representations that will contribute to a richer representation of the chocolate chip cookie. The concept of degeneracy is also evident in this example. Visual inspection of the cookie may tell you whether it is burnt, hard, soft or gooey but touch and taste will give additional and more detailed information that will create a much richer representation about the cooked state of the cookie. Even audition could contribute to that representation. The

sound of breaking apart a hard or burnt cookie is very different from the sound made by breaking apart a soft gooey chocolate chip cookie.

Reentry leads to the establishment of reentrant maps. We can use the previous example of the chocolate chip cookie to demonstrate what a reentrant map is and how it is established. The sound difference between a hard or burnt cookie as compared to a soft and gooey cookie would be meaningless by itself. The sound that a hard cookie makes when broken apart is only meaningful, or rather only comes to represent "the sound that a hard cookie makes when it is broken," after experiencing that sound in conjunction with the tactile experience of a hard cookie and the formation of a reentrant map that combines that sound and that tactile experience with the concept of "hard cookie."

How the idea of establishing reentrant maps plays out in in development is well exemplified by a study that looked at how babies develop an understanding of transparency (Titzer, Thelen, & Smith, 2003). Transparency is a rather unique concept because previously established visual-haptic maps would leave an infant ill-prepared to cope with transparency. The study found that 8-month-olds who were given transparent buckets to play with at home for one month were, at 9 months, able to retrieve a toy from a transparent container and demonstrate an understanding of the concept of transparency. In contrast, infants who were given opaque buckets to play with at home for one month were, at 9-months, unable to successfully retrieve a toy from a transparent container. 8-month-old infants who were exposed to the transparent buckets were able to establish visual and haptic representations of transparency and associate those representations through a reentrant map, which

then lead to successful navigation of a transparent container for toy retrieval at 9 months.

It is clear from the literature reviewed up to this point that multisensory processing, specifically intersensory redundancy, is a key cognitive mechanism that helps us navigate and interpret our environment in ways that contribute to cognitive development, perceptual development, and continued learning across the lifespan. The value of intersensory redundancy processing to language development in particular suggests that possible deficits in intersensory redundancy processing should be considered in cases of atypical language development.

MULTISENSORY PROCESSING IN SLI

A consideration of the multisensory contributions to language development raises interesting questions for children with Specific Language Impairment (SLI). SLI is defined as a developmental language disorder characterized by the inability to master spoken and written language comprehension and production despite normal hearing, normal nonverbal intelligence and no observable oral-motor or neurological impairments (Bishop, 2014). Characteristics of the disorder include deficits in the acquisition and use of lexical, grammatical, and morphosyntactic aspects of the language system.

Deficits & Multisensory Implications

As has been discussed previously, research has shown that sensitivity to the relationship between auditory and visual speech signals plays an important and predictive role in a number of emerging language abilities including: orienting attention towards speech (Hollich et al., 2005), phoneme discrimination (Teinonen et al., 2008; Tsao et al., 2004), and word learning (Gogate et al., 2001; Tsao et al.,

2004). Findings showing that children with SLI do not orient to speech automatically, unlike typically developing peers, suggest that children with SLI attend to speech differently (Shafer, Ponton, Datta, Morr, & Schwartz, 2007). Additionally, a number of studies have shown deficits in phoneme discrimination abilities in SLI. For example, children with SLI are less consistent in their categorization of phonemes (Coady, Kluender, & Evans, 2005; Sussman, 1993). Children with SLI also exhibit worse performance on categorical perception tasks when the integrity and familiarity (i.e., using synthesized speech or nonwords) of tokens are manipulated (Coady, Evans, Mainela-Arnold, & Kluender, 2007). Elliott and Hammer (1988) found that children with SLI have more difficulty discriminating phonemes that vary in voice onset time (VOT) as compared to typically developing peers, and at younger ages children with SLI also exhibit difficulty discriminating phonemes based on place of articulation differences. Research has also shown deficits in word learning in SLI. For example, children with SLI are less efficient than their peers when learning novel words and mapping those novel words to novel objects (e.g., Dollaghan, 1987). The alignment of these language deficits in SLI with language abilities that are supported by audiovisual processing as these language abilities develop suggests that an underlying difficulty in audiovisual processing may be contributing to some of the language deficits seen in SLI.

Audiovisual Processing: The McGurk Effect

There is an emerging body of literature that has begun to investigate audiovisual processing in SLI (Boliek, Keintz, Norrix, & Obrzut, 2010; Hayes, Tiippana, Nicol, Sams, & Kraus, 2003; Kaganovich, Schumaker, Leonard, Gustafson, & Macias, 2014; Kaganovich, Schumaker, Macias, & Gustafson, 2014; Leybaert et

al., 2014; Norrix, Plante, & Vance, 2006; Meronen, Tiippana, Westerholm, & Ahonen, 2013; Norrix, Plante, Vance, & Boliek, 2007; Pons, Andreu, Sanz-Torrent, Buil-Legaz, & Lewkowicz, 2012). Most of these studies have investigated audiovisual processing in SLI using a McGurk paradigm (Boliek et al., 2010; Hayes et al., 2003; Kaganovich et al., 2014; Leybaert et al., 2014; Meronen et al., 2013; Norrix et al., 2006; Norrix et al., 2007). During a McGurk paradigm, an auditory CV speech token (e.g., /ba/) is dubbed onto a visually articulated CV speech token (e.g., /ga/) and then typically results in an integrated novel percept (e.g., /da/) (McGurk & MacDonald, 1976). Findings from these studies consistently indicated a weaker McGurk effect in individuals with SLI, and further, with the exception of one study (Hayes et al., 2013), suggested that the weaker McGurk response stemmed from reduced visual speech influence (Boliek et al., 2010; Kaganovich et al., 2014; Leybaert et al., 2014; Meronen et al., 2013; Norrix et al., 2006; Norrix et al., 2007).

Exact methodology and measures of interest varied across studies and these additional findings contribute to our understanding of the nature of audiovisual processing in SLI. For example, Boliek et al. (2010) tested the McGurk effect in a younger age group (6-9 year olds) and an older age group (10-12 year olds) in both typically developing children and children with learning disorders (LD) and found that the typically developing children showed a stronger McGurk effect with age; however, the strength of the McGurk effect did not improve with age for the children with LD. Relatedly, to our knowledge, only one study has investigated the McGurk effect in adults with SLI, and findings from this study indicate that a weaker McGurk effect persists into adulthood (Norrix et al., 2006). Audiovisual processing typically follows a protracted developmental trajectory such that audiovisual integration increases with

age, with proficiency typically occurring during adolescence (Desjardins, Rogers, & Werker, 1997; Hillock, Powers, & Wallace, 2011; Lewkowicz, Minar, Tift, & Brandon, 2015; Massaro, Thompson, Barron, & Laren, 1986; McGurk & MacDonald, 1976).

A number of studies tested the McGurk effect in various noise conditions and found that, regardless of the degree of noise, the degree to which visual speech cues influenced the responses of individuals with SLI remained consistent and weak (Hayes et al., 2003; Leybaert et al., 2014; Meronen et al., 2013). Visual speech cues improve intelligibility when an acoustic signal is degraded by noise (Sumby & Pollack, 1954), and so noise added to the acoustic signal typically encourages more reliance on visual cues (Buchan, Paré, and Munhall, 2008). Relatedly, two of these studies investigated lip-reading (i.e., the ability to identify a closed set of phonemes from visual speech information alone) as a possible explanation for the weaker influence of visual speech information seen in SLI, and found poorer lip-reading skills in individuals with SLI (Leybaert et al., 2014; Meronen et al., 2013). In summary, the above described studies suggest a reduced sensitivity to the McGurk effect in SLI, which persists into adulthood and which may be explained, at least in part, by a reduced sensitivity to the influence of visual speech information and/or an impaired ability to make use of visual speech information.

Audiovisual Processing: Temporal Considerations

While impaired lip-reading skills may explain reduced sensitivity to the McGurk effect in SLI, there are alternative explanations. For example, the ability to integrate auditory and visual signals, or to even identify a relationship between auditory and visual signals, critically depends on sensitivity to temporal coherence across sensory signals (Meredith, Nemitz, & Stein, 1987). An impaired ability to detect overlapping or

redundant temporal features across sensory signals would interfere with audiovisual processing. Alternative explanations will need to be considered if impairments in audiovisual processing extend to non-linguistic tasks, which, until recently, had not been investigated in SLI (Kaganovich et al., 2014). Kaganovich et al. (2014) investigated sensitivity to audiovisual temporal synchrony in children with SLI during a simple nonlinguistic simultaneity judgment task (SJT). Participants were asked to judge whether a 2000 Hz pure tone and a flashed visual shape were presented simultaneously. Stimuli were presented at various timing offsets. Results indicated that children with SLI were much less sensitive to temporal asynchronies as compared to typically developing peers. Findings were consistent regardless of stimulus order when stimuli were offset (i.e., auditory was presented first or visual was presented first). Results also indicated a relationship between performance on the SJT and language ability. Within the SLI group, children who demonstrated superior performance on the SJT task also received higher scores on standardized language measures. In summary, findings from Kaganovich et al. (2014) reveal that individuals with SLI have difficulty identifying the nature of the temporal relationship between auditory and visual signals and, furthermore, these findings reveal a strong relationship between sensitivity to audiovisual temporal synchrony and language ability in SLI.

One additional study has investigated sensitivity to audiovisual temporal synchrony in children with SLI, in this case during a linguistic task (Pons et al., 2012). Pons et al. (2012) assessed sensitivity to audiovisual speech synchrony based on gaze behavior to two side-by-side videos of a talking face while participants listened to an auditory track. One video was temporally synchronous with the auditory track

while the other video was temporally asynchronous with the auditory track by a magnitude of either 366 ms or 666 ms. Both auditory first and visual first asynchronies were tested. Findings indicated that neither typical children nor children with SLI were able to detect asynchrony at 366 ms; however, children with SLI showed reduced sensitivity to audiovisual synchrony (i.e., similar looking behavior to both videos) when the video preceded the auditory track by 666 ms. Typically developing children looked significantly more at the synchronous video when the asynchronous video was offset by 666 ms, and results were consistent for both the auditory first asynchrony and the visual first synchrony. Taken together, these findings, along with the findings from Kaganovich et al. (2014), indicate that children with SLI have difficulty detecting temporal coherence across both auditory and visual speech signals and non-linguistic auditory and visual signals.

Auditory Processing: Temporal Considerations

An implied and necessary ability for detecting temporal synchrony among sensory signals is the ability to process temporal parameters within each sensory signal. Recent accounts focusing on temporally related auditory processing in SLI have proposed an underlying deficit in acoustic entrainment to speech rhythm (Corriveau, Pasquini, & Goswami, 2007; Cumming, Wilson, & Goswami, 2015). Specifically, this research has proposed and provided evidence for reduced sensitivity to amplitude envelope rise times (ARTs) (Corriveau et al., 2007; Cumming et al., 2015; Richards & Goswami, 2015). ARTs signify syllabic properties (i.e., stress and boundaries) based on amplitude variation across time (duration) (Goswami & Leong, 2013). Furthermore, sensitivity to ARTs plays an important role in tracking the temporal contour of syllable beat structure in language (i.e., the rhythmic structure of

language), which, in turn, is foundational to language development (Cumming et al., 2015; Goswami & Leong, 2013). For example, 6 to 8-month-old infants use rhythm to identify phrase and clause boundaries in a continuous stream of speech (Hirsh-Pasek et al., 1987). 9-month-olds use the rhythmic structure of speech to facilitate identification of possible word candidates (Morgan & Saffran, 1995). Importantly, research has shown that entrainment to the rhythmic units of speech occurs in both the auditory and visual cortex and entrainment in each of these modalities can influence entrainment in the other modality (Luo, Liu, & Poeppel, 2010). Thus, difficulty processing temporal aspects of an auditory signal could interfere with entrainment, which subsequently may affect the ability of individuals with SLI to perceive redundant temporal information across the auditory and visual modalities.

Visual Processing: Temporal Considerations

Furthermore, recent accounts of audiovisual processing have suggested that deficits in *visual* entrainment may disrupt auditory processing, specifically neural phase-locking in the auditory cortex (Power, Mead, Barnes, & Goswami, 2012). Neural phase-locking, also known as rhythmic entrainment, describes a process by which neural oscillations phase-lock to the temporal structure of an input stream so that the phases during which neurons are in a highly excitable state coincide with the occurrence of events in the stimulus stream (Golumbic, Poeppel, & Schroeder, 2012; Goswami, 2011; Power et al., 2012). Research has suggested that visual input can affect and even facilitate entrainment of the auditory cortex. Specifically, it has been suggested that the contributions of visual speech to the perception of an auditory speech signal (Sumby & Pollack, 1954) are the result of visual entrainment facilitating auditory entrainment (Schroeder, Lakatos, Kajikawa, Partan, & Puce, 2008)

The research available on visual processing in SLI, particularly as it relates to temporal processing, is limited. As discussed above, a number of studies looking at the McGurk affect in SLI suggest a weaker influence of visual speech information, which indirectly suggests possible deficits in processing temporal aspects of a visual signal (Boliek et al., 2010; Leybaert et al., 2014; Meronen et al., 2013; Norrix et al., 2006; Norrix et al., 2007). Kaganovich et al. (2014) found significantly lower accuracy in the SLI group as compared to the typically developing group to visual-only trials during the SJT (different button responses were required for judgments of simultaneous presentation versus not simultaneous presentation), which essentially required a simple response to the presence of a visual stimulus. This finding also only indirectly suggests possible deficits in processing a visual signal, which may then be contributing to audiovisual processing deficits (Kaganovich et al., 2014).

Audiovisual, Auditory, & Visual Proccessing: Summary

There is mounting evidence for audiovisual processing deficits in SLI. Difficulty in entrainment to the temporal structure of auditory and/or visual signals may contribute to these audiovisual processing deficits. However, more research is needed to explore the pervasiveness of audiovisual processing deficits in SLI and the potential downstream effects of deficits in audiovisual processing. Of particular importance is deepening our understanding of audiovisual processing abilities in adults with SLI.

Developmental Trajectory of Audiovisual Processing

As has been briefly mentioned, audiovisual processing follows a complex and protracted developmental trajectory (Desjardins et al., 1997; Hillock et al., 2011; Lewkowicz et al., 2015; Massaro et al., 1986; McGurk & MacDonald, 1976). For

example, auditory and visual signals may be perceived as being synchronous even with some degree of temporal separation between the signals (see Vroomen & Keetels, 2010, for a review). However, the size of this time window changes over the course of development such that it is widest during infancy (Lewkowicz, 1996) and late adulthood (Diderich et al., 2008; Laurienti & Hugenschmidt, 2012). The size of this time window may continue to be relatively large throughout childhood and adolescents (Hillock et al., 2011; Hillock-Dunn & Wallace, 2012); however, research in this age range is very limited. Additionally, the influence of visual information during audiovisual processing changes over the course of development such that infants and adults are more heavily influenced by visual information than pre-school and school-age children (Mcgurk & MacDonald, 1976; Soto-Faraco et al., 2012). The influence of visual information appears to be reduced in early childhood and then steadily increases to reach full maturity during adolescence (Massaro et al., 1986; Mcgurk & MacDonald, 1976; Soto-Faraco et al., 2012). Notably, far fewer studies exist investigating the relative influence of visual information on audiovisual processing throughout childhood and adolescence.

To summarize, not only are audiovisual processing abilities much less stable during childhood, as compared to during infancy or adulthood, but, also, the available research on audiovisual processing in childhood is sparse, which means our understanding of audiovisual processing in childhood is not well established. What this suggests for audiovisual processing research in SLI is that investigating audiovisual processing in adults with SLI may be a better approach. Investigating audiovisual processing once this ability has stabilized (e.g., in adulthood) will give us a better sense of how robust and persistent deficits in audiovisual processing are in

SLI. Furthermore, because our understanding of audiovisual processing in adults is somewhat more enriched, we may be able to better interpret the meaning and significance of differences in SLI.

GOAL OF THE DISSERTATION

The purpose of this dissertation is twofold: 1) examine and further characterize intersensory redundancy processing in adults per the predictions of the IRH in order to use these findings as a mechanism for 2) examining audiovisual processing in the form of intersensory redundancy processing and contributing unisensory processing skills in adults with SLI. Addressing our first goal, while a literature on intersensory redundancy processing in adults exists (much of which has been reviewed here) and has forged inroads into characterizing intersensory redundancy processing in adults, very few studies have tested intersensory redundancy processing under the parameters proposed by the IRH. As a result, gaps remain in our knowledge about how intersensory redundancy facilitates performance in adults (e.g., which measurable behaviors are facilitated) and under what conditions adults demonstrate facilitation. These remaining questions need to be addressed prior to pursuing our second goal of investigating intersensory redundancy processing in adults with SLI. If adults with SLI do not demonstrate deficits in intersensory redundancy processing, then it may be the case that cross-modal matching variants of multisensory processing mature more slowly in SLI, but eventually fall within the typical range. This finding may have important implications for clinical intervention strategies over the lifespan of an individual with SLI.

Using behavioral and eye-tracking methods, the questions addressed in this dissertation are as follows:

1) In typical adults, during a temporally based executive function task, is behavioral performance facilitated by intersensory redundancy (i.e., audiovisual information) as compared to having access to only unisensory information (i.e., audio-only or visual-only) (Chapter 2)?;

2) In typical adults, how is intersensory facilitation affected by timing and signal quality (Chapter 3)?;

3) Do adults with and without SLI experience similar patterns of intersensory facilitation and further, is there evidence of differences in unisensory processing or gaze patterns, which may contribute to any existing group differences in intersensory facilitation (Chapter 4)?

This dissertation thoroughly examines a number of factors that influence intersensory redundancy processing in adults with and without SLI. The research included in this dissertation contributes to the characterization of intersensory redundancy processing in adults and highlights important methodological considerations for future multisensory processing research. Furthermore, this research contributes to the growing body of literature on multisensory processing in SLI and lays the groundwork for a multisensory approach to research and hopefully, to more effective intervention strategies for individuals with SLI.

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CHAPTER 2: INTERSENSORY FACILITATION IN EXECUTIVE PROCESSES: TESTING PREDICTIONS OF THE INTERSENSORY REDUNDANCY HYPOTHESIS

ABSTRACT

Prior research suggests that access to information from more than one sensory modality (e.g., auditory and visual), as compared to information from a single modality, can lead to a variety of performance enhancements (Rowe, 1999). The Intersensory Redundancy Hypothesis (IRH) more specifically outlines the nature of perceptual processing in multisensory and unisensory contexts and makes the prediction that, under certain circumstances, adults will experience perceptual facilitation when synchronous multisensory information is available, as compared to when only unisensory information is available (Bahrick, 2010). In this study, we tested whether this hypothesis extends to a temporally based executive function task in a group of thirty young adults. Accuracy and reaction times were examined on a go/no-go detection task presented in unisensory (auditory-only or visual-only) or temporally synchronous multisensory (auditory and visual) conditions. Results indicated specific, limited enhancements to performance when multisensory information was available. These results only partially support the IRH predictions. Task design and previous findings from research looking at the interaction between multisensory facilitation and the processing strengths of individual modalities are considered as possible explanations for the current findings.

INTRODUCTION

In the everyday environment, human beings have access to an array of sensory information. Therefore, perception and consequent learning occur neither in vacuums nor in neatly constrained environments where individual modality specific information is experienced in isolation. In the everyday environment, human beings are *constantly* bombarded by sounds, sights, smells, and tactile experiences, and this multisensory milieu contributes to what and how humans learn about the world. The ability to process information from multiple sensory sources simultaneously, associatively, and selectively may be the driving force behind the development of effective and efficient cognitive processing and learning. At any given time, the natural environment provides an abundance of perceptual information from a variety of sensory sources, and this begs the question: Is multisensory information useful for extracting and predicting regularities about the environment? Furthermore, if multisensory information is particularly useful in some regards, what factors determine how and when it is useful?

Multisensory Advantages

A number of studies suggest that multisensory information, as compared to the availability of unisensory information (i.e., information comprised of only one type of sensory information), is beneficial to some aspects of perception and action in a variety of ways. The most ecologically valid examples come from studies of audiovisual speech perception, speech perception in noise, and perception of nonlinguistic communicative acts like emotional expression. Audiovisual speech, defined as speech in which both the acoustic speech signal and lip cues from the speaker's face are available, yields more accurate perceptions of the intended

speech signal than speech produced by either modality alone (see Massaro, 2004, for a review; Massaro & Cohen, 1995). Additionally, the availability of visual speech cues significantly improves the intelligibility of a speech signal degraded by the addition of background noise (Dodd, 1977; Sumby & Pollack, 1954). This finding holds across child, adolescent and adult populations (Barutchu et al., 2010; Dodd, 1977; Erber, 1971; Sumby & Pollack, 1954), suggesting that visual speech cues are used to support speech perception across a wide range of developmental stages. Studies have also found that access to visual speech cues can improve the intelligibility of accented speech from a non-native speaker (Arnold & Hill, 2001; Veinott, Olson, Olson, & Fu, 1997). Similarly, sensitivity to hard to perceive perceptual features, such as non-native phonemic contrasts, improves with access to audiovisual speech as compared to speech presented in by either modality alone (Navarra & Soto-Faraco, 2007). Accurate identification of nonlinguistic communicative acts, such as emotional expression, is also improved by the presence of both auditory and visual cues as compared to the presence of cues from either modality alone (Collignon et al., 2008).

The findings described above give way to additional questions about the mechanisms of multisensory information. Specifically, how does multisensory information facilitate language processing and paralinguistic cue processing? We might derive some hints by considering the nature of behavioral responses that are sensitive to multisensory information. Reaction times are faster in the presence of coordinated multisensory information than when only unisensory information is present (Gielen, Schmidt, & Van Den Heuvel, 1983; Hershenson, 1962; see Rowe, 1999, for a review). This effect has been shown for both bimodal and trimodal

combinations of auditory, visual and tactile inputs (Diederich & Colonius, 2004). Accuracy, as measured by detection probability (d'), also improves in the presence of multisensory information as compared to unisensory information (Frassinetti, Bolognini, & Ladavas, 2002; Lovelace, Stein, & Wallace, 2003; see Rowe, 1999, for a review; Watkins & Feehrer, 1965). These studies have primarily used auditory and visual information to compare multisensory and unisensory conditions. Additionally, most of these studies have used very basic detection tasks, in which participants were asked to make button responses to the presence of a singular visual target, a singular auditory target, or a singular audiovisual target (e.g., Gielen et al., 1983; Hershenson, 1962; Diederich & Colonius, 2004; Watkins & Feehrer, 1965, but see Lovelace et al., 2003). Non-target trials were typically defined by the absence of the target stimulus rather than the presence of a foil non-target stimulus (Frassinetti et al., 2002; Lovelace et al., 2003). These paradigms are only abstractly related to the sort of multisensory discriminative judgments that are ubiquitous in language comprehension. It is therefore useful to consider evidence from other paradigms.

Additional evidence for the beneficial nature of multisensory information comes from studies of adults' learning and memory in multisensory and unisensory contexts (see Shams & Seitz, 2008; Shams, Wozny, Kim, & Seitz, 2011; Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010, for reviews). For example, Seitz, Kim, and Shams (2006) trained adults on a visual motion perception task that is challenging enough to require many training sessions. One group of adults was trained using audiovisual stimuli, whereas the other group was trained using the typical visual-only stimuli. Both groups' learning was measured by performance on a visual-only version of the task. Results indicated that adults trained using audiovisual stimuli learned

significantly faster than adults trained using visual-only stimuli, even though the test more closely resembled the latter group's training stimuli. Lehmann and Murray (2005) investigated the effects of multisensory presentation on recognition memory for previously presented items, and found improved recognition memory for items that had been presented audiovisually, as compared to items that had only been presented visually. Similarly, von Kriegstein and Giraud (2006) found improved recognition memory for voices after initial multisensory exposure (voice and face), as compared to initial unisensory exposure (voice only).

Evidence for the beneficial effects of multisensory information has also been reported in infants and children, suggesting that multisensory processing might play an important role in early learning processes across a wide age range. A number of studies have demonstrated the facilitative effects of multisensory information on perception and learning in infancy (see Bahrick 2010, 2012, for reviews; Bahrick, Lickliter, & Flom, 2004; Lewkowicz, 2000). For example, Bahrick and Lickliter (2000) found that 5-month-old infants were able to detect a change in the tapping tempo of a toy hammer only when the event was presented audiovisually, but not when it was presented via auditory-only or visual-only conditions. Bahrick, Flom, and Lickliter, (2002) replicated this finding in 3-month-old infants. Furthermore, studies investigating infants' ability to identify emotions, a property of human communication that can be expressed across multiple modalities, suggest that infants initially need multisensory input in order to identify emotions (Walker-Andrews, 1997) or to detect changes in prosody associated with specific emotions (Bahrick, 2010, 2012). In summary, the processing benefits of multisensory information are evident across a wide age range, in a number of behavioral measures and during a variety of tasks.

Constraints on Multisensory Processing

The literature on multisensory processing also suggests that there are constraints both on how performance improves with access to multisensory information and on what kind of multisensory information best facilitates performance. For example, previous findings in infants, adolescents and adults suggest that temporally synchronous multisensory stimuli are much more likely to capture attention than asynchronous multisensory stimuli (Cunillera, Càmara, Laine, & Rodríguez-Fornells, 2010; Dodd, 1977; 1979). This suggests that attention-orienting systems are sensitive to temporal synchrony across modality-specific energy sources, and thus, may help to explain why temporally synchronous stimuli may be critical for receiving maximum facilitation effects from access to multisensory stimuli (Bahrick & Lickliter, 2000; Shams & Seitz, 2008; Talsma et al., 2010). Relatedly, spatially congruent multisensory stimuli are more likely to capture attention (see Talsma et al., 2010, for a review) and elicit facilitative effects on performance (Frassinetti et al., 2002; Gingras, Rowland, & Stein, 2009; Seitz et al., 2006; Spence & Driver, 1996).

Research has also shown that the availability of multisensory information affects which perceptual features are most salient and thus most likely to be attended to and processed (see Bahrick & Lickliter, 2012, for a review). Naturally occurring phenomena provide both modality-specific information as well as modality general information. The Intersensory Redundancy Hypothesis (IRH) makes predictions about the kind of information that is processed (i.e., modality-specific or modality-general), and about subsequent effects on performance, based on the availability of multisensory (e.g., auditory and visual) versus unisensory (e.g., only auditory or only visual) information. More specifically, the IRH describes an orienting mechanism that

guides selective attention towards certain perceptual features based on the availability of multisensory information versus unisensory information (Bahrick, 2010). For example, according to the IRH, synchronous auditory and visual information facilitates perception of modality-general or redundant features (which Bahrick, 2010, calls 'amodal' features), such as tempo (e.g., beats per minute in music), rhythm (e.g., a repetitive temporal pattern of sequenced energy changes), duration, intensity, and spatial co-location (Bahrick, 2010). Bahrick (2010) defines *intersensory redundancy* as the *simultaneous* co-occurrence of amodal information across two or more modalities.

Bahrick and Lickliter (2012) propose that *intersensory facilitation* occurs when redundant multisensory information is available and thus makes amodal information salient enough to recruit selective attention. The IRH predicts that intersensory facilitation occurs throughout the lifespan, but its conditions are somewhat age specific. For example, intersensory facilitation occurs in adults during tasks that are difficult for their level of experience and during tasks with high cognitive or attention demands (e.g., novel learning, divided attention, increased self-regulation, increased executive function, or higher effort).

Although there is converging evidence from infant studies for predictions of the IRH (see Bahrick & Lickliter, 2012, for a review), there is limited direct evidence from adult studies (Bahrick et al., 2009; Bahrick & Lickliter, 2012). Prior research, reviewed above, demonstrates facilitative effects of access to multisensory information but has not necessarily included all three critical elements of the IRH: (1) the presence of intersensory redundancy; (2) assessing perception of the redundant feature; and (3) assessing performance on a demanding task. For example, studies

that have demonstrated multisensory facilitation effects on reaction times have largely failed to present stimuli representing true intersensory redundancy. Multisensory stimuli are often not matched for onset and/or duration (Diederich & Colonius, 2004; Gielen et al., 1983; Hershenson, 1962), which is necessary in order to achieve true intersensory redundancy (Bahrick, 2010).

Furthermore, studies demonstrating multisensory facilitation effects on both reaction times and accuracy, have largely relied on simple stimulus detection tasks, in one modality or the other (Diederich & Colonius, 2004; Frassinetti et al., 2002; Gielen et al., 1983; Hershenson, 1962; Lovelace et al., 2003; Watkins & Feehrer, 1965). These measures do not assess sensitivity to redundant or amodal stimulus features, but rather detection thresholds for modality-specific stimulus properties, or detection thresholds for a stimulus item, without specific interest in any particular stimulus feature. These findings do not provide direct support for the IRH, which specifically predicts that perception of *redundant* features is facilitated by multisensory presentation. Additionally, the use of simple detection tasks does not test the prediction of the IRH that intersensory facilitation is elicited in demanding task contexts. In summary, much of the prior work on facilitative effects of multisensory information indicates that multisensory information is more likely to capture attention, and thereby improve performance in simple perceptual tasks. These results are also consistent with the IRH (Bahrick & Lickliter, 2012), but the IRH further predicts that redundant (amodal) information conferred by temporally patterned multisensory information can facilitate selective attention, and improve subsequent performance, even in demanding tasks. To date, research has directly tested the IRH by assessing performance on a demanding task based on perception of spatially redundant

audiovisual features (Seitz, Kim, & Shams, 2006), but has not yet tested IRH predictions for *temporally* redundant audiovisual features. Because amodal temporal redundancy is a ubiquitous feature of spoken language processing, this suggests a highly ecologically relevant test of the IRH.

Present Study

Two goals motivated the current project. Our first goal was to directly test the predictions of the IRH in the temporal domain in adults. Our second goal was to more clearly define the IRH framework as it relates to how and under what circumstance intersensory redundancy facilitates behavior in adults, given that both of these components of the hypothesis are only loosely characterized. Specifically, we ask whether adults experience intersensory facilitation when temporally redundant audiovisual features are available during a demanding task as compared to conditions where only unisensory information is available. We selected an executive function test based on Bahrick and Lickliter's (2012) claim that such tasks are sufficiently demanding to maximally benefit from intersensory facilitation. In particular, we selected a go/no-go task that has been used frequently to assess response inhibition (see Simmonds, Pekar, & Mostofsky, 2008, for a review), which is often considered a coherent executive function (Garavan, 2002). Based on previous research, we assessed performance facilitation in terms of reaction time (RT) and accuracy (Rowe, 1999). The IRH predicts that adults will show faster RTs and higher accuracy when presented with redundant audiovisual stimuli as compared to unisensory auditory-only or visual-only stimuli.

METHODS

Participants

A group of thirty monolingual English speaking college students (2 males, 28 females, *M* = 22.04 years, *SD* = 2.84) were recruited from college campuses in the San Diego area. Participants were brought into the lab for two separate testing sessions (see below) and received either class credit or $5/session for their participation.

All participants reported normal or corrected vision and no history of fluency difficulty (e.g., stuttering), motor speech difficulty (e.g., apraxia of speech or dysarthria), attention deficit disorder (ADD) or attention deficit hyperactivity disorder (ADHD), frank neurological impairment, language or learning disability, mental illness, or social difficulties (e.g., autism spectrum disorder).

To ensure normal hearing, all participants were given a bilateral hearing screening at 500, 1000, 2000, and 4000 Hz at 25 dB HL (American National Standards Institute, 1996).[3] All participants demonstrated a nonverbal intelligence quotient (IQ) within the normal range of 85 or greater (*M* = 97, *SD* = 7.60) as measured by the Test of Nonverbal Intelligence, Fourth Edition (TONI-IV; Brown, Sherbenou, & Johnsen, 2010).

To ensure normal language ability, all participants were administered a battery of standardized language measures designed to screen for presence of language impairment in adults (Fidler, Plante, & Vance, 2011). This battery included: (1) the spelling test from Fidler et al. (2011), (2) a modified version of the Token Test (Morice

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[3] One participant failed the hearing screening at 500 Hz in one ear but was still included in the study since hearing acuity was within normal limits bilaterally for the frequency range of experimental stimuli.

& McNicol, 1985), and (3) the Clinical Evaluation of Language Fundamentals (4th ed.) Word Definition subtest (CELF-4-WD; Semel, Wiig, & Secord, 2003). Scores from this battery were entered into an analysis described by Filder et al. (2011) to classify adults as having normal language or a language impairment. All participants included in the analyses had language abilities within the normal range (*M* = -.96, *SD* = .57, where a score less than 0 constitutes normal language).

Another 22 participants were tested but excluded from the analyses: 12 were identified as having a language impairment, three were excluded for failure to understand the task[4], three had significant second language experience, two reported a history of one or more concussions resulting in loss of consciousness, one failed to return for the second session, and one demonstrated atypical social interaction skills determined to be outside the normal range.

Stimuli

The auditory stimuli consisted of four different 1000 Hz pure-tone pairs, which differed only in their duration pattern. Short tones (75 ms) and long tones (175 ms) were combined in four different duration patterns: (1) short-short (75 ms + 75 ms), (2) short-long (75 ms + 175 ms), (3) long-long (175 ms + 175 ms), (4) long-short (175 ms + 75 ms). Three interstimulus intervals (ISIs) were imposed between the tones in tone pairs: 60 ms, 150 ms, and 300 ms. All tones were presented at 70 dB. Auditory stimuli were created using Sound Studio software.

The visual stimuli for the task consisted of four symmetrical shapes: a circle, a diamond, a square, and a hexagon. Each shape was bright yellow and set against a

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[4] For each of these three participants, the participant confused the target and non-target items in one of six conditions resulting in very low accuracy in that condition. However, they were above chance for accuracy in all other conditions. Given the inconsistency in performance, these participants were excluded entirely from the analyses.

black background of height and width ranged from 75-90 pixels. Shapes were presented at midline on the x-axis of the screen but presented 20% higher than the midline on the y-axis of the screen (to ensure that fixation data were not confounded by a tendency to fixate the center of the screen). Shapes were randomly assigned to conditions such that only one shape was used in any given condition. Shapes were presented in duration pairs that were identical in duration and pattern to the tone pairs. Visual stimuli were created using Adobe Photoshop CS4 (see Figure 2.1 for examples).

Procedure

Participants completed two testing sessions (~1.5 hours each) in experimental testing rooms in the School of Language, Speech, and Hearing Sciences on the SDSU campus. The first session began by obtaining informed consent and reviewing the participant's background questionnaire (previously completed). Participants then completed experimental tasks and standardized language and cognitive tests. The second session began with a reminder about informed consent, followed by experimental testing, and then standardized language and cognitive testing.

Experimental Tasks

Participants were seated in a comfortable chair approximately 70 cm from a display monitor. Tasks were presented on a PC computer using SR Research Eyelink Experiment Builder Software (SR Research Ltd, Mississauga, Ontario, Canada, 2011). Participants were given ~2 minute breaks in between tasks.

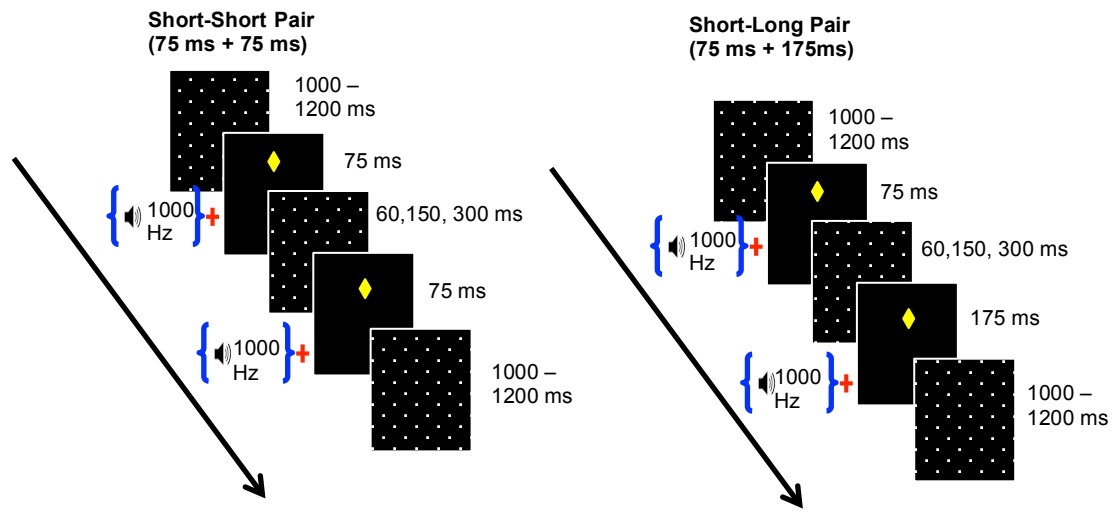*Synchronous Audiovisual Go/No-Go Task*

The synchronous audiovisual task was based on a go/no-go task design. Participants were presented with one of two kinds of audiovisual target/non-target

designs: either (1) short-short versus short-long or (2) long-long versus long-short (see Figure 2.1 for examples). These target/non-target designs were counterbalanced across participants. The short-short, short-long, and long-short stimuli served equally often as the target. The long-long pair was only used as a target for the single-modality tasks. In order to create synchronous audiovisual targets and non-targets, the auditory and visual stimuli described above were presented concurrently and matched for onset and duration.

Within each task, participants were presented with 20 target stimuli at each ISI (60 ms, 150 ms, and 300 ms) for a total of 60 target trials, as well as 8 non-target stimuli at each ISI (60 ms, 150 ms, and 300ms) for a total of 24 non-target trials. Thus, 70% of the trials were target trials and 30% of the trials were non-target trials. This high target to non-target ratio was expected to impose higher task difficulty (Donkers & van Boxtel, 2004; Johnstone et al., 2007). Target and non-target trials were presented in a fixed random order. Time between trials varied randomly between 1000 ms and 1200 ms.

Initially, task instructions were presented on the monitor while the experimenter described and explained the instructions to the participant. Participants were told that they would be presented with two different kinds of tone pairs. Two examples of each tone pair, one with a 60 ms ISI and one with a 300 ms ISI, were played for the participants on an iPod touch. Participants were told that one tone pair was the target pair, and asked to press the space bar on the keyboard when they heard that pair. Participants then completed six practice trials, including three target stimuli (one per ISI), and three non-target stimuli (one per ISI) in a fixed random order. Participants were then reminded about which tone pair was the target pair,

before beginning the experimental trials (Figure 2.1). Auditory stimuli were presented

through headphones during practice and experimental trials.

Figure 2.1 Example of one set of target/non-target pairs (short-short vs. short-long) for synchronous audiovisual task.

Visual-Only Go/No-Go Task

The design of the visual-only go/no-go task was identical to the audiovisual

go/no-go task except for two design differences and one procedural difference. The

first design difference was that only visual stimuli were presented for the visual-only

go/no-go task. Second, only one target/non-target pair was used: long-long versus

long-short (see Figure 2.2 for examples). Also, the long-long visual pair was always

designated as the target pair. The reasoning behind this design variation stemmed

from findings in the literature and from our pilot data on the visual-only go/no-go task.

Prior research has shown that temporal processing is superior in the auditory

modality as compared to the visual modality (see Talsma, Senkowski, Soto-Faraco, &

Woldorff, 2010, for a review). In addition, our pilot data suggested that the visual-only

go/no-go task was very challenging for participants. We therefore selected the tone pair that was likely to be most easily perceived in the visual modality as the target tone pair in both single modality tasks. Since participants completed all three tasks within the same session, we excluded the long-long pair as a possible target from the audiovisual synchrony go/no-go task in order to minimize practice effects.

The procedural difference occurred during presentation of example stimuli. Rather than playing examples of tone-pairs for the participants, during the visual-only go/no-go task, participants were shown short video clip examples of the visual-only trials using an ipod touch. Similarly to the other two tasks, two examples of each visual pair were played. One example had a 60 ms between stimulus items of a visual pair duration and the other example had a 300 ms between stimulus items of a visual pair duration.

Long-Short Pair
(175 ms + 75 ms)

1000 – 1200 ms

175 ms

60,150, 300 ms

75 ms

1000 – 1200 ms

Long-Long Pair
(175 ms + 175ms)

1000 – 1200 ms

175 ms

60,150, 300 ms

175 ms

1000 – 1200 ms
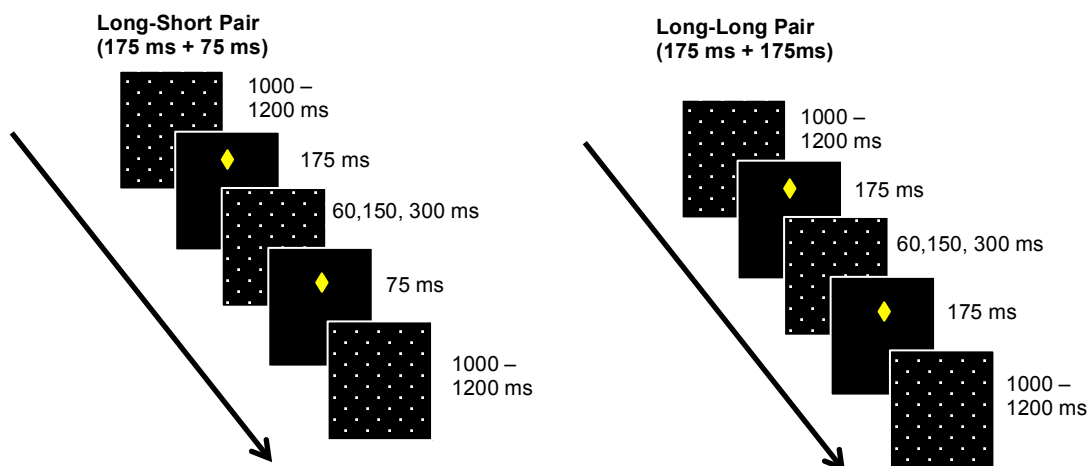
Figure 2.2 Example of one set of target/non-target pairs (long-short vs. long-long) for visual-only task.

Auditory-Only Go/No-Go Task

The design of the auditory-only go/no-go task was identical to the audiovisual go/no-go task except for two design differences. First, only auditory stimuli were presented for the auditory-only go/no-go task. Participants remained seated in front of the computer screen in order to make keyboard responses; however, the computer screen remained entirely black during the task. Second, only one target/non-target pairing was used: long-long versus long-short (see Figure 2.3 for examples). Additionally, the long-long tone pair was always designated as the target pair. The reasoning for this design choice is described above.
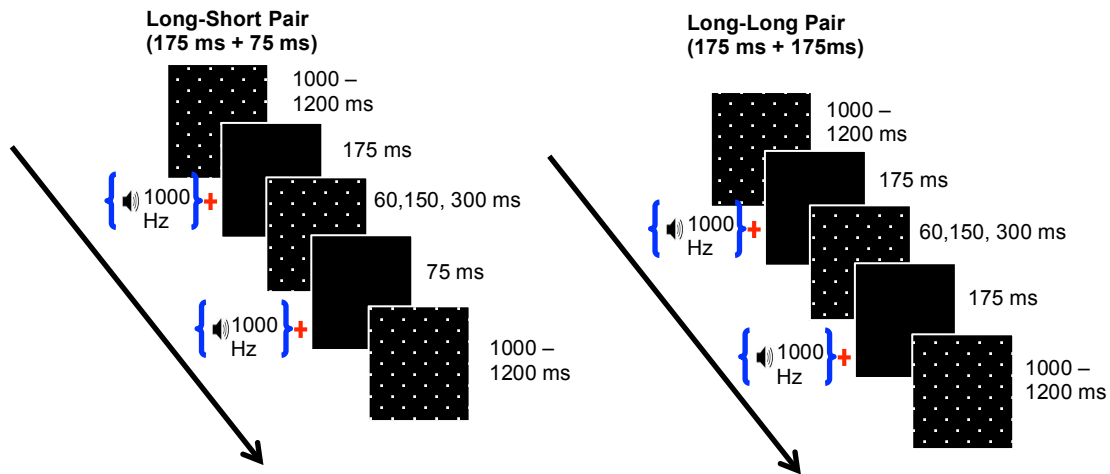
Figure 2.3 Example of one set of target/non-target pairs (long-short vs. long-long) for auditory-only task.

Data Analyses

Hit rate and false alarm rates for each participant in each task were computed and converted to d-prime (*d'*) scores. *D'* is considered to be a more accurate measure of target/non-target discrimination than raw accuracy, because it factors in both correct responses (hit rate) to the target stimulus and false alarms (e.g., incorrectly responding to a non-target stimulus, in this case pressing a button) (Green & Swets,

1966). Furthermore, previous work has shown that *d'* provides a superior model for recognition memory data than other models of discrimination accuracy, such as the two-high threshold model (Slotnick, Klein, Dodson, & Shimamura, 2000). Higher *d'* values indicate better discrimination accuracy. The complement to *d'*, *C*, is an index of each participant's response bias; it was also calculated for each participant in each task. Response bias is an index of each participant's tendency to respond liberally (i.e., readily identify a stimulus as a target) or conservatively (i.e., reject a stimulus as a target). *C* values above 0 indicate a conservative bias while values below 0 indicate a liberal bias. Finally, average RT calculated was calculated for each participant and based only on correct target trial responses.

RESULTS

Accuracy (*d'*) and RT data were analyzed to determine if results supported the IRH prediction that access to intersensory redundancy boosts performance. In order to test these predictions for individual modalities, separate analyses were run to compare the audiovisual go/no-go task to the auditory-only go/no-go task, and to compare the audiovisual go/no-go task to the visual-only go/no-go task.

Accuracy

Paired-samples t-tests were used to compare accuracy (operationalized as *d'*) between tasks. Accuracy was significantly higher in the auditory-only task (*M* = 2.78, *SD* = .90) than in the audiovisual task (*M* = 2.12, *SD* = 1.04), *t*(29) = -4.26, *p* <.001, *r* = .62, (see Figure 2.4). Higher accuracy in that auditory-only condition, as compared to the audiovisual condition, contradicts the predictions of the IRH.
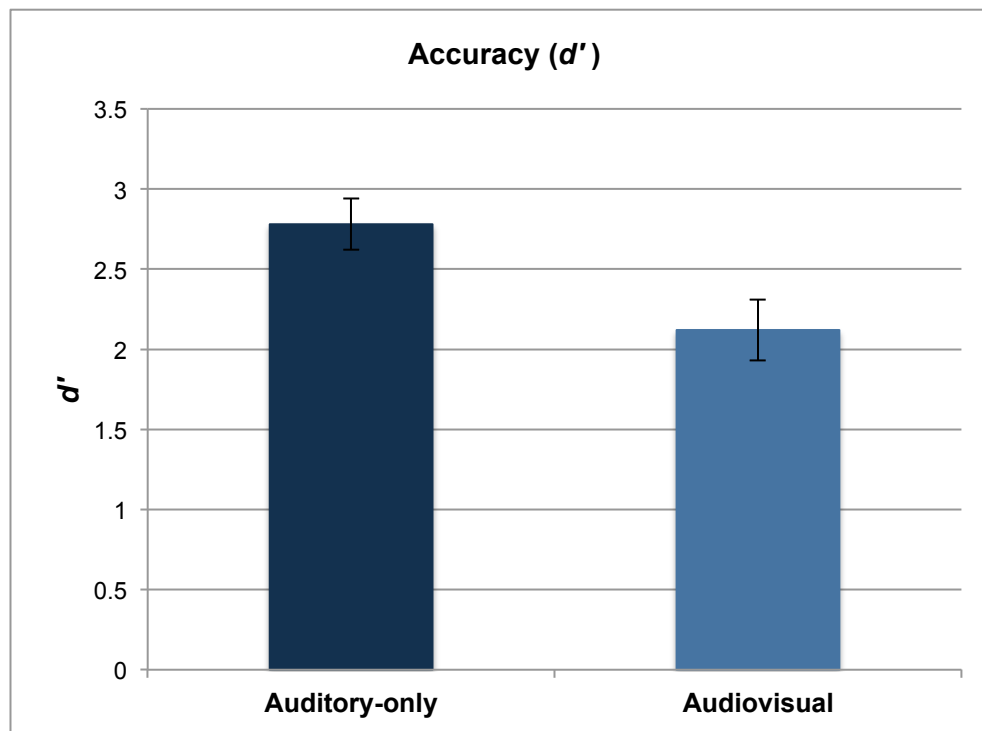
Figure 2.4 Auditory-only vs. Audiovisual: *d'* performance by condition

By contrast, accuracy in the visual-only go/no-go task (*M* = 1.01, *SD* = .53), was significantly *lower* than in the audiovisual go/no-go task (*M* = 2.12, *SD* = 1.04), *t*(29) = 6.02, *p* < .001, *r* = .75, (see Figure 2.5). Lower accuracy in the visual-only condition as compared to the audiovisual condition is consistent with the predictions of the IRH.[5]

---

[5] Since a different target was used in the auditory-only and visual-only tasks than in the audiovisual-tasks, data from a subset of 12 participants, who were exposed to the same tone pairs in the audiovisual task that were used in the auditory-only and visual-only tasks (i.e., long-long and long-short), but with the opposite pair as the target, were reanalyzed to ensure that the difference in tone-pairs used across tasks did not confound results. Accuracy results were consistent across both analyses (see Appendix 2.A for additional analyses).
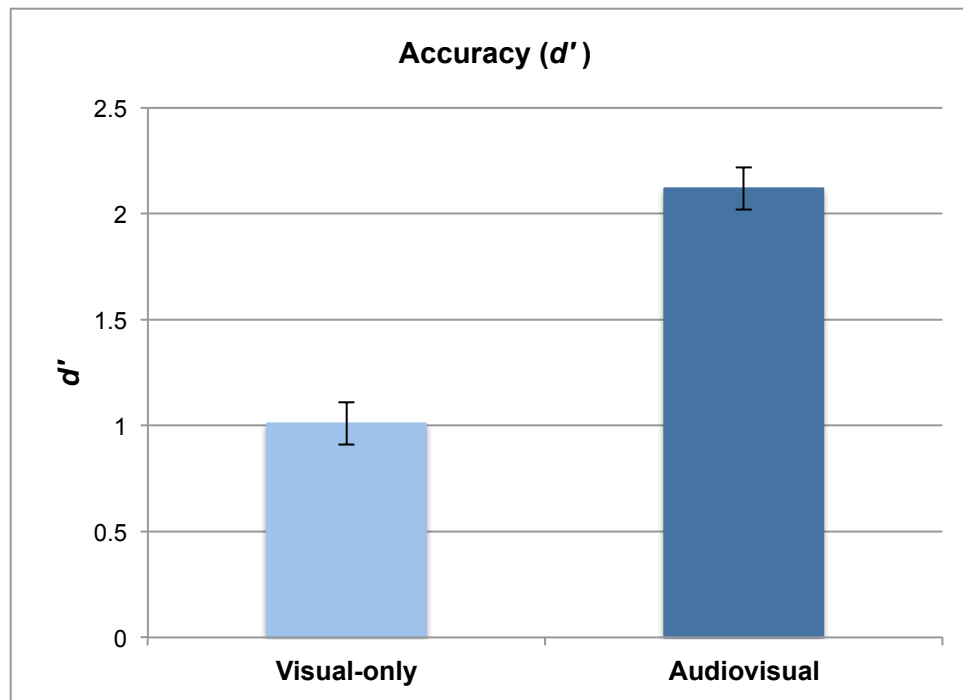
Figure 2.5 Visual-only vs. Audiovisual: *d'* performance by condition

Response Bias

Paired-sample t-tests were used to compare *C*, the standard measure of response bias, between tasks. There was no difference between the audio-only go/no-go task (*M* = -.01, *SD* = .42), and the audiovisual go/no-go task (*M* = .12, *SD* = .45), *t*(29) = 1.77, *p* = .087, *r* = .31, (see Figure 2.6).
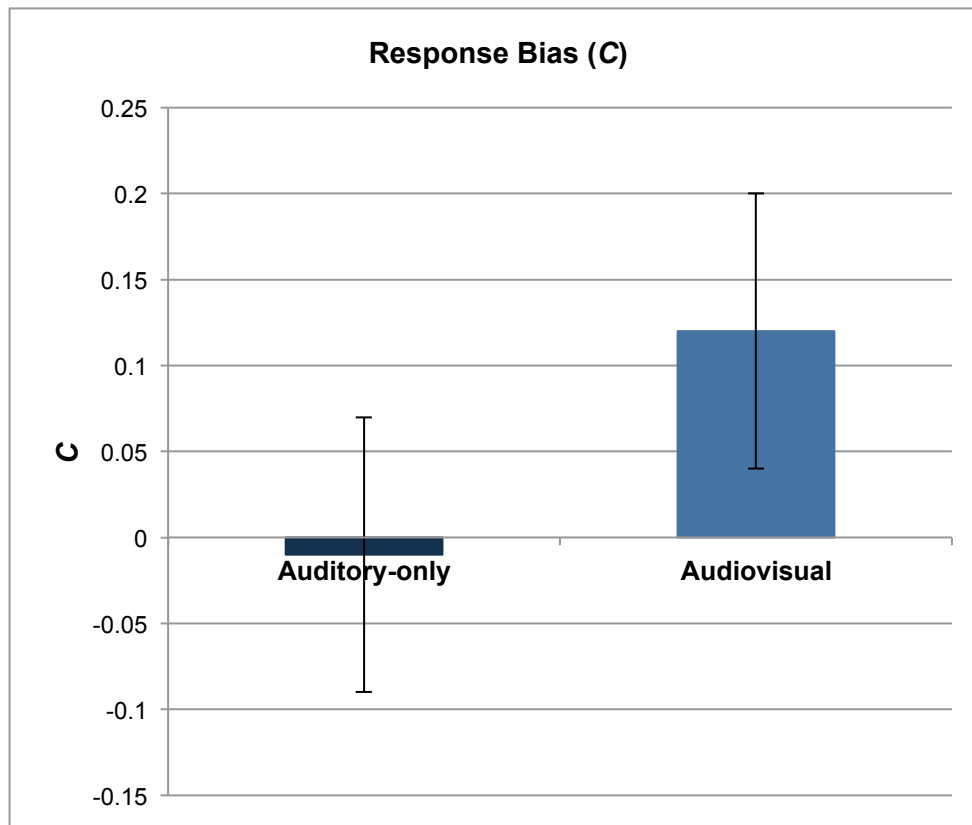
Figure 2.6 Auditory-only vs. Audiovisual: *C* performance by condition

However, adults were significantly more liberal in the visual-only go/no-go task (*M* = -.02, *SD* = .37), than in the audiovisual go/no-go task (*M* = .12, *SD* = .45), *t*(29) = 3.65, *p* = .001, *r* = .56, (see Figure 2.7). These data indicate that participants more readily identified stimuli as targets in the visual-only condition than in the audiovisual condition.[6]

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[6] Response bias data were also reanalyzed using the subset of 12 participants described above. Response bias differences between the audiovisual and visual-only tasks disappeared upon reanalysis (see Appendix 2.A for additional analyses).

Figure 2.7 Visual-only vs. Audiovisual: *C* performance by condition

Reaction Time

Paired-sample t-tests were used to compare RT on correct target trials between tasks. RT was significantly faster in the audiovisual go/no-go task (*M* = 565.42, *SD* = 88.26) than in the auditory-only go/no-go task (*M* = 601.62, *SD* = 92.53), *t*(29) = -2.20, *p* = .036, *r* = .38, (see Figure 2.8). Faster RTs during the audiovisual task as compared to the audio-only task are consistent with the predictions of the IRH.
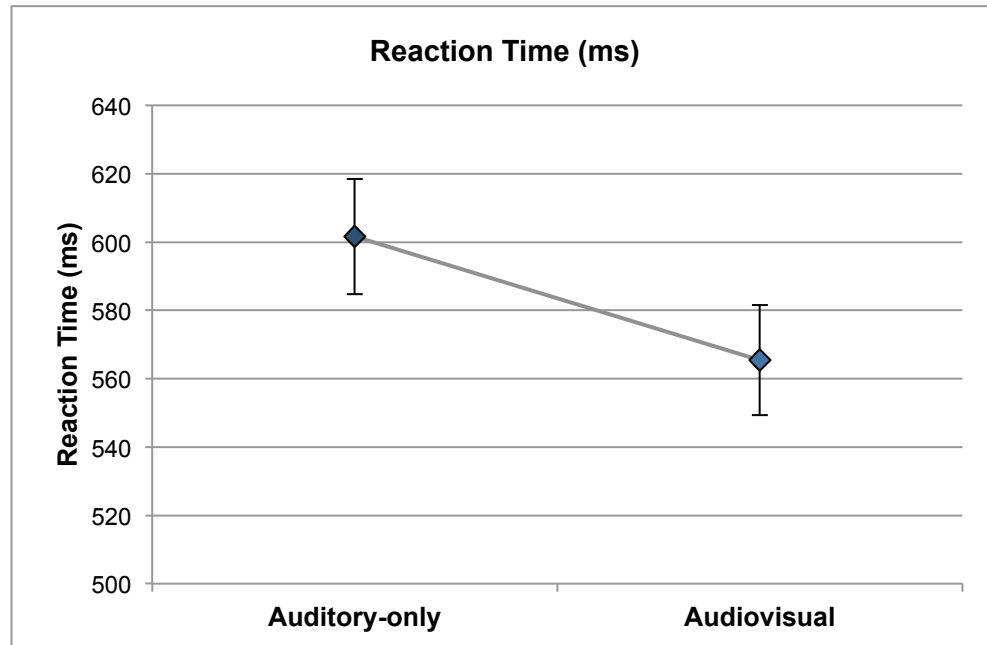
Figure 2.8 Auditory-only vs. Audiovisual: RT performance by condition

RT in visual-only go/no-go task (*M* = 569.52, *SD* = 81.30) did not significantly differ from RT in the audiovisual task (*M* = 565.42, *SD* = 88.26), *t*(29) = -.27, *p* = .786, *r* = .05 (see Figure 2.9). Similar RTs in both the visual-only task and the audiovisual task are not consistent with the predictions of the IRH.[7]

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[7] RT data were also reanalyzed using the subset of 12 participants described above. RT results were consistent across both analyses (see Appendix 2.A for additional analyses).

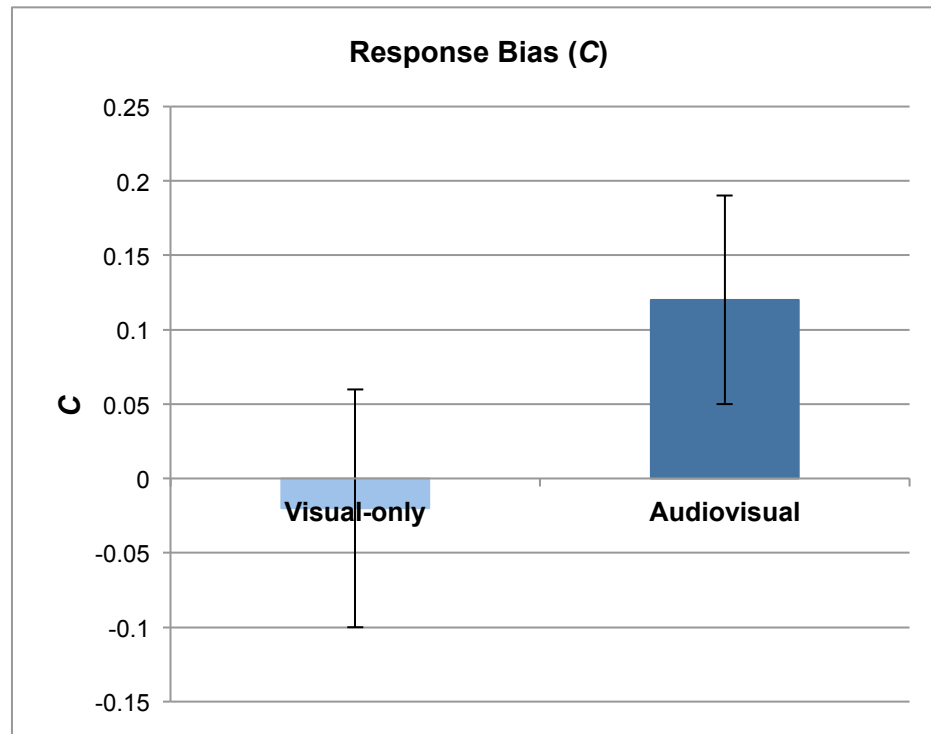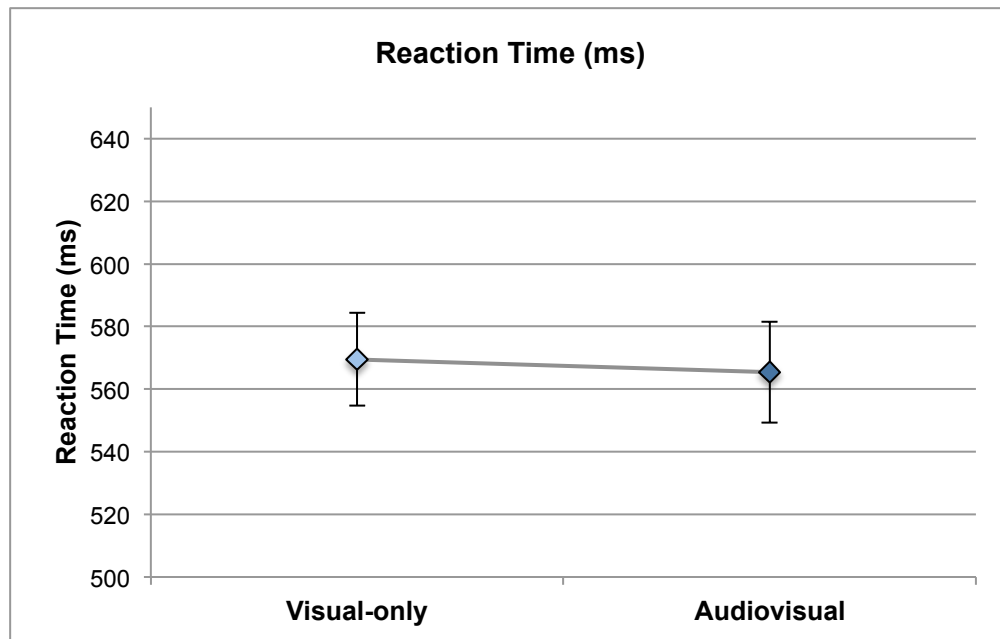**Figure 2.9** Visual-only vs. Audiovisual: RT performance by condition

DISCUSSION

The overall goal of this study was to test the prediction made by the IRH that amodal information is more easily perceived when multisensory information is available and intersensory redundancy is present, as compared to when only unisensory information is available. To test this prediction, we asked, more specifically if, during an executive function task, access to synchronous audiovisual information would lead to measurable boosts in behavioral performance when compared to access to only auditory information or access to only visual information. Evidence from the current study provides only partial support for the IRH.

Access to synchronous audiovisual information only boosted accuracy performance when compared to processing of unisensory visual-only information. However, in direct opposition to the IRH, when compared to unisensory auditory-only

information, accuracy was significantly better for unisensory auditory-only information. According to the predictions of the IRH, audiovisual synchrony should have improved accuracy when compared to *both* unisensory auditory-only information and unisensory visual-only information.

Partial support for the IRH was also seen in reaction time performance. Access to synchronous audiovisual information only boosted reaction time performance when compared to access processing of unisensory auditory-only information. When compared to unisensory visual-only information, reaction times to synchronous audiovisual information were not significantly different. Again, according to the predictions of the IRH, audiovisual synchrony should have improved reaction times when compared to *both* unisensory auditory-only information and unisensory visual-only information.

The current findings beg the question: why are we seeing a scattered pattern of partial support for the IRH? In light of prior research on the processing strengths of each individual modality and the resulting impact on multisensory processing, these results may be less surprising. Previous work has established that an inverse relationship exists between the effectiveness of multisensory stimuli and the effectiveness of unisensory stimuli (Meredith & Stein, 1983; 1986; Stanford, Quessy, & Stein, 2005; Stein & Meredith, 1993). Specifically, the principle suggests that enhancements in performance due to the presence of multisensory stimuli are most pronounced when performance in the presence of each unisensory stimulus is particularly weak. Enhancement in performance due to the presence of multisensory stimuli becomes less and less pronounced as performance in the presence of each unisensory stimulus improves. Eventually the presence of multisensory stimuli can

even lead to worse performance if performance in the presence of a given unisensory stimulus is particularly strong (Stanford, Quessy, & Stein, 2005). Previous work has also established that there is variability in the processing strengths of individual modalities. For example, compared to the visual modality, the auditory modality is superior for processing temporal information (see Talsma et al., 2010; Welch & Warren, 1980, for reviews).

The current study investigated performance on a task where performance was based on discrimination of a temporal distinction, the length of the tones in a particular tone pair. Based on research findings, which suggest that temporal resolution is superior in the auditory modality, it is not surprising that performance was superior in the presence of unisensory auditory-only stimuli as compared to unisensory visual-only stimuli. More importantly, based on the established inverse relationship between multisensory and unisensory stimulus effectiveness, the temporal processing strength of the auditory modality may have enabled fairly effective performance in the presence of unisensory stimuli, with somewhat weak and variable enhancements to performance in the presence of multisensory stimuli. In this case, accuracy may have been optimal in the presence of auditory-only stimuli and thus weakened by the addition of a redundant visual cue. However, access to a redundant visual cue may have increased the salience of the stimuli somewhat, and thus led to gains in reaction times, even while accuracy rates were lower. Similarly, weaker temporal resolution in the visual modality may have enabled only moderately effective performance in the presence of unisensory stimuli, while having access to a redundant auditory cue with multisensory stimuli also allowed for access to superior

temporal resolution, and led to gains in accuracy performance. However, the presence of a redundant auditory cue had no impact on reaction times.

One possible reason that reaction times were not faster in the presence of multisensory stimuli as compared to visual-only stimuli may be related to the nature of the task. As previously stated, temporal resolution is weaker in the visual domain as compared to the auditory domain. The majority of participants reported feeling as though the visual task was very difficult and that their performance was quite poor. Despite this, accuracy scores suggested that participants were capable of performing the task. Nevertheless, if participants felt the task was too challenging, participants may have been less intentionally purposeful about their responses during the visual-only task. Less intentional responses may have led to unusually fast reaction times and, in turn, negated the boost in reaction time performance typically seen when participants are presented with multisensory stimuli as compared to unisensory stimuli (Gielen et al., 1983; Hershenson, 1962; see Rowe, 1999, for a review). The more liberal response bias seen during the visual-only go/no-go task may be indicative of somewhat less purposeful response behavior during the visual-only go/no-go task.[8]

It is also possible that RT facilitation effects across the audiovisual and visual-only tasks were reduced due to differences in the nature of the stimuli used in each of these tasks. Targets used in the audiovisual task largely had shorter durations and, as such detectability of these targets might have been slightly lower. Slightly more

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[8] While response bias results disappeared in the reanalysis with a subset of 12 participants, and thus no longer provide evidence supporting this suggested explanation of our RT results, it is still possible that our RT results may be explained by participants' perception of their own ability to perform the visual-only task. See Chapter 5 for alternative explanations of our RT results.

challenging detectability of the targets in the audiovisual task may have lengthened response times, somewhat, and, as a result, reduced expected facilitation effects.

The predictions of the IRH tested here are predicated on selecting a task that is sufficiently demanding to elicit intersensory facilitation effects. Given the pattern of results, it is possible that the task used here was only marginally demanding and thus intersensory facilitation effects were scattered. Intersensory facilitation effects may be more consistent and more robust during tasks with higher executive function demands or steeper learning curves, as has been shown in previous work demonstrating intersensory facilitation during learning of a challenging spatial task (Seitz, Kim, & Shams, 2006). It is also possible that intersensory facilitation effects in adults are weaker in general for tasks contingent upon simple temporal dynamics like duration rather than more complex temporal dynamics like rhythm and tempo or other amodal properties like spatial dimension.

The current experimental design was limited in that the target stimulus pair used for the visual-only and auditory-only tasks was never used as a target stimulus pair for the audiovisual task. This design choice was made in order to maximally manage practice effects and processing trade-offs. As discussed, the challenge in designing the current experiment was to develop a set of tasks that sufficiently taxed the superior temporal processing skills of the auditory modality while not exceeding the inferior temporal processing skills of the visual modality. Our results indicate that no task yielded superior behavioral performance across all behavioral measures, which suggests that the slight variation in task design did not create substantial variation in task difficulty. However, future research on temporal processing, particularly as it relates to multisensory and unisensory comparisons, may seek to

confirm these findings and to explore alternative experimental designs to mitigate the challenge posed by processing trade-offs in the auditory and visual modalities.

Results from the current study only provide partial support for the predictions of the IRH tested, suggesting the possibility of necessary additional constraints on predictions of the IRH that have not yet been considered. Additional research is needed to determine if level of difficulty is a relevant factor for intersensory facilitation and, if it is, additional research is also needed to provide a clearer definition of the kind of task that is sufficiently challenging to elicit intersensory facilitation. Furthermore, research is needed to investigate whether stronger intersensory facilitation effects are seen for certain amodal features, like spatial dimension, as compared to others, like simple temporal dynamics.

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Acknowledgement

Appendix 2.A. Reanalyses

Audiovisual vs. Auditory-only comparisons (paired-sample t-tests) for accuracy (*d'*), response bias (*C*), and RT (N=12)

	Audiovisual: Average (standard deviation)	Auditory-only: Average (standard deviation)	*p*-value (*r*)
Accuracy (*d'*)	2.08 (1.21)	2.78 (.90)	.015 (.64)
Response Bias (*C*)	.01 (.44)	.002 (.38)	.940 (.02)
RT	538.84 (97.62)	621.85 (104.00)	.006 (.70)

Auditory-only vs. Audiovisual: Accuracy (*d'*) by condition
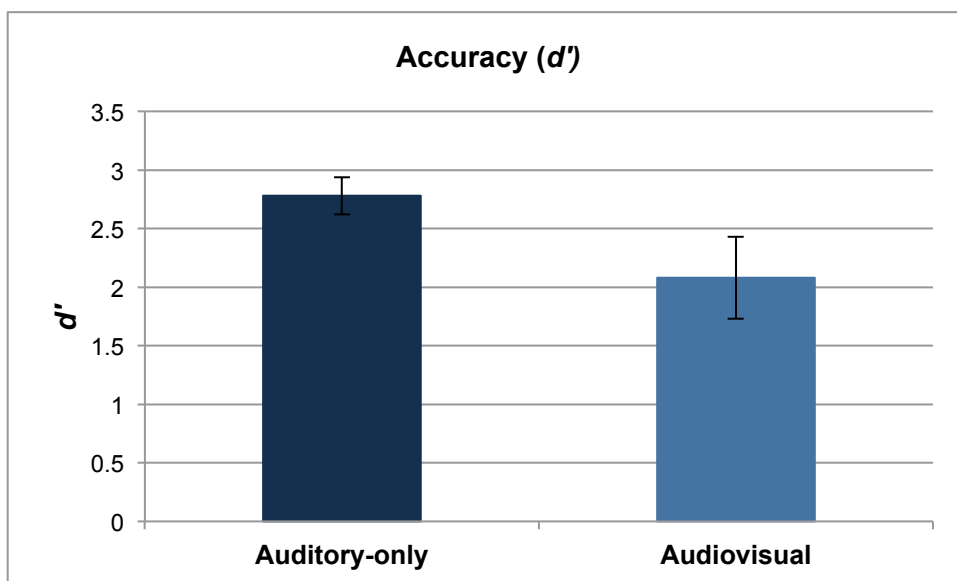
Auditory-only vs. Audiovisual: Response Bias (*C*) by condition
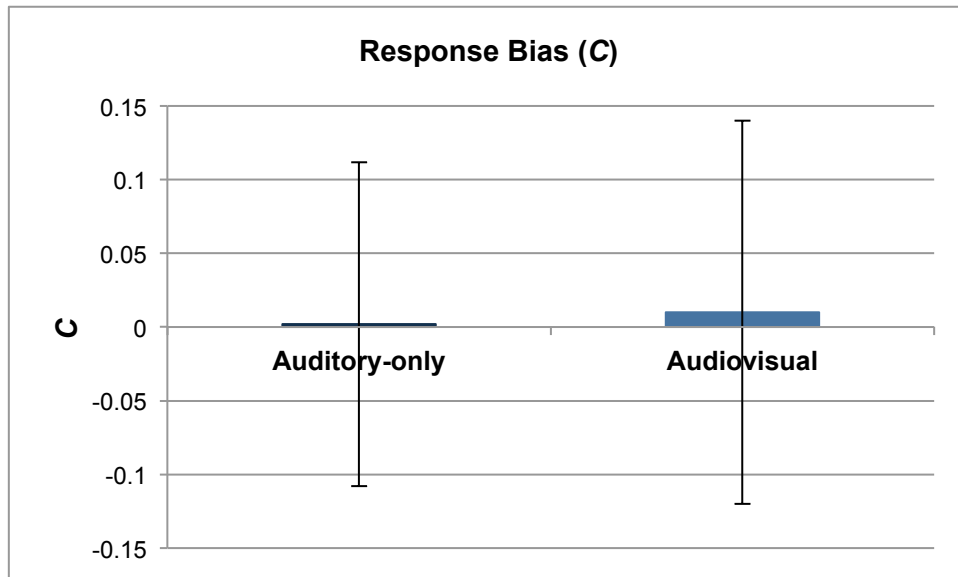
Auditory-only vs. Audiovisual: RT (ms) by condition
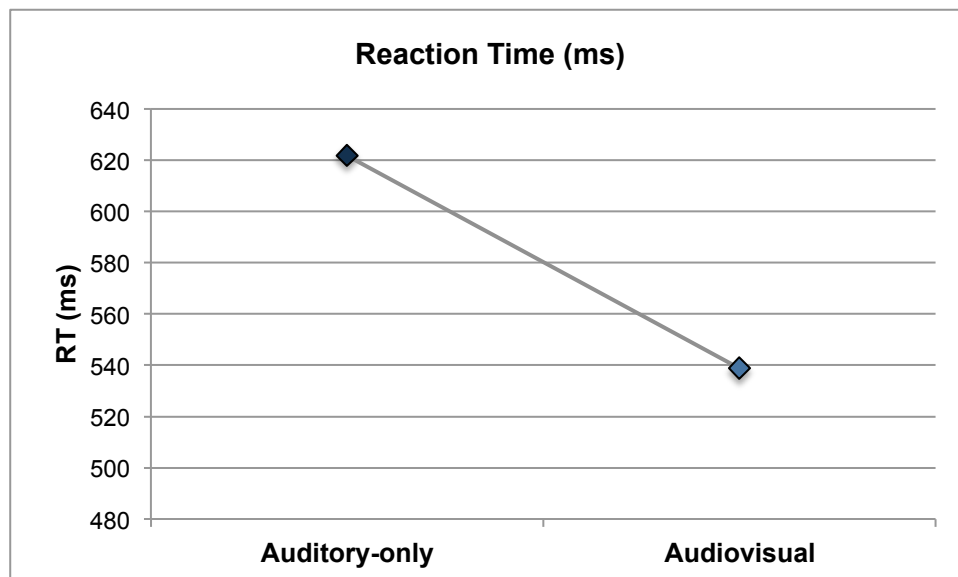
Audiovisual vs. Visual-only comparisons (paired-sample t-tests) for accuracy (*d'*), response bias (*C*), and RT (N=12)

	Audiovisual: Average (standard deviation)	Visual-only: Average (standard deviation)	*p*-value (*r*)
Accuracy (*d'*)	2.08 (1.21)	.85 (.56)	.001 (.78)
Response Bias (*C*)	.01 (.44)	-.09 (.37)	.445 (.22)
RT	538.84 (97.62)	579.19 (102.00)	.113 (.44)

Visual-only vs. Audiovisual: Accuracy (*d'*) by condition
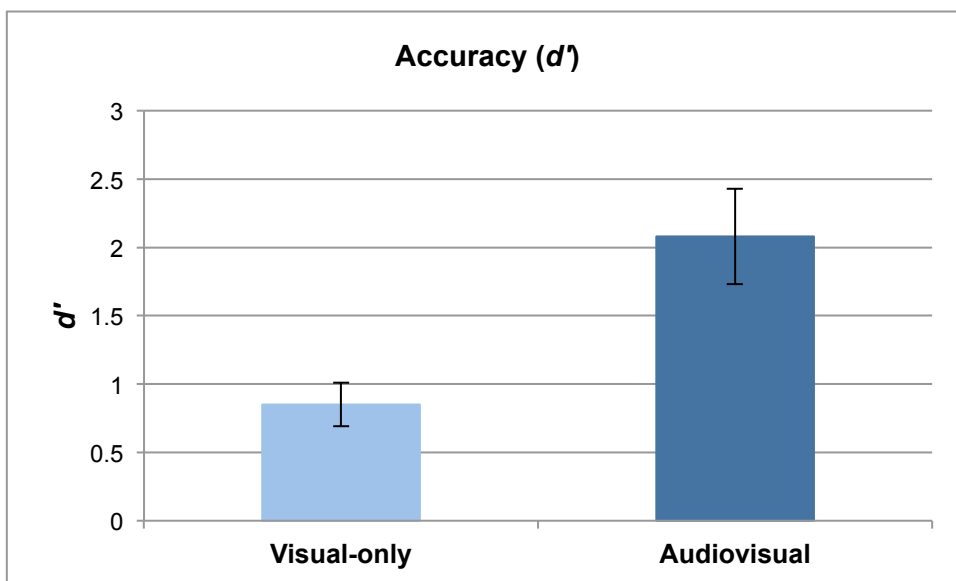
Visual-only vs. Audiovisual: Response Bias (*C*) by condition
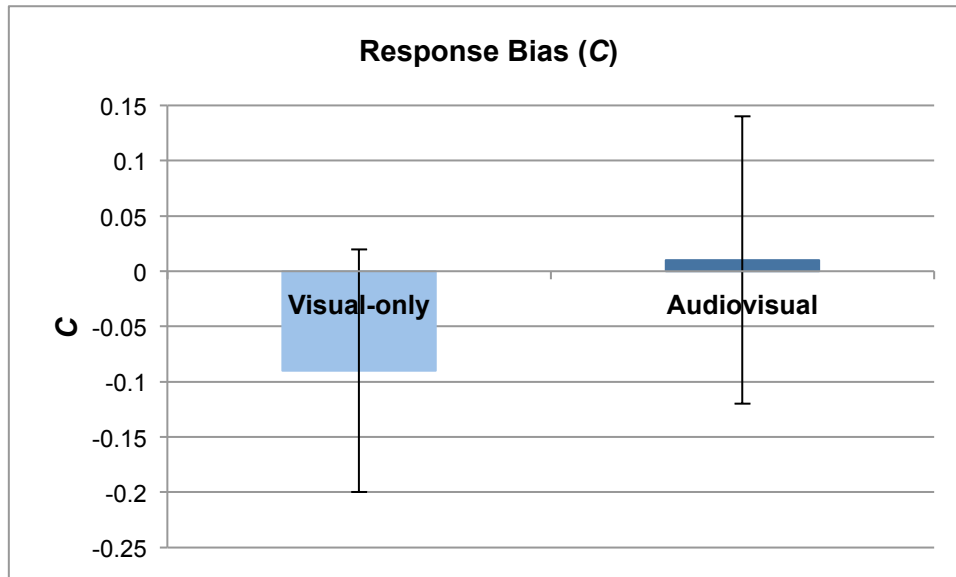
Visual-only vs. Audiovisual: RT (ms) by condition
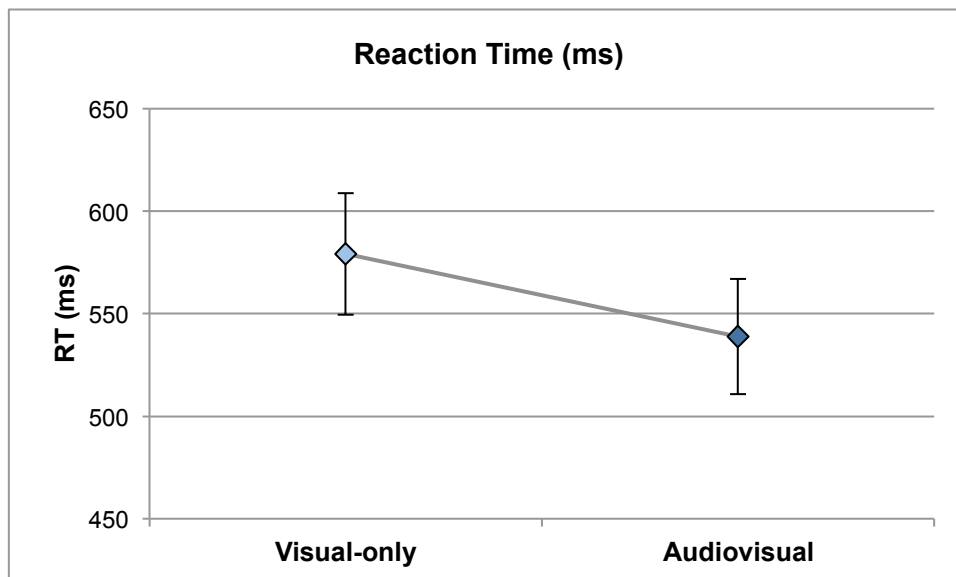
CHAPTER 3: INFLUENCES ON INTERSENSORY FACILITATION IN ADULTS: TIMING & SIGNAL QUALITY

ABSTRACT

The Intersensory Redundancy Hypothesis (IRH) provides a framework for characterizing the influence of multisensory information on perceptual processing and makes specific predictions about the facilitative impact of multisensory information on perceptual processing in adults (Bahrick, 2010). Extensive support for the IRH is found within the developmental literature (see Bahrick & Lickliter, 2012, for a review); however, research that specifically tests the predictions of the IRH in adults is limited (Bahrick et al., 2009; Gelfand et al., 2015; Seitz, Kim, & Shams, 2006). In this study, we tested the impact of temporal synchrony (Experiment 1), predictive value (i.e., redundancy) (Experiment 2), and signal quality (Experiment 3) on the predictions of the IRH in a group of thirty adults. Accuracy, reaction time and looking behavior were assessed on a go/no-go detection task with and without audiovisual synchrony. For each experiment, participants' performance was compared across conditions. Results suggest that facilitation effects may be less dependent on temporal synchrony than on high predictive value (i.e., redundancy) and that degrading signal quality enhances facilitation effects. Furthermore, our results across all three experiments suggest that reaction times may be the most robust and sensitive behavioral measure for facilitation effects.

INTRODUCTION

The natural environment provides humans with a wealth of multisensory information. This abundance of sensory information can make everyday information processing in the natural environment a chaotic and noisy experience. Therefore, it is imperative that humans have mechanisms for differentiating signal from noise and for determining which sensory information is relevant and related at any given time. Research has suggested that certain kinds of sensory information act as cues to focus perception on relevant signals and not on noise (see Bahrick, 2010, for a review). Specifically, it has been suggested that when information conveyed across two or more sensory modalities (e.g., auditory and visual) is *redundant*, the redundant information becomes especially salient and attracts attention (Bahrick & Lickliter, 2012). This idea has been formalized in the intersensory redundancy hypothesis (IRH) (Bahrick, 2010; Bahrick & Lickliter, 2012; Bahrick, Lickliter, & Flom, 2004).

Information that can be redundant across auditory and visual signals includes patterns such as tempo (e.g., a metronome – beats per minute or rate), rhythm (e.g., a temporally patterned repetitive sequence), duration, intensity, and spatial co-location (Bahrick, 2010). Bahrick (2010) refers to these redundancies in auditory and visual signals as *amodal* information. Bahrick (2010) defines *intersensory redundancy* as the *simultaneous* co-occurrence of amodal information across two or more sensory modalities. Fundamental to the definition of intersensory redundancy is the occurrence of *temporal synchrony*. Importantly, Bahrick and Lickliter (2012) explain that temporal synchrony is the foundational amodal property that then allows for the detection of nested amodal properties like tempo, rhythm, duration, and intensity.

The overarching goal of the IRH is to explain how intersensory redundancies facilitate selective attention. Bahrick (2010) argues that when intersensory redundancy occurs across modalities, the intersensory redundancy serves as an orienting mechanism, which focuses selective attention. Bahrick (2010) describes a dynamic and cyclic process by which the kind of sensory information present in the environment differentially affects how selective attention is guided, which then determines what information in the environment is perceived, learned and remembered. Bahrick (2010) goes on to suggest that eventually the information that is perceived, learned and remembered generates experience and expertise, which, in turn, influences what is subsequently attended to in the environment. According to Bahrick and Lickliter (2012), these principles may be summarized as a hierarchy of processing priority based on: (1) the availability of multisensory information (e.g., visual information *and* auditory information), (2) the availability of unisensory information (e.g., *only* auditory information or *only* visual information), (3) the experience or expertise of the perceiver and (4) the difficulty of the task. Thus, the IRH describes a powerful learning mechanism that is guided by the availability of sensory information in the environment.

The salience of and reliance on intersensory redundancies in infancy is well documented (see Bahrick 2010, 2012, for reviews; Bahrick et al., 2004; Lewkowicz, 2000), particularly with respect to audiovisual speech perception, (Dodd, 1979; Kuhl & Meltzoff, 1984; Rosenblum, Schmuckler, & Johnson, 1997; see Soto-Faraco, Calabresi, Navarra, Werker, & Lewkowicz, 2012, for a review). Furthermore, research has shown that intersensory redundancies play an important role in infants' ability to learn paired associations (i.e., linking a label to an object). For example,

infants are able to learn object-label pairs when redundancy is present through the synchronous movement and labeling of objects; however, when objects remain static or when movement and naming are temporally asynchronous, conditions during which redundancy is not present, infants are not able to learn object-label pairs (Gogate & Bahrick, 1998).

Evidence suggests that intersensory facilitation effects, meaning perceptual facilitation of redundant information, in infancy are not limited to the language domain. For example, Bahrick and Lickliter (2000) found that 5-month-old infants were able to detect a change in the tapping tempo of a toy hammer when the event was presented audiovisually and the audiovisual information was temporally synchronous. Under auditory-only or visual-only unisensory conditions or when the audiovisual presentation was asynchronous, 5-month-old infants were not able to detect a change in tempo. Bahrick, Flom, and Lickliter (2002) replicated this finding in 3-month-old infants; however, an audiovisual asynchrony condition was not run in this study. Studies investigating infants' ability to identify emotions, a property of human communication that can be expressed across multiple modalities, also provide evidence for the facilitation effects of intersensory redundancy. These studies suggest that infants initially need multisensory input in order to identify emotions (Walker-Andrews, 1997) or detect changes in prosody associated with specific emotions (Bahrick, 2010, 2012).

The current work is particularly concerned with how the availability of multisensory information, or rather the presence of intersensory redundancy, affects perception in young adults. According to the IRH, intersensory facilitation only occurs in adults under certain conditions. For example, intersensory facilitation occurs in

adults during tasks that are difficult for their level of experience and during tasks with high cognitive or attention demands (e.g., novel learning, divided attention, increased self-regulation, increased executive function, or higher effort). Apart from predicting that selective attention will be recruited towards redundantly specified amodal information, the IRH does not make specific predictions about how intersensory redundancy facilitates behavior.

Evidence for intersensory facilitation effects in adults as predicted by the IRH is still limited (Bahrick et al., 2009; Bahrick & Lickliter, 2012). According to the IRH, intersensory facilitation occurs in adults during tasks that are difficult given the perceiver's level of experience and during tasks that increase cognitive load and tax attention. Examples include tasks that require novel learning, divided attention, increased self-regulation, increased executive function, or higher effort. To date, only a few studies have met the criteria necessary to test the IRH's predictions about intersensory facilitation in adults. Those studies do, however, offer generally confirmatory evidence. Bahrick et al. (2009) assessed intersensory facilitation effects on perception of tempo changes and found that adults' mean accuracy scores were better when tempo was presented audiovisually than just visually. Seitz et al. (2006) examined intersensory facilitation effects on perception of motion, which can be conveyed redundantly across multiple modalities. Adults were trained on a visual motion perception task that is typically difficult for adults and requires multiple training days. One group of adults was trained on the task using audiovisual stimuli, and another group was trained using typical visual-only stimuli. Learning in both groups was measured by performance in a visual-only version of the task. Results showed that adults trained using audiovisual stimuli learned significantly faster than adults

trained using visual-only stimuli, providing evidence for the facilitative effects of intersensory redundancy. Gelfand et al. (in prep., chpt. 2) assessed intersensory facilitation effects on adults' perception of temporal information. Temporal information is a property that may be conveyed redundantly across multiple modalities. Accuracy and reaction times were measured during a go/no-go task requiring detection of specific duration patterns. The task was presented in three different stimulus presentation conditions: audiovisual presentation, auditory-only presentation, and visual-only presentation. Performance during the audiovisual condition was superior to performance during each unisensory condition, in either accuracy or reaction time measures, but not in both measures. The IRH suggests a general improvement in performance when multisensory instead of only unisensory information is available. However, results from this study did not show a consistent pattern of improvement, but rather enhancement of either accuracy or reaction time when multisensory information was available. Given this inconsistent pattern, results from the study did not provide definitive evidence for the facilitative effects of intersensory redundancy in adults.

Beyond the confines of the IRH, a larger body of work exists documenting multisensory facilitation effects in adults. However, these adult studies do not tightly control for key features of the IRH including: 1) the presence of intersensory redundancy and 2) testing perception of redundant features. For example, mostly during simple detection tasks, research has shown multisensory facilitation effects in reaction times (Diederich & Colonius, 2004; Gielen, Schmidt, & Van Den Heuvel, 1983; Hershenson, 1962; see Rowe, 1999, for a review) and in accuracy, as measured by detection probability (d') (Frassinetti, Bolognini, & Ladavas, 2002;

Lovelace, Stein, & Wallace, 2003; see Rowe, 1999, for a review; Watkins & Feehrer, 1965). Thus, multisensory facilitation effects on adults have been demonstrated both in faster reaction times and in higher accuracy, but, in some cases, these facilitative effects are present even when multisensory stimuli are not temporally synchronous (i.e., true intersensory redundancy is not present) (Diederich & Colonius, 2004; Gielen et al., 1983; Hershenson, 1962).

In fact, a subset of the literature on multisensory facilitation effects has been devoted to investigating the effects of asynchronous multisensory stimuli on performance. Facilitation effects are detectable in reaction times to multisensory stimuli even when a visual stimulus precedes an auditory stimulus by as much as 120 ms (Bernstein, Clark, & Edelstein, 1969; Miller, 1986; Morrell, 1968; Nickerson, 1970). These effects are less robust and occur within a more limited range of asynchrony when an auditory stimulus precedes a visual stimulus (Miller, 1986; Morrell, 1968; Nickerson, 1970). Researchers have suggested that multisensory facilitation effects that occur when the visual stimulus precedes the auditory stimulus stem from generally slower processing in the visual domain than in the auditory domain (Morrell, 1968; Miller, 1986). Accordingly, if the auditory signal is presented within a delay that outpaces visual processing time, then facilitation effects are obtained.

Based on the literature reviewed above, temporal synchrony and, by extension, intersensory redundancy, are not necessary for adults to experience multisensory facilitation effects. Yet, according to the IRH, temporal synchrony is a critical and defining feature of intersensory redundancy and, further, facilitation effects should only occur in the presence of intersensory redundancy. Perhaps multisensory processing is more resilient in adults and, as a result, information from more than one

sensory modality presented in temporal *proximity*, but not necessarily tightly constrained temporal *synchrony*, is sufficient to facilitate performance. However, IRH does specify that intersensory facilitation is seen in adults only during demanding tasks. Aside from the few multisensory facilitation studies that directly address the predictions of the IRH, research on multisensory facilitation in adults has only very basic detection tasks, wherein a subject is asked simply to respond to the presence of any stimulus item or the presence of a particular stimulus – either visual or auditory (Bernstein, Clark, & Edelstein, 1969; Diederich & Colonius, 2004; Frassinetti et al., 2002; Gielen et al., 1983; Hershenson, 1962; Lovelace et al., 2003; Miller, 1986; Morrell, 1968; Nickerson, 1970; Watkins & Feehrer, 1965). Therefore, it is possible that adults do not require temporal synchrony to show facilitation effects in these simple detection tasks, but in more difficult tasks, synchrony may be crucial.

Present Study

The current project further examines the predictions of the IRH in adults. Specifically, we ask whether presenting information in two sensory modalities within temporal *proximity* is sufficient to facilitate adults' performance during a demanding task, or, whether, as the IRH predicts, temporal synchrony is necessary for facilitation. We assessed performance during an executive function task, which Bahrick and Lickliter (2012) suggest is sufficiently demanding to render intersensory redundancy beneficial. We used a go/no-go task, which is used widely to assess response inhibition (see Simmonds, Pekar, & Mostofsky, 2008, for a review). Response inhibition is conventionally construed as a kind of executive function (Garavan, 2002), and the go/no-go task is tailored to be demanding for each individual participant (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000).

Given that previous work on multisensory facilitation has demonstrated facilitation effects in reaction times and accuracy, in the current study we will also assess facilitation effects based on reaction times (RTs) and accuracy. The IRH predicts performance facilitation in adults to synchronous (intersensory redundancy) stimuli as compared to asynchronous stimuli during a difficult task. However, the IRH does not make specific predictions about which behavioral responses will be facilitated. Therefore, it is predicted on the assumption of speed/accuracy trade-offs that adults will demonstrate either faster RTs or higher accuracy in response to synchronous stimuli as compared to asynchronous stimuli.

The IRH does make specific predictions about the orientation of attention. The IRH predicts that in adults, during a difficult task, redundantly-specified amodal information (i.e., synchronous stimuli) will capture attention more than amodal information that is not redundantly specified (i.e., asynchronous stimuli). Looking behavior is thought to closely reflect how attention is being deployed (Findlay, 2004; Henderson, 2013; Kowler, Anderson, Dosher, & Blaser, 1995; Liversedge & Findlay, 2000). In the following experiments, we will use looking behavior to investigate the prediction made by the IRH that intersensory redundancy is especially salient and therefore recruits selective attention. If, in fact, intersensory redundancy is especially salient and does recruit selective attention, then we would expect a higher proportion of time spent looking at visual stimuli during conditions where intersensory redundancy is present, as compared to conditions where intersensory redundancy is not present.

Experiment 1

METHOD

Participants

A group of thirty monolingual English speaking college students (2 males, 28 females, *mean age* = 22.04 years, *SD* = 2.84) were recruited from college campuses in the San Diego area. Participants were brought into the lab for two separate testing sessions (see below) and received either class credit or $5/session for their participation.

All participants reported normal or corrected vision and no history of fluency difficulty (e.g., stuttering), motor speech difficulty (e.g., apraxia of speech or dysarthria), attention deficit disorder (ADD) or attention deficit hyperactivity disorder (ADHD), frank neurological impairment, language or learning disability, mental illness, or social difficulties (e.g., autism spectrum disorder).

To ensure normal hearing, all participants were given a bilateral hearing screening at 500, 1000, 2000, and 4000 Hz at 25 dB HL (American National Standards Institute, 1996).[9] All participants demonstrated a nonverbal intelligence quotient (IQ) within the normal range of 85 or greater (*M* = 97, *SD* = 7.60) as measured by the Test of Nonverbal Intelligence, Fourth Edition (TONI-IV; Brown, Sherbenou, & Johnsen, 2010).

To ensure normal language ability, all participants were administered a battery of standardized language measures designed to screen for presence of language impairment in adults (Fidler, Plante, & Vance, 2011). This battery included: (1) the

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[9] One participant failed the hearing screening at 500 Hz in one ear but was still included in the study since hearing acuity was within normal limits bilaterally for the frequency range of experimental stimuli.

spelling test from Fidler et al. (2011), (2) a modified version of the Token Test (Morice & McNicol, 1985), and (3) the Clinical Evaluation of Language Fundamentals, 4th edition, Word Definition subtest (CELF-4-WD; Semel, Wiig, & Secord, 2003). Scores from this battery were entered into an analysis described by Fidler et al. (2011) to determine if adults should be classified as having normal language or a language impairment. To be included in the current study, participants needed to demonstrate language abilities within the normal range (M = -.96, SD = .57, where a score less than 0 constitutes normal language).

Another 22 participants were tested but were excluded from the analyses: 12 for meeting criteria for a language impairment, 3 for failure to remember which stimulus type was the target and which was the foil[10], 3 for significant second language experience, 2 for a self-reported history of one or more concussions resulting in loss of consciousness, 1 for failing to return for the second session, and 1 for failing to complete the experimental tasks due to feeling nauseated.

Stimuli

The auditory stimuli consisted of four different pure-tone pairs, which differed only in the duration pattern of the tones. All tones were 1000 Hz presented at 70 dB. Short tones were 75 ms long and long tones were 175 ms long. Four different duration patterns were used in the study: (1) short-short (75 ms + 75 ms), (2) short-long (75 ms + 175 ms), (3) long-long (175 ms + 175 ms), (4) long-short (175 ms + 75 ms). Three interstimulus intervals (ISIs) between tones of the tone pairs were used:

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[10] For each of these three participants, the participant confused the target and non-target items for only one out of six conditions resulting in 0% or nearly 0% accuracy. Target and non-target confusion was assumed based on above chance accuracy for all other conditions for each participant. Given the inconsistency in performance, these participants were excluded entirely from the analyses.

60 ms, 150 ms and, 300 ms. Auditory stimuli were created using Sound Studio software.

The visual stimuli for the task consisted of three different shapes. These included: a circle, a diamond, and a square. Each shape was bright yellow and set against a black background and height and width ranged from 75-90 pixels. Shapes were centered at midline on the x-axis of the screen but presented 20% higher than the midline on the y-axis of the screen. Shapes were presented above the center point of the screen to ensure that fixation data were not confounded by a preference to stare at the center of the screen. Shapes were varied across conditions in a fixed random order; however, only one shape was used within any given condition. Shapes were presented in duration pairs that were identical in duration and pattern to the tone pairs. Visual stimuli were created using Adobe Photoshop CS4 (see Figure 3.1 for examples).

Procedure

Participants were brought in for two testing sessions each lasting ~1.5 hours. Testing took place in experimental testing rooms on the SDSU campus in the School of Language, Speech, and Hearing building. The first session began with an explanation of consent forms, a general explanation of the testing session, and review of information provided in the background questionnaire, which was completed prior to the session. Participants then completed experimental tasks followed by standardized language and cognitive testing. The second session began with a reminder about informed consent and participants' rights followed by experimental testing, and then standardized language and cognitive testing.

Experimental Tasks

Participants were seated in a comfortable chair 70 cm from a display monitor (1024 x 768 pixels). Participants were asked to use a chinrest and a headrest during the experimental tasks and to remain situated for the duration of the experimental tests. This apparatus is a feature of the EyeLink tower mount set-up and ensures stability and consistency of eye recordings within and across participants. Participants were given an opportunity to move and adjust their position in between tasks. Each experimental task began with a 5-point manual calibration and validation phase during which participants were asked to look directly at a bull's-eye image, which appeared sequentially at five different locations on the screen. The calibration procedure allows the eye-tracker (SR Research Eyelink 2000 Eyetracker with the tower mount configuration, SR Research, Ltd) to capture specific characteristics of each participant's eye in order to reduce error in automatic estimates of the participant's saccade trajectories and fixation centroids. Tasks were presented on a PC computer using SR Research Eyelink Experiment Builder Software (SR Research Ltd, Mississauga, Ontario, Canada, 2011). Participants were given ~2 minute breaks in between tasks.

Recording Eye Movements

Eye movement data (fixations, saccades, and blinks) were recorded from the onset to the offset of each trial, at a rate of 1000 Hz, using an SR Research Eyelink 2000 Eyetracker with the tower mount configuration (SR Research, Ltd). Blinks and saccades were automatically omitted to derive fixation data for further analyses. Specific events within each trial were tagged with a label (e.g., onset of first visual stimulus) in the data output file for offline data analyses.

Synchronous Audiovisual Go/No-Go Task

The synchronous audiovisual task consisted of a go/no-go task design. Participants were presented with one of two kinds of audiovisual target/non-target designs: 1) short-short versus short-long, or 2) long-long versus long-short. These target/non-target designs were counterbalanced across participants. The short-short, short-long, and long-short stimuli served equally often as the target. In order to create synchronous audiovisual targets and non-targets, the auditory and visual stimuli described above were presented concurrently and matched for onset and duration. Three different durations were used between the stimulus items within a pair (60 ms, 150 ms, and 300 ms).

Participants were presented with 60 target stimuli (20 at each between stimulus items duration) and 24 non-target stimuli at each of the between stimulus items durations (60 ms, 150 ms, and 300ms) for a total of 60 target trials and 24 non-target trials. This 70% target to 30% non-target ratio was used because this design was judged to be difficult enough to generate sufficient performance variance to detect any possible influence of inter-stimulus synchronicity (Donkers & van Boxtel, 2004; Johnstone et al., 2007). Target and non-target trials were presented in a fixed random order. The between-trial interval varied randomly between 1000 ms and 1200 ms (See figure 3.1 and 3.2).

Instructions for the task were presented on the screen while the experimenter read and explained them to the participant. Participants were told that they would be presented with two different kinds of tone pairs. Two examples of each tone pair, one with a 60 ms between stimulus items duration and one with a 300 ms between stimulus items duration, were played for the participants. Participants were told that

one of these tone pairs was the target pair and that they should press the space bar on the keyboard whenever they heard the target tone pair. Instructions were followed by six practice trials consisting of three target stimuli and three non-target stimuli at each of the three between stimulus items durations. Practice trials were presented in a fixed random order. Participants were then reminded of which pair was the target tone pair, and finally the experimental trials were begun (see Figure 3.1 for examples of experimental trials). Auditory stimuli were presented through headphones (at 70 dB) and visual stimuli appeared on the screen during the practice and experimental trials.
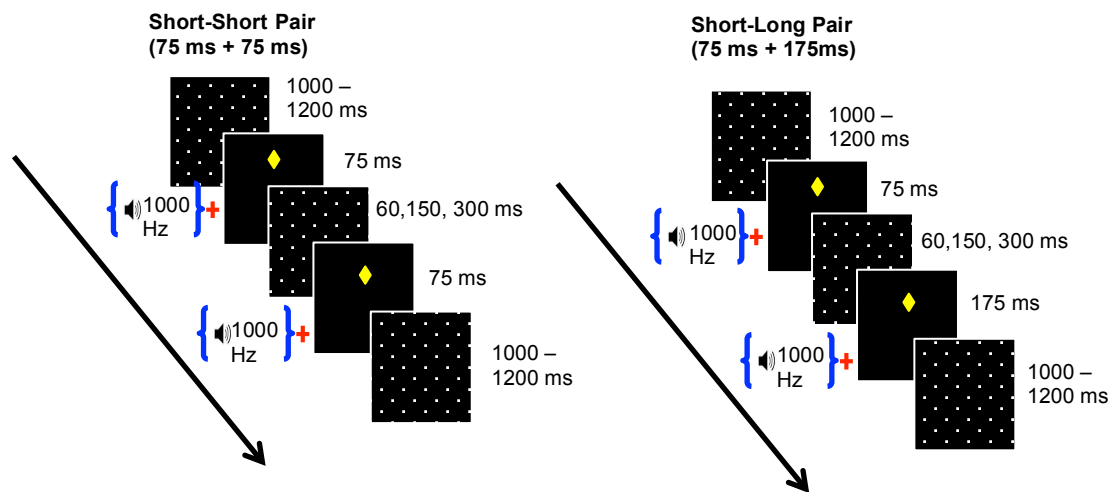
Figure 3.1 Example of one set of target/non-target pairs (short-short vs. short-long) for synchronous audiovisual task.

Asynchronous Audiovisual Go/No-Go Task

The asynchronous audiovisual go/no-go task was identical to the synchronous audiovisual go/no-go task with the exception of the onset timing of the auditory and visual stimuli. Visual stimuli were presented and completed exactly 400 ms prior to the onset of the auditory stimuli. However, the duration pattern of the auditory stimuli

always matched the duration pattern of the visual stimuli. For example, a long-long visual stimulus pair with 150 ms between stimulus items would be followed by a long-long auditory stimulus pair with 150 ms between stimulus items (see Figure 3.2 for examples). The 400 ms offset in timing with visual stimuli preceding auditory stimuli was determined to be representative of audiovisual asynchrony based on previous work that used similar timing differences to assess audiovisual asynchrony (Dodd, 1977; 1979), and 2) and findings that integration of auditory and visual stimuli is reduced as stimuli offsets exceed 200 ms (see Laurienti & Hugenschmidt, 2012, for review).
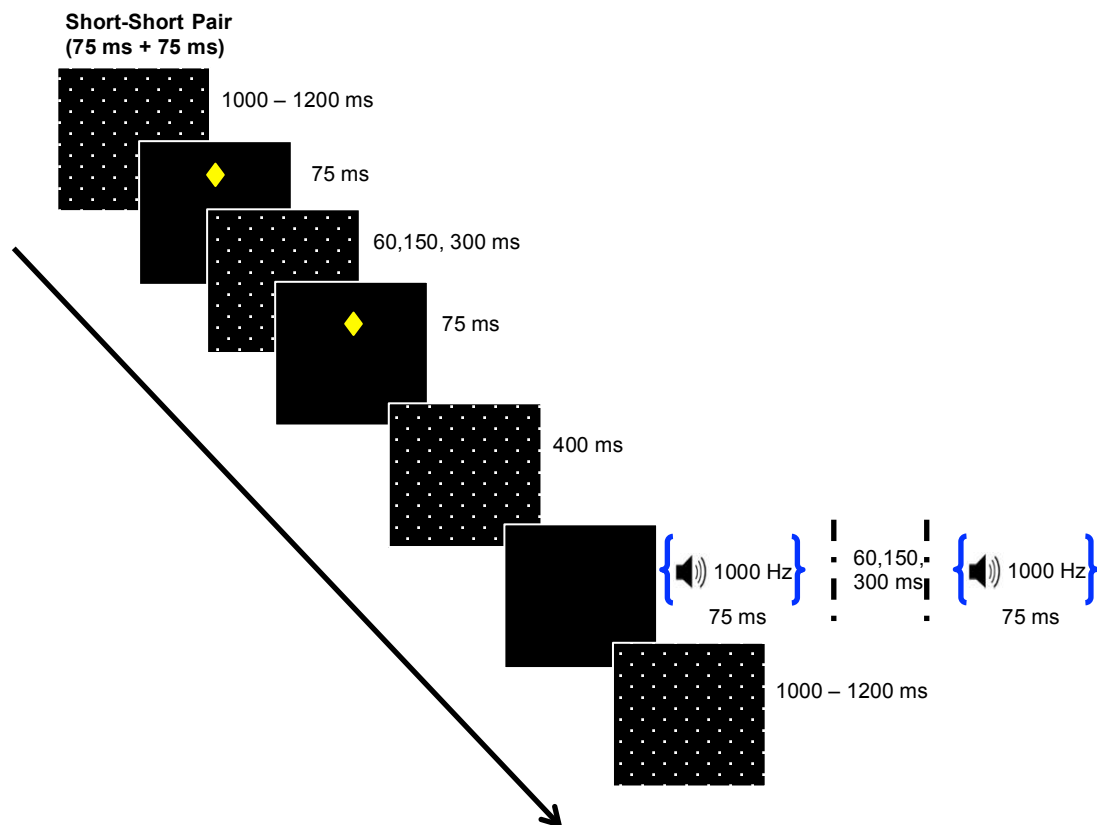
Figure 3.2 Example of one target or non-target pair (short-short) for asynchronous audiovisual task.

RESULTS

Accuracy was calculated using d-prime (d'). (Green & Swets, 1966). Bias was calculated using *C*. Average RTs were calculated for correct trials only. Average proportion of time spent looking at the visual stimulus out of the total trial duration was calculated for each participant. To allow for analysis of equivalent time windows across synchronous and asynchronous conditions, the total trial duration was defined as beginning with the onset of the first visual stimulus and ending with the offset of the second visual stimulus. All trials were included in the looking time analysis. Average proportion of time spent looking was determined based on eye movement data recordings generated by Eyelink's built-in software. Participants' fixations were considered looks to the visual stimulus if they fell within a predefined region of interest, the visual stimulus and immediate surrounding area, defined as a 400 x 400 pixel square centered around the visual stimulus. Average gaze duration within this region of interest out of total trial duration was calculated to determine proportion of time spent looking at the visual stimulus for each participant.

Accuracy

A paired-samples t-test was used to compare accuracy (operationalized as *d'*) across tasks. Accuracy was significantly higher in the asynchronous audiovisual condition (*M* = 2.57, *SD* = .95) than in the synchronous audiovisual condition (*M* = 2.12, *SD* = 1.04), *t*(29) = -2.70, *p* = .012, *r* = .48, (see Figure 3.3). This suggests that accuracy was facilitated by audiovisual asynchrony.
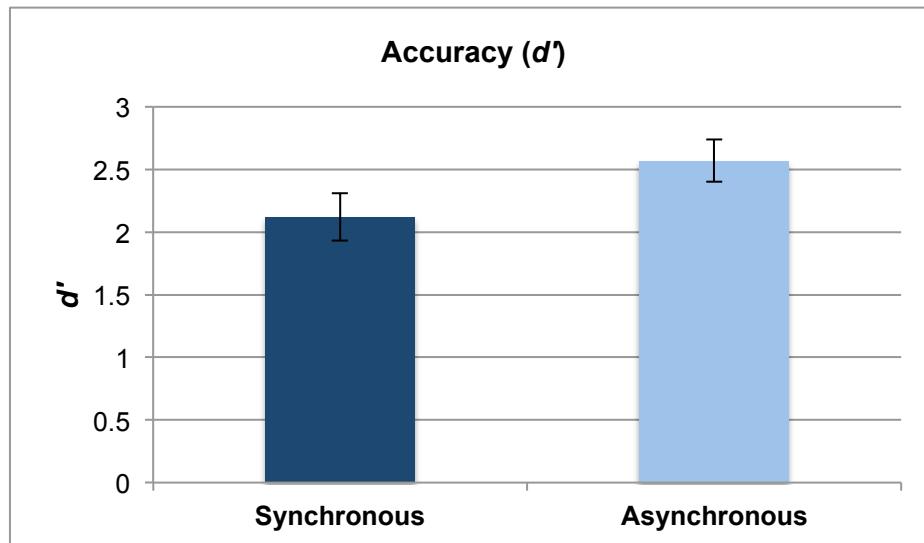
Figure 3.3 Experiment 1 Synchronous vs. Asynchronous: *d'*
performance by condition

Response bias (operationalized as *C*) was no different in the asynchronous condition
(*M* = .18, *SD* = .42) than in the synchronous condition (*M* = .12, *SD* = .45), *t*(29) = -
.71, *p* = .482, *r* = .13 (see Figure 3.4), indicating that synchronous audiovisual
information did not, in itself, promote or inhibit responding.
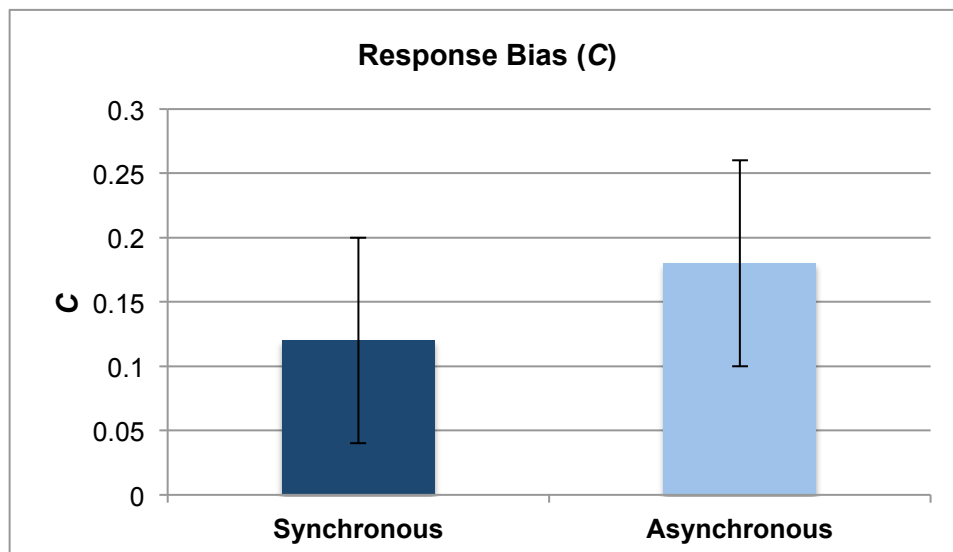
Figure 3.4 Experiment 1 Synchronous vs. Asynchronous: *C* (response
bias) performance by condition

Reaction Time

A paired samples t-test revealed that RTs were significantly faster in the synchronous audiovisual condition (*M* = 565.42, *SD* = 88.26) than in the asynchronous audiovisual condition (*M* = 604.04, *SD* = 121.94), *t*(29) = -2.35, *p* = .026, *r* = .40, (see Figure 3.5). Thus, audiovisual synchrony facilitated response speed.
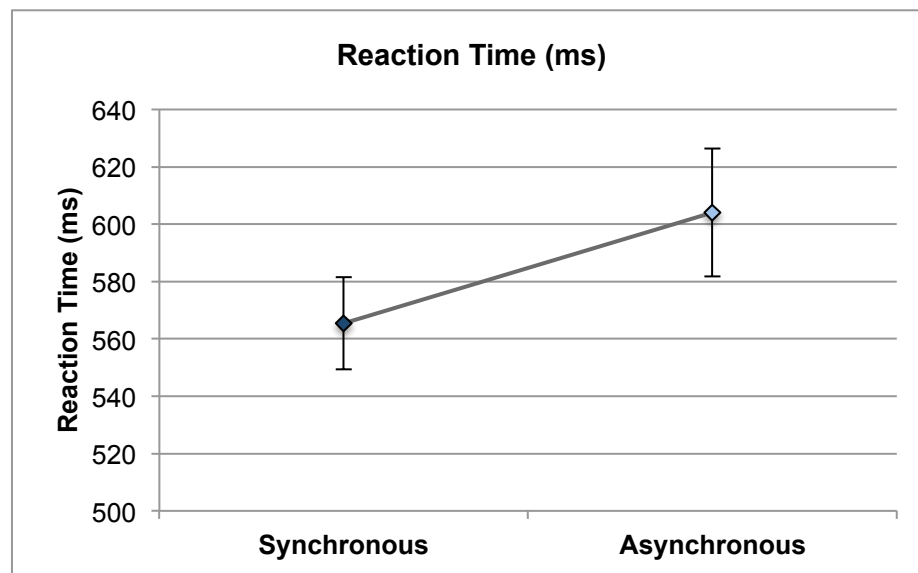
Figure 3.5 Experiment 1 Synchronous vs. Asynchronous: Reaction time by condition

Proportion of Looking

A paired samples t-test was used to compare proportion of time spent looking at the visual stimulus across conditions. Similar to RTs, the proportion of time spent looking at the visual stimulus was significantly greater in the synchronous condition (*M* = .76, *SD* = .32), than in the asynchronous condition (*M* = .57, *SD* = .38), *t*(29) = 3.23, *p* = .003, *r* = .51, (see Figure 3.6). Looking behavior results suggest that

audiovisual synchrony attracted a higher proportion of time spent looking at the visual stimulus.
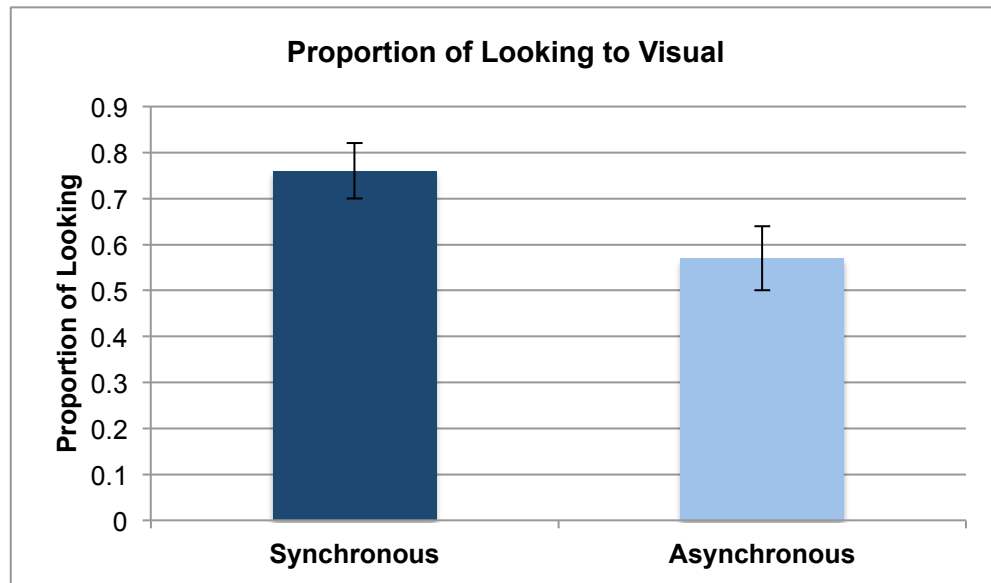
Figure 3.6 Experiment 1 Synchronous vs. Asynchronous: Proportion of time spent looking at the visual stimulus by condition

DISCUSSION

The overall goal of this study was to test a factor of the predictions of the IRH that temporal synchrony is a necessary component for adults to experience intersensory facilitation. To test this, we compared adults' performance during an executive function task when audiovisual information was presented synchronously to their performance during the same task when audiovisual information was presented asynchronously. The results showed that participants were more accurate in correctly detecting the target in the asynchronous condition; however, RTs were faster and the proportion of target looking was greater in the synchronous audiovisual condition. Evidence from the current study suggests that synchrony leads to greater attention to the visual stimulus, and faster processing speed, but not increased accuracy,

whereas asynchrony in the timing of auditory and visual stimuli leads to greater accuracy. Furthermore, this evidence suggests that synchrony may not be as critical for facilitation effects as suggested by the IRH model.

The audiovisual asynchrony in this experiment was created by presenting the visual stimuli out of phase with the auditory stimuli by 400 ms. By using a single duration to offset the audio and visual stimuli to create this asynchrony, there is the possibility instead that the timing of the visual stimuli relative to the auditory stimuli may have somehow facilitated performance in the asynchronous condition. In adults, multisensory behavioral facilitation effects are fairly resilient to moderate timing differences in stimulus presentation (Diederich & Colonius, 2004; Diederich, Colonius, & Schomburg, 2008; Laurienti & Hugenschmidt, 2012). We selected a 400 ms time offset based on research indicating that the perception of audiovisual synchrony and the subsequent facilitation effects begin to rapidly decline when time offsets exceed 200 ms (see Laurienti & Hugenschmidt, 2012, for a review). Furthermore, previous work comparing performance during synchronous and asynchronous audiovisual presentations has successfully used a similar design, with redundant visual information preceding auditory information by a set interval (Dodd, 1977, 1979). The research that has investigated the time window over which multisensory information can still support facilitation has largely relied on RT measures (Diederich & Colonius, 2004, 2009). In the current study, adults' faster RTs in the synchronous condition suggest that synchrony is critical in order for facilitation effects to occur. This is consistent with the predictions of the IRH.

However, contrary to the predictions of the IRH, we found that asynchronous audiovisual information was associated with better accuracy than synchronous

information. Importantly, the literature on multisensory facilitation is replete with reports of multisensory performance boosts based only on reaction time data. Research also exists demonstrating accuracy performance boosts due to multisensory redundancy (Frassinetti, Bolognini, & Ladavas, 2002; Lovelace, Stein, & Wallace, 2003; see Rowe, 1999, for a review; Watkins & Feehrer, 1965), but this literature is much more limited. Furthermore, to our knowledge, no study has reported both measures, particularly in a test that requires cognitive effort. Thus, previous work based on *either* reaction time *or* accuracy did not clarify whether the two measures show similar effects of intersensory redundancy, or, whether one type of information is more sensitive to facilitation effects than the other, or even if different kinds of intersensory redundancy might show distinct effects on performance (e.g., either speed or accuracy is facilitated, determined by specific context).

The IRH makes broad predictions about intersensory facilitation effects, but does not specify in which behaviors these facilitation effects might appear. In fact, the only specific behavioral prediction that the IRH makes is about the recruitment of attention. Looking behavior is thought to be a useful measure that closely reflects deployment of attention (Findlay, 2004; Henderson, 2013; Kowler, 1995; Liversedge & Findlay 2000). Therefore, eye movement data provides an opportunity to investigate the more specific attention prediction of the IRH. Our eye movement data showed that a higher proportion of time was spent looking at the visual stimuli during the audiovisual synchrony condition, suggesting that, per the prediction of the IRH, audiovisual synchrony did in fact recruit more visual attention.

The goal of the current study was to investigate the predictions made by the IRH. In that respect, our reaction time and looking behavior findings uphold the

predictions of the IRH; however, our accuracy findings are inconsistent with the predictions of the IRH. According to the IRH, temporal synchrony is critical in order for adults to experience intersensory facilitation. Therefore, we expected that audiovisual synchrony would facilitate accuracy performance, not audiovisual asynchrony. The IRH and the larger literature on multisensory facilitation do not make specific predictions about which behavioral measures denote intersensory facilitation nor do they specify whether intersensory facilitation is defined by performance enhancements across all behavioral measures. One possibility is that the highly predictive relationship between the auditory and visual signals in the asynchronous condition, created by using a redundant visual signal with a constant time offset, facilitated accuracy, suggesting that this asynchronous design may not have created a true "asynchrony" between the auditory and visual signals. Another possibility is that the time interval used in the current experiment was wide enough to allow participants to disregard the visual stimulus entirely and treat the asynchronous condition like an auditory-only task. This possibility is supported by previous data showing an identical pattern of results across behavioral measures during a synchronous audiovisual task and an auditory-only task (Gelfand et al., in prep., chpt. 2).

The current results raise questions about the use of simple timing offsets as tests of asynchrony. The boosts in accuracy during the asynchronous condition suggest that the preceding visual signal may have served as a prime or a cue for the subsequent auditory signal. In the current paradigm, the visual stimulus had a high predictive cue value, both because it indicated that an auditory signal would occur soon, and because it provided redundant information for the following auditory signal.

It is unknown if a non-redundant visual signal, which would have little predictive value, would also yield boosts in accuracy. Given that the current study relied on a potentially controversial test of audiovisual asynchrony, the question remains: is the mere presence of information from more than one modality sufficient for adults to experience performance facilitation, even if the stimulus items are both asynchronous and non-predictive of temporal parameters?

Experiment 2

In Experiment 2, we address the potential predictive nature of the asynchronous timing of the visual stimuli in Experiment 1 by altering the degree to which the auditory and visual stimuli are asynchronous. During Experiment 2, visual and auditory signals were not presented at consistent time-offsets and the visual signal did not provide a predictive cue of the duration pattern of the auditory signal. In Experiment 2 we used a qualitatively different kind of asynchrony in order to evaluate our initial question about the importance of tightly constrained temporally synchrony to intersensory facilitation. We again compared adults' reaction times and accuracy performance across synchronous and asynchronous conditions. We could not make a direct comparison between the asynchrony condition from Experiment 1 and the asynchrony condition from the current experiment, Experiment 2, because more than element of the design was changed from Experiment 1 to Experiment 2, making the asynchrony conditions in each experiment qualitatively distinct. If intersensory facilitation is expressed more in RTs, with trade-offs allowing for faster reaction times but potentially reduced accuracy, then changing the predictability of the stimuli in the asynchrony condition should not significantly alter our findings. On the other hand, if, in Experiment 1, higher accuracy in the asynchrony condition was driven by predictive

cueing, then in Experiment 2 asynchrony should mean reduced accuracy and RTs, as predicted by the IRH. Additionally, based on the IRH and the results of Experiment 1, we expect adults to spend a greater proportion of time looking at the visual stimulus during the synchronous condition than during the asynchronous condition.

METHODS

The same group of participants who participated in Experiment 1 also completed Experiment 2. To examine the role of predictive asynchrony, participants' performance in Experiment 2 was compared to their performance in the synchronous condition in Experiment 1. While the same participants completed Experiments 1 and 2 and the experimental tasks for each took place on the same day within the same session, Experiments 1 & 2 are reported here as separate experiments because these experiments were not initially designed to be within subjects comparisons. Accordingly, stimuli and procedure were identical to Experiment 1; however, Experiment 2 consisted of a new asynchronous audiovisual condition designed to minimize the predictive nature of the asynchrony.

Experimental Tasks

Asynchronous Audiovisual Go/No-Go Task

Two primary goals informed the design of the asynchronous audiovisual go/no-go task and, in particular, the design of the visual stimuli in this condition. The first goal was to create an audiovisual asynchrony where the visual signal had little to no predictive value. The second goal was to create an audiovisual asynchrony where the predictive value, or lack thereof, of the visual signal was not overtly obvious. In order to achieve these goals, two critical design changes were made to the presentation of the visual signal. The first change involved the duration patterns of the

visual signal. As previously described in the design of experiment 1, two target/non-target pairings were used during the task: either 1) short-short vs. short-long or 2) long-long vs. long-short. During the new asynchrony condition, the auditory and visual signals were selected from different pairings in order to ensure that the visual stimuli were not predictive of the auditory stimuli. For example, if a participant received an auditory signal comprised of short-short vs. short-long pairs as the target/non-target comparison, then the visual signal was comprised of long-long vs. long-short pairs (see Figure 3.7 for examples). Likewise, if a participant received an auditory signal comprised of long-long vs. long-short pairs as the target/non-target comparison, then the visual signal was comprised of short-short vs. short-long pairs (see Figure 3.7 for examples). In this way, the auditory and visual signals were matched for onset; however, duration patterns were never predictable between the two signals.
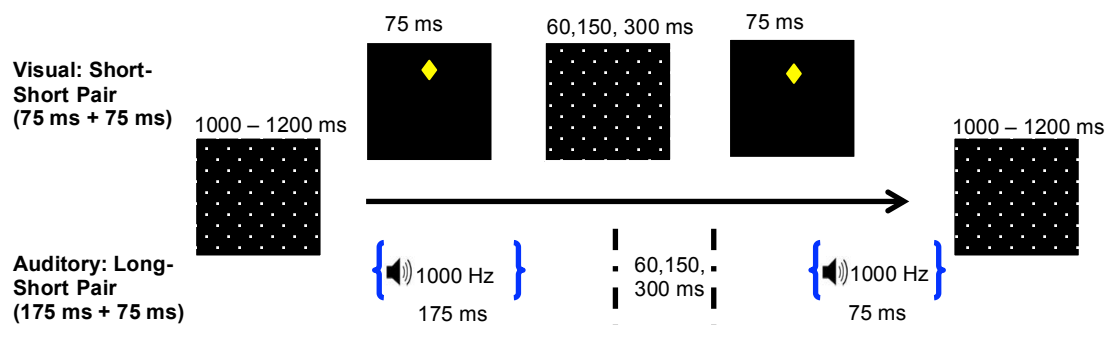
Figure 3.7 Asynchronous audiovisual task trial example of target tone and visual pair (audio: long-short, visual: short-short) in which both visual stimulus items for the visual stimulus pair appear.

Since these timing differences were slight and potentially fell within the time window where facilitation effects might persist, an additional design change was made to the presentation of the visual signal. For 25% of the trials, the first visual stimulus of the visual pair was removed, so that participants only saw the standard

black background (see Figure 3.8 for examples). For another 25% of the trials, the second visual stimulus of the visual pair was removed (see Figure 3.7 for examples). Thus, for 50% of the trials, a single visual stimulus item appeared on the screen at some point during the presentation of the auditory stimulus pair (see Figure 3.8 for examples). For the remaining 50%, a visual stimulus pair (i.e., two visual stimulus items) was presented during the presentation of the auditory stimulus pair. These trials still represent asynchrony because of the differences in duration of the auditory and visual stimuli (see Figure 3.7 for examples). As in Experiment 1, during the task, participants were instructed to respond by pressing the space bar on the keyboard when hearing the target tone pair.
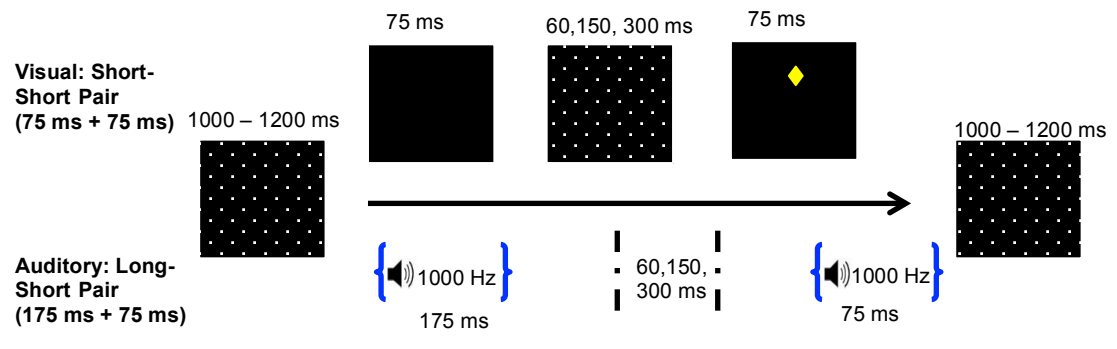
Figure 3.8 Asynchronous audiovisual task trial example of target tone and visual pair (audio: long-short, visual: short-short) in which only one visual stimulus item for the visual stimulus pair appears.

Data Analysis

Behavioral measures calculated for data analyses in Experiment 1 were also calculated for the new asynchronous audiovisual task used in Experiment 2. These measures included d', C (response bias), RT, and average proportion of time spent looking at the visual stimulus. Participants' performance was compared to the synchronous audiovisual condition from Experiment 1.

RESULTS

Accuracy

A paired-sample t-test was used to compare accuracy (*d'*) across tasks. Participants' accuracy in the asynchronous condition (*M* = 2.23, *SD* = .79) did not differ significantly from their performance in the synchronous condition (*M* = 2.12, *SD* = 1.04), *t*(29) = -.71, *p* = .48, *r* = .09 (Figure 3.9), indicating that participants' detection performance was not enhanced in the synchronous condition.
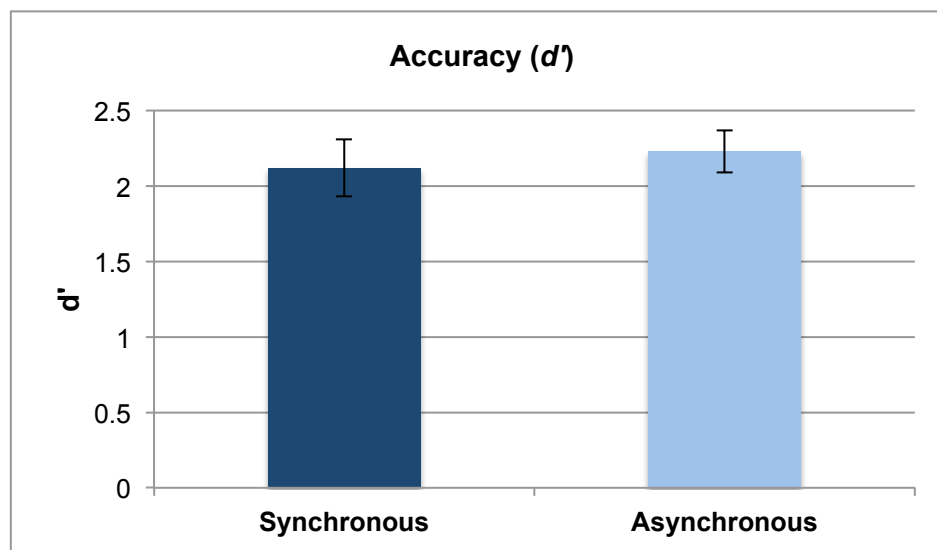
Figure 3.9 Experiment 2 Synchronous vs. Asynchronous: *d'* performance by condition

Participants' response bias (*C*) was no different across the asynchronous (*M* = .26, *SD* = .34) and synchronous conditions (*M* = .12, *SD* = .45), *t*(29) = -1.79, *p* = .08, *r* = .32 (Figure 3.10). Thus, as expected, removing the predictability of the visual stimuli in Experiment 2 removed the accuracy advantage observed for asynchronous trials in Experiment 1.
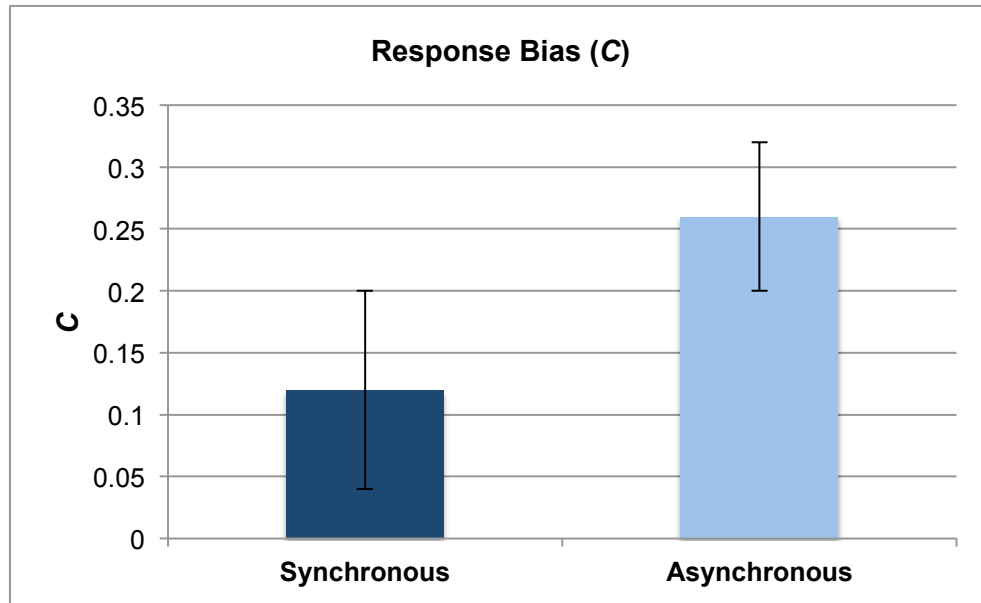
Figure 3.10 Experiment 2 Synchronous vs. Asynchronous: *C* (response bias) performance by condition

Reaction Time

A paired-sample t-test was used to compare RT for correct trials in the synchronous and asynchronous conditions. Participants' RTs were significantly faster in the synchronous condition (*M* = 565.42, *SD* = 88.26) than in the asynchronous condition (*M* = 599.65, *SD* = 74.40), *t*(29) = -2.49, *p* = .019, *r* = .42 (Figure 3.11). Thus, consistent with Experiment 1, facilitation effects were observed for RTs during the synchronous relative to the asynchronous condition.
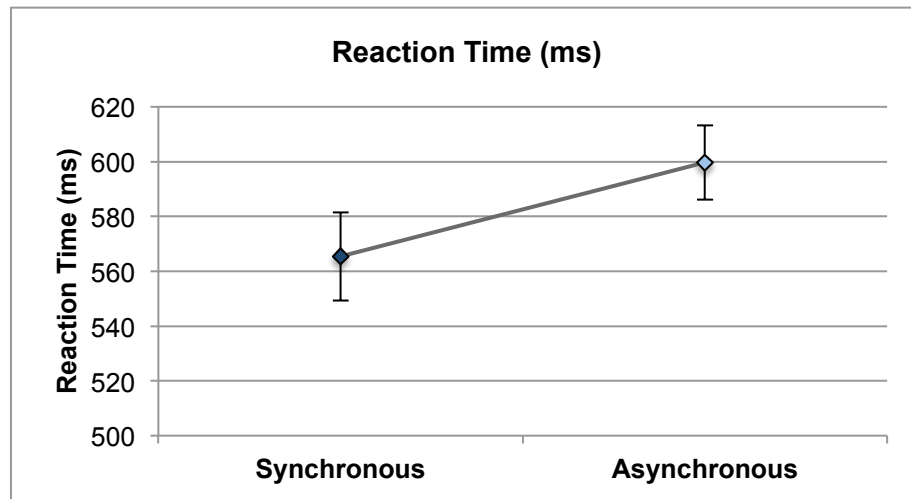
Figure 3.11 Experiment 2 Synchronous vs. Asynchronous: Reaction time by condition

Proportion of Looking

Proportion of looking across all trials did not differ in the asynchronous audiovisual condition (*M* = .65, *SD* = .33) as compared to synchronous condition (*M* = .76, *SD* = .32), *t*(29) = 1.95, *p* = .062, *r* = .34 (see Figure 3.12); however, a strong trend was observed indicating that looking-time proportions were higher in the synchronous condition than in the asynchronous conditions.
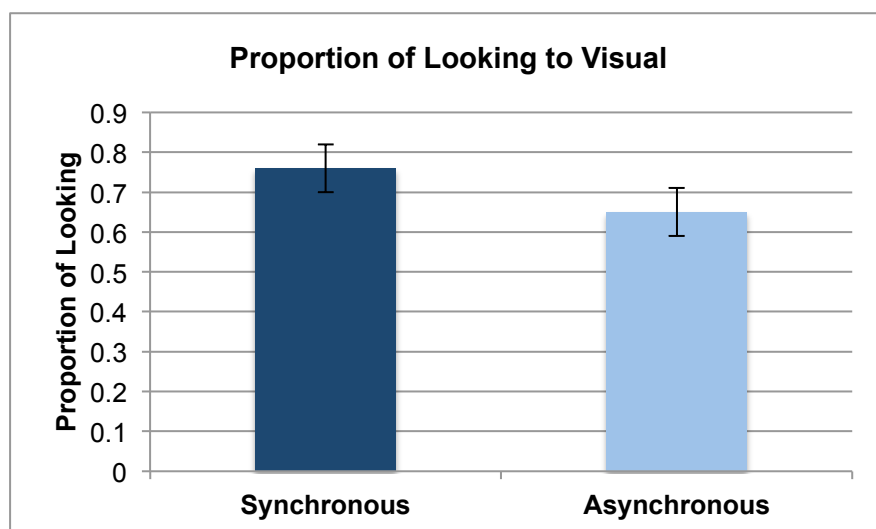
Figure 3.12 Experiment 2 Synchronous vs. Asynchronous: Proportion of time spent looking at the visual stimulus by condition

DISCUSSION

The goal of Experiment 2 was to expand our test of the predictions of the IRH by comparing performance effects of synchronous audiovisual information to performance effects of asynchronous audiovisual information with little to no predictive value. Results from Experiment 2 showed that audiovisual synchrony led to robust observable facilitation effects in RTs. Given the variability in observable facilitation effects, our data provide only partial support for the IRH on the current executive function task in young adults. Additionally, results from Experiment 2 help to clarify findings from Experiment 1.

Similarly to Experiment 1, evidence for the facilitation effects gained from synchronous audiovisual information was found in the comparison of reaction times across conditions. In both experiments, reaction times were significantly faster during the synchronous audiovisual condition as compared to the asynchronous audiovisual condition. These findings support the predictions of the IRH that intersensory redundancy facilitates performance in adults. The consistency of our RT findings across Experiments 1 and 2 suggests that RT might be a more sensitive behavioral measure for detecting the effects of intersensory facilitation.

Again, similarly to Experiment 1, a comparison of accuracy performance across conditions did not provide evidence in support of the IRH. However, unlike Experiment 1, for Experiment 2, accuracy performance was not significantly different across conditions. This finding lends support to our previous suggestion that high predictive value was embedded within the design of the asynchronous audiovisual condition used in Experiment 1, which then contributed to measurable boosts in accuracy performance.

Looking behavior data indicated that adults evidenced no significant difference in looking behavior across conditions; however, a strong trend was observed indicating a higher proportion of looking in the synchronous condition than in the asynchronous condition. As previously discussed, the IRH would predict that adults would spend less time looking at the visual information during the asynchronous audiovisual condition, because the visual signal was not redundant and therefore would not capture the same level of attention. However, the specific goal for the design of the asynchrony condition for Experiment 2 was to create an asynchrony where the predictive value, which inherently has a strong relationship with redundancy, of the visual signal was not overtly obvious. Results from our looking behavior data (i.e., no significant differences in looking behavior across conditions) suggest that we accomplished this goal. Adults may have spent relatively similar amounts of time looking at the visual stimuli across conditions because, in the case of synchronous audiovisual information, the visual stimuli were redundant, captured attention, and provided useful information, and, in the case of asynchronous audiovisual information, the redundancy and value of the visual stimuli were difficult to determine and therefore may have captured more visual attention. For the asynchronous condition, the value of the visual signal may have been difficult to determine given the slight timing differences between the auditory and visual stimuli. As previously discussed, the perception of audiovisual synchrony is relatively resilient to slight timing differences (Diederich & Colonius, 2004; Diederich, Colonius, & Schomburg, 2008; Laurienti & Hugenschmidt, 2012). Thus, the asynchronous condition may have encouraged a higher proportion of looking to the visual stimulus because it may have required a good deal of exposure and visual attention before

adults realized that there was no consistent relationship between the auditory and visual signals.

Results from Experiment 2 suggest that the manipulations made to the asynchronous condition provided a slightly stronger test of the IRH. Evidence for this comes from the similarity in accuracy scores across conditions in Experiment 2, which was not the case in Experiment 1. In Experiment 1, our asynchrony condition actually boosted accuracy performance, and possibly not because the auditory and visual stimuli were asynchronous but because the visual stimuli, while not time-locked to the auditory stimuli, were still predictive of the onset and pattern of the auditory stimuli. Our reaction time results from Experiment 2 suggest that in go-no/go tasks, speed of processing increases when auditory and visual stimuli are synchronous.

Across Experiments 1 & 2, our most consistent and robust evidence in support of the IRH comes from reaction time data. It is possible that reaction time is simply the most sensitive behavioral measure of intersensory facilitation effects. Research to date cannot adequately speak to this. However, it is also possible that there is yet a stronger test of the IRH, which would result in more consistent findings of facilitation effects across behavioral measures. Prior research has suggested that the facilitative effectiveness of multisensory information is inversely related to the effectiveness of the component unisensory stimuli (Meredith & Stein, 1983; 1986; Stanford, Quessy, & Stein, 2005; Stein & Meredith, 1993). In other words, enhancements in performance due to the presence of multisensory stimuli are most pronounced when performance in the presence of each unisensory stimulus is particularly weak. Our prior work on the unisensory components used for this particular task, suggests that, at least for the unisensory auditory stimulus, adults' performance is fairly good (Gelfand et al., in

prep., chpt. 2). Therefore, manipulating the effectiveness of the auditory signal so that it is, for example, harder to perceive, may provide an even stronger test of the IRH and lead to more robust facilitation effects across behavioral measures.

Experiment 3

In Experiment 3, we examined the predictions of the IRH further by comparing the impact of synchronous audiovisual information to the impact of asynchronous audiovisual information (i.e., asynchrony as defined in Experiment 2) under degraded listening conditions. Speech perception research has shown that the availability of visual support, in the form of visual speech cues, significantly improves the intelligibility of speech signals degraded by background noise (Dodd, 1977; Sumby & Pollack, 1954). This has been shown in child (Barutchu et al., 2010; Erber, 1971), adolescent (Dodd, 1977) and adult populations (Sumby & Pollack, 1954). Furthermore, eye-tracking studies have shown a shift in gaze patterns to the face when noise is added to a speech signal. Specifically, Buchan, Paré, & Munhall (2008) found that, under noisy conditions, duration of fixations to the nose and mouth increase. The implications of this prior work suggest that degraded auditory signals encourage more reliance on redundant visual cues. These implications are in line with the idea that the effectiveness of multisensory stimuli is inversely related to the effectiveness of each unisensory component (Meredith & Stein, 1983; 1986; Stanford et al., 2005; Stein & Meredith, 1993). Thus, degrading the quality of the auditory signal in our task may provide an even stronger test of the IRH, by increasing the difficulty of the task and by encouraging more reliance on the redundant cues provided by the visual signal. If facilitation effects in Experiment 2 were attenuated by strong auditory performance, then degrading the auditory signal should enhance

them. If intersensory facilitation was not attenuated by ceiling auditory performance, then degrading the auditory signal should not meaningfully affect performance, and we would then expect the pattern of results to match those from Experiment 2.

METHODS

The same participants who completed Experiments 1 and 2 also completed Experiment 3. After participating in Experiments 1 and 2, participants were brought back and completed Experiment 3 during a separate testing session, which took place on a different day. During Experiment 3, auditory signal quality was manipulated by reducing volume so that all auditory stimuli were presented at 35 dB as compared to 70 dB in Experiments 1 & 2. For Experiment 3, participants completed two experimental tasks: 1) a synchronous audiovisual go/no-go task, which was identical to the synchronous audiovisual go/no-go task used in Experiment 1, aside from reducing the volume of the auditory stimuli, and 2) an asynchronous audiovisual go/no-go task, which was identical to the asynchronous audiovisual go/no-go task from Experiment 2, aside from reducing the volume of the auditory stimuli. Except for reducing volume, design and procedures for these two conditions were identical to the design and procedures used during Experiments 1 and 2.

RESULTS

Data for all four behavioral measures (d', C, RT, looking-time proportion) were calculated and analyzed to determine if results for Experiment 3, in which the auditory signal was degraded, provided stronger support for the predictions of the IRH. In order to test this, analyses were run comparing behavioral results across the synchronous and asynchronous conditions.

Accuracy

A paired-sample t-test was used to compare accuracy (*d'*) across conditions. As in Experiment 2, accuracy in the synchronous condition (*M* = 2.34, *SD* = 1.14) was not significantly different from accuracy in the asynchronous condition (*M* = 2.21, *SD* = .95), *t*(29) = .90, *p* = .38, *r* = .16 (see Figure 3.13), indicating that synchrony did not facilitate participants' discrimination accuracy above and beyond asynchrony.

Accuracy (*d'*)

Synchronous	Asynchronous
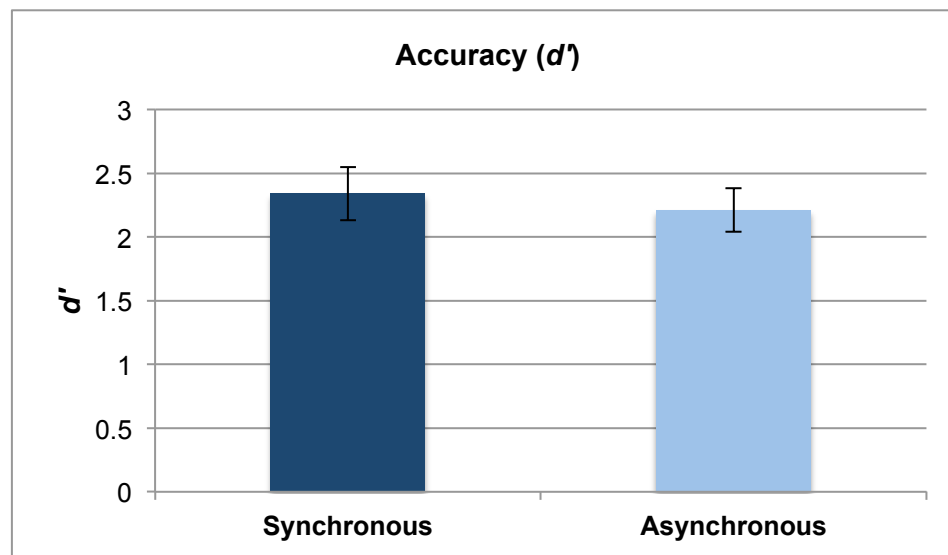
Figure 3.13 Experiment 3 Synchronous vs. Asynchronous: *d'* performance by condition

Response bias (*C*) in the synchronous condition (*M* = .08, *SD* = .44) was significantly lower than in the asynchronous condition (*M* = .25, *SD* = .39), *t*(29) = -2.29, *p* = .029, *r* = .39 (see Figure 3.14). While response bias was significantly different across conditions, results for both conditions showed a positive average response bias score, which indicates that for both conditions, response bias was somewhat conservative. Our results suggest that response bias was more conservative, and thus somewhat more cautious, in the asynchronous condition.
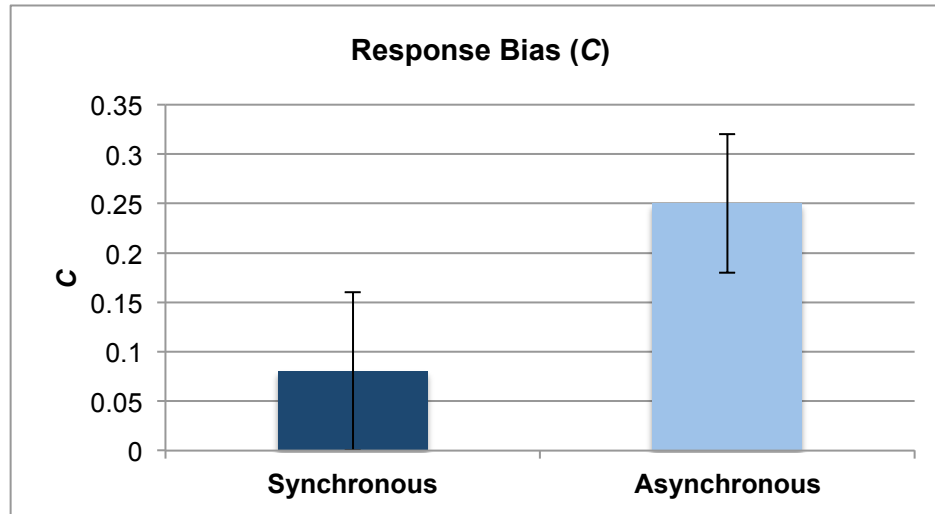
Response Bias (*C*)

Figure 3.14 Experiment 3 Synchronous vs. Asynchronous: *C* (response bias) performance by condition

Reaction Time

As in Experiments 1 and 2, average RT for correct trials in the synchronous condition (*M* = 580.04, *SD* = 101.33) was significantly faster than average RT for correct trials in the asynchronous audiovisual condition (*M* = 631.99, *SD* = 89.96), $t(29) = -3.57$, $p = .001$, $r = .55$ (see Figure 3.15). Therefore, based on RT data, facilitation effects were observed in the synchronous condition.
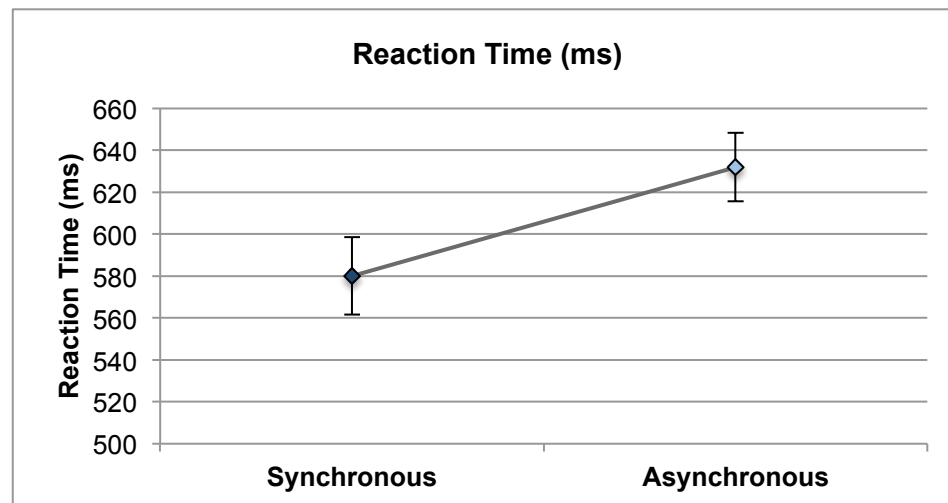
Figure 3.15 Experiment 3 Synchronous vs. Asynchronous: Reaction time by condition

Proportion of Looking

Consistent with findings in Experiment 1 and with the trend observed in Experiment 2, the proportion of time spent looking at the target in the synchronous condition (M = .67, SD = .38) was significantly higher than in the asynchronous condition (M = .39, SD = .35), $t(29)$ = 4.26, p < .001, r = .62 (see Figure 3.16). A higher proportion of looking to the visual stimulus was observed in the synchronous condition, suggesting more recruitment of visual attention in this context.
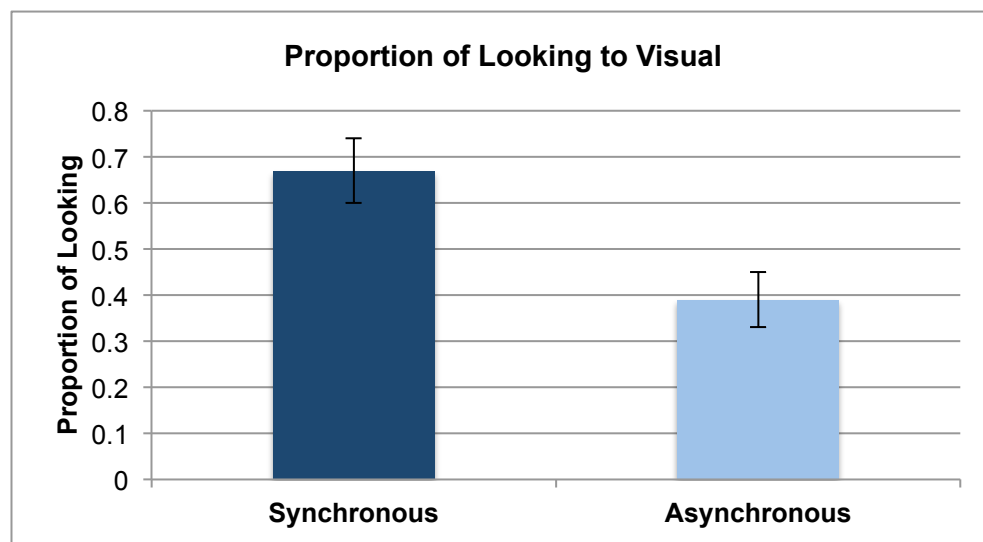
Figure 3.16 Experiment 3 Synchronous vs. Asynchronous: Proportion of time spent looking at the visual stimulus by condition

DISCUSSION

The goal of Experiment 3 was to expand our testing of the predictions of the IRH by considering the impact of signal strength on intersensory facilitation effects. Thus far, our testing of the IRH has revealed that reaction time may be the most sensitive and robust measure of intersensory facilitation effects. Our testing has also revealed that both timing and predictive cue value interact with facilitation effects to determine which behaviors are facilitated and in which contexts. More specifically, our

results thus far indicate that synchrony does consistently improve speed of processing (e.g., reaction time), but not accuracy, whereas an asynchronous but predictive temporal relationship improves accuracy but not necessarily speed of processing. In each case, our testing of the IRH provided somewhat mixed results, which suggests either that intersensory facilitation is not especially strong in adults, or that our tests were not providing conditions during which intersensory facilitation is especially strong. Experiment 3 attempted to push our understanding of the IRH with a stronger test of its predictions. Results from Experiment 3 provided the strongest support for the predictions of the IRH; however, results remained constrained to RTs and looking-time proportion.

Similarly to Experiments 1 & 2, the predictions of the IRH were not borne out in accuracy performance. Our non-significant findings across conditions indicate that the presence of intersensory redundancy did not facilitate accuracy performance. However, our findings for the complementary response bias measure do suggest that the presence of intersensory redundancy affected performance. Our findings indicate that response bias was significantly less conservative during the synchronous condition. While average response bias was conservative across both conditions, less conservative bias behavior during the synchronous condition indicates that participants were more willing to make a button response (i.e., categorize a given stimulus item as a target item). The adoption of a less conservative response strategy during the synchronous condition may be a reflection of an increase in participants' confidence in their response decisions.

Again similarly to Experiments 1 & 2, results from RT behavior during Experiment 3 provide support for the predications of the IRH. Per the IRH, the

presence of intersensory redundancy should facilitate faster RTs. Indeed, during Experiment 3, the presence of intersensory redundancy during the synchronous condition facilitated significantly faster RTs as compared to RTs during the asynchronous condition.

Lastly, our looking behavior results from Experiment 3 also support the predictions made by the IRH. Results from our looking data indicate that adults spent a greater proportion of time looking at the visual stimuli in the synchronous condition than in the asynchronous condition. The premise of the theory behind the IRH is that redundant multisensory information recruits attention, which then allows the observer to utilize the additional cues provided by a redundant signal to facilitate performance. If intersensory redundancy does uniquely recruit attention, then, in the case of our experiment, we would expect adults to spend more time looking at the visual stimuli when the visual stimuli provide redundant information. Results from Experiment 3 did, in fact, show that adults spent more time looking at the visual stimuli when redundant information was available.

GENERAL DISCUSSION

Overall, in the current series of studies we provide supporting evidence for the IRH, identify which behavioral measures are most sensitive to intersensory facilitation, and further clarify conditions under which adults are more likely to experience intersensory facilitation. Across all three experiments, RT appeared to be the most sensitive and robust measure of intersensory facilitation. This was demonstrated by significantly faster RTs in the synchronous conditions as compared to the asynchronous conditions, a finding that upholds the predictions of the IRH, during performance on an executive function task in young adults. Accuracy

appeared to be the least sensitive behavioral measure for detecting intersensory facilitation effects. However, within the confines of the experiments reported here, accuracy was potentially a robust measure of the predictive cue value of asynchronous stimuli (i.e., Experiment 1). Response bias, a complementary measure to accuracy, proved to be more sensitive than accuracy to changes in behavioral responses due to the presence of intersensory redundancy, but only in the most challenging processing context (Experiment 3). Scores indicated a less conservative response bias in the synchronous conditions than in the asynchronous conditions. This finding was marginal in Experiment 2, but significant in Experiment 3, during which our test of intersensory facilitation effects was strongest, due to increased processing demands, and as confirmed by findings most consistent with the predictions of the IRH. Likewise, looking behavior data also reflected changes in behavioral response due to the presence of intersensory redundancy. Across all three experiments, proportion of time spent looking at the visual stimuli was higher in the synchronous conditions than in the asynchronous conditions. This finding was significant in Experiments 1 and 3 and trended in this direction in Experiment 2. Therefore, our looking behavior data suggest that intersensory redundancy does, in fact, capture attention and affect looking behavior in adults, as suggested by the IRH.

The IRH posits that the temporal relationship – specifically temporal synchrony among multisensory stimuli – is integral to the definition of intersensory redundancy and therefore critical in order for facilitation effects to occur (Bahrick & Lickliter, 2012). Our results from Experiment 1 suggest that the temporal relationship that must exist among multisensory stimuli in order for facilitation effects to occur may be less restrictive than the IRH predicts. Furthermore, our results suggest that the

predictive value or redundancy (i.e., analogous characteristics, in the case of this study, duration pattern) of stimulus items may be an important factor for facilitation effects. Prior work has shown that facilitation effects persist to a point even with asynchronous presentation (Bernstein, Clark, & Edelstein, 1969; Miller, 1986; Morrell, 1968; Nickerson, 1970). However, work on multisensory processing, and related facilitation effects, has not thoroughly investigated the impact of predictive value on facilitation effects. Considering our results from Experiment 1, where stimuli were asynchronous but predictive value was high, and our results from Experiment 2, where stimuli were asynchronous and predictive value was very low, it may be the case that the presence of multisensory information without temporal synchrony is sufficient to boost some aspects of behavioral performance (e.g., accuracy), but only if stimulus items have some amount of predictive value. Additional research is needed to determine: 1) how much predictive value is needed in order to observe facilitation effects and 2) the time window during which facilitation effects persist given a certain degree of predictive value.

The multisensory processing literature at large supports the idea that multisensory processing is most effective when neither sensory stimulus alone is especially effective (Meredith & Stein, 1983; 1986; Stanford et al., 2005; Stein & Meredith, 1993). Evidence for this comes from an eclectic body of research ranging from studies of speech in noise to basic non-linguistic detection tasks (Barutchu et al., 2010; Dodd, 1977; Erber, 1971; Meredith & Stein, 1983; 1986; Stanford et al., 2005; Stein & Meredith, 1993; Sumby & Pollack, 1954). The predictions of the IRH do not, at any point, factor in the quality of the input as an influential component to the presence or robustness of intersensory facilitation effects. Along with prior research,

our data suggest that the quality of the input is a necessary consideration. The strength of support for the IRH from our behavioral data increased as the quality of the auditory stimulus decreased from Experiment 2 to Experiment 3.

Our findings provide support for and add to the predictions of the IRH, as well as contribute to the larger body of multisensory processing literature. We explored only a few factors that govern the predictions of the IRH: synchrony, predictive value, and input quality; however, more work is needed to not only further explore the limits of these parameters, but also to explore additional factors that govern the predictions of the IRH, like the impact of variation in task difficulty or the strength of these predictions for other modality combinations. Additionally, research has not thoroughly investigated the impact of predictive value on multisensory facilitation effects. More research is needed to explore the characteristics of predictive value that lead to facilitation. For example, our data suggest that optimal multisensory facilitation effects may depend on a symbiotic relationship between temporal factors and predictive value; however, the endurance and specific characteristics of this relationship are yet to be determined.

Lastly, to our knowledge, this is the first study to investigate multisensory facilitation effects using a constellation of behavioral measures. Our findings yielded two important implications that warrant further investigation: 1) RT may be the most robust measure for detecting multisensory facilitation effects and 2) the impact of multisensory information may not follow a consistent trend across behavioral measures.

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CHAPTER 4: PATTERNS OF INTERSENSORY FACILITATION IN ADULTS WITH AND WITHOUT SLI: IMPLICATIONS FOR AUDIOVISUAL PROCESSING IN SLI

ABSTRACT

Many aspects of language development rely on the ability to process simultaneously co-occurring signals from multiple sensory sources (Gogate, Walker Andrews, & Bahrick, 2001). Thus, deficits in multisensory processing may contribute to atypical language development. Theories suggest that sensitivity to the temporal relationship among sensory signals is critical to multisensory processing (Bahrick & Lickliter, 2012). Evidence suggests that children with language impairment (SLI) have deficits in temporal auditory processing (Corriveau et al., 2007; Cumming et al., 2015) and reduced sensitivity to the temporal relationship between synchronous auditory and visual signals (Kaganovich et al., 2014; Pons et al., 2012). However, the following questions remain: 1) do deficits in temporal auditory processing underlie deficits in processing audiovisual synchrony, 2) are deficits in processing synchronous audiovisual information global (i.e., for nonlinguistic tasks), and 3) do deficits persist into adulthood? In the current study, we investigated these questions by comparing performance in adults with and without SLI across nonlinguistic synchronous audiovisual and auditory-only or visual only tasks (Experiment 1), nonlinguistic synchronous and asynchronous audiovisual tasks (Experiment 2), and nonlinguistic synchronous and asynchronous audiovisual tasks, in which the quality of the auditory signal was reduced (Experiment 3). Results indicate that adults with SLI may continue to demonstrate deficits in temporal auditory processing; however, the similar patterns of performance in adults with and without SLI across tasks suggest that deficits in processing synchronous audiovisual information may not represent a global or persistent feature of SLI.

INTRODUCTION

Humans experience the world through a constant and diverse supply of sensory input. As a result, information processing can become a chaotic, desultory, and noisy experience. In order to cope with the realities of the natural environment, humans must have a strategy for differentiating signal from noise and for determining which sensory information is relevant and related at any given time. Research has suggested that mechanisms exist to help guide human perception towards relevant signals and away from noise (Bahrick, 2010; see Bahrick & Lickliter, 2012, for a review). Furthermore, the ability to simultaneously, selectively, and associatively process information from multiple sensory sources may be fundamental to effective and efficient processing and subsequent learning. In fact, Smith and Gasser (2005) suggest that the ability to experience the world through multiple sensory modalities is foundational to the development of knowledge and rich representations. In line with this proposal, evidence from experimental studies suggests that, in important ways, multisensory information affects processing and contributes to learning (see Bahrick, 2010; Bahrick & Lickliter, 2012, for reviews; Gogate & Bahrick, 1998). The intersensory redundancy hypothesis (IRH) in particular, describes an orienting mechanism, which focuses selective attention contingent upon the nature of the sensory information that is available (Bahrick, 2010; Bahrick & Lickliter, 2012; Bahrick, Lickliter, & Flom, 2004) .

Naturally occurring phenomena provide both modality-specific information as well as modality-general information. Modality-specific information is information that can only be conveyed in a particular modality (e.g., color can only be conveyed through the visual modality). Modality-general information, also known as *amodal*

information, is information that is not unique to a particular modality and thus may be conveyed across more than one modality (e.g., duration information can be conveyed through both the auditory and visual modalities). Redundancy occurs in the signal when the same amodal information is conveyed through multiple modalities. The IRH suggests that information that is expressed *redundantly* across multiple sensory modalities (e.g., auditory and visual) is especially salient and, as a result, attracts attention (Bahrick & Lickliter, 2012). Additional examples of information that can be expressed redundantly across auditory and visual signals include: tempo (e.g., a metronome – beats per minute or rate), rhythm (e.g., a patterned sequence), duration, intensity, and spatial co-location (Bahrick, 2010). Bahrick (2010) refers to this specific kind of attention capturing redundancy as *intersensory redundancy* and defines it as the *simultaneous* co-occurrence of amodal information across two or more sensory modalities. *Temporal synchrony* is a foundational component of intersensory redundancy, because, as Bahrick and Lickliter (2012) explain, temporal synchrony is the quintessential amodal property that then allows for the detection of nested amodal properties, such as tempo, rhythm, duration, and intensity.

The orienting mechanism described by the IRH leads to a dynamic and cyclic process by which the kind of sensory information present in the environment differentially affects how selective attention is guided, which then determines what information in the environment is perceived, learned and remembered (Bahrick, 2010; Bahrick & Lickliter, 2012). Eventually, the information that is perceived, learned and remembered generates experience and expertise, which, in turn, influences what is subsequently attended to in the environment (Bahrick, 2010). These principles are foundational to the predictions made by the IRH and may be summarized as a

hierarchy of processing priority based on: (1) the availability of multisensory information (e.g., visual information *and* auditory information), (2) the availability of unisensory information (e.g., *only* auditory information or *only* visual information), (3) the experience or expertise of the perceiver and (4) the difficulty of the task. In essence, the IRH describes a powerful learning mechanism that is guided by the availability of sensory information in the environment. Consequently, any difficulty in processing information from various sensory sources could ultimately have appreciable downstream effects on perception and learning. The current work is particularly concerned with how sensitivity to multisensory information, or rather the presence of intersensory redundancy, affects perception.

The contributions of multisensory processing to development, especially to language development, have been well established in the developmental literature. Much of this research provides evidence for the ideas described by the IRH. A number of these studies have looked at sensitivity to multisensory synchrony (i.e., intersensory redundancy), specifically audiovisual synchrony, as a means of investigating speech perception during infancy. Findings indicate that beginning at a very young age (10-16 weeks), infants are both sensitive to and more attentive to synchronous audiovisual speech (Dodd, 1979; see Soto-Faraco, Calabresi, Navarra, Werker, & Lewkowicz, 2012, for a review). Studies have also shown that infants are both sensitive to and more attentive to audiovisual congruence in speech (Kuhl & Meltzoff, 1982; Kuhl & Meltzoff, 1984; Pons, Lewkowicz, Soto-Faraco, & Sebastián-Gallés, 2009; Soto-Faraco et al., 2012). Audiovisual congruence in speech represents an instance of intersensory redundancy created by the expression of the same phonetic information across the auditory and visual modalities. These findings

parallel the idea laid out by the IRH that intersensory redundancy is especially salient and captures attention.

Given that these abilities are present from early stages of development, sensitivity and attentiveness to intersensory redundancy likely play an important role during development. Broadly, the functional purpose of these abilities is to help humans process and navigate a natural and often noisy environment. The IRH more specifically posits that the functional purpose of sensitivity to intersensory redundancy is to determine what is perceived and subsequently learned, by guiding and focusing attention in specific ways. Findings from developmental research, particularly in the area of language development, support this notion.

The infant's language environment is noisy, cluttered by multiple speakers, multiple simultaneously occurring conversations, and additional non-linguistic background noise. It would be particularly advantageous for the infant to have the ability to select out and attend to one signal in particular, amongst the noise. Herein, sensitivity to intersensory redundancy serves a functional purpose. Infants are, in fact, able to selectively attend to one particular speech stream amongst noise (i.e., additional unrelated speech streams), if synchronous auditory and visual speech cues for the particular speech stream are available (Hollich, Newman, & Jusczyk, 2005). Additionally, research has shown that infants deploy more visual attention to a speaker's mouth when speech is unfamiliar (Lewkowicz & Hansen-Tift, 2012). Taken together, these studies suggest both that intersensory redundancy (e.g., synchronous audiovisual speech) captures attention and that infants rely on synchronous audiovisual information to facilitate speech perception. Intersensory redundancy, in the form of synchronous auditory and visual speech cues, also facilitates infants'

phonetic discrimination abilities (Teinonen, Aslin, Alku, & Csibra, 2008). Importantly, infants' phonetic discrimination abilities at 6 months are predictive of their future language abilities (Tsao, Liu, & Kuhl, 2004).

Beyond speech perception, studies have shown that intersensory redundancy facilitates infants' word comprehension skills (see Gogate et al., 2001, for a review). More specifically, intersensory redundancy facilitates infants' ability to learn paired associations (Gogate & Bahrick, 1998) and to engage in joint attention (Baldwin & Markman, 1989; Woodward, Markman, & Fitzsimmons, 1994), both integral skills for building word comprehension. Taken together, all of these findings highlight the valuable role that multisensory processing, specifically the ability to process intersensory redundancy, plays in language development.

The importance of intersensory redundancy processing to language development implicates intersensory redundancy processing as a potential area of deficit for individuals who do not experience typical language development. Findings for one population in particular, specific language impairment (SLI) (Bishop, 2014), suggest that an investigation of intersensory redundancy processing is warranted. In recent studies, children with SLI were compared to typically developing peers with respect to sensitivity to synchronous audiovisual speech (Kaganovich, Schumaker, Leonard, Gustafson, & Macias, 2014; Pons, Andreu, Sanz-Torrent, Buil-Legaz, & Lewkowicz, 2012). Results indicated that children with SLI are less sensitive to audiovisual speech asynchrony than typically developing peers. In other words, the ability to detect temporal synchrony between auditory and visual events may be impaired in SLI. As previously discussed, the ability to detect temporal synchrony is a fundamental component of intersensory redundancy processing, and further, allows

for the detection of nested amodal features like duration, rhythm, tempo, and intensity.

Underlying deficits in auditory processing have been a long-standing theory in the SLI literature. Recent accounts focusing on temporally related auditory processing in SLI have proposed an underlying deficit in acoustic entrainment to speech rhythm (Corriveau, Pasquini, & Goswami, 2007; Cumming, Wilson, & Goswami, 2015). Specifically, this research has proposed and provided evidence for reduced sensitivity to amplitude envelope rise times (ARTs) (Corriveau et al., 2007; Cumming et al., 2015; Richards & Goswami, 2015). ARTs signify syllabic properties (i.e., stress and boundaries) based on amplitude variation across time (duration) (Goswami & Leong, 2013). Furthermore, sensitivity to ARTs plays an important role in tracking the temporal contour of syllable beat structure in language (i.e., the rhythmic structure of language), which, in turn, is foundational to language development (Cumming et al., 2015; Goswami & Leong, 2013). For example, 6 to 8-month-old infants use rhythm to identify phrase and clause boundaries in a continuous stream of speech (Hirsh-Pasek et al., 1987). 9-month-olds use the rhythmic structure of speech to facilitate identification of possible word candidates (Morgan & Saffran, 1995). Importantly, research has shown that entrainment to the rhythmic units of speech occurs in both the auditory and visual cortex and entrainment in each of these modalities can influence entrainment in the other modality (Luo, Liu, & Poeppel, 2010). Thus, difficulty processing temporal aspects of an auditory signal could interfere with entrainment, which subsequently may affect the ability of individuals with SLI to perceive redundant temporal information across the auditory and visual modalities.

The ability to perceive this redundant temporal information is critical for intersensory redundancy processing.

Relatedly, it has been suggested that deficits in *visual* entrainment may impair auditory processing, specifically neural phase-locking in the auditory cortex (Power, Mead, Barnes, & Goswami, 2012). Neural phase-locking, also known as rhythmic entrainment, describes a process by which neural oscillations phase-lock to the temporal structure of an input stream so that the phases during which neurons are in a highly excitable state coincide with the occurrence of events in the stimulus stream (Golumbic, Poeppel, & Schroeder, 2012; Goswami, 2011; Power et al., 2012). Research has suggested that visual input can affect and even facilitate entrainment of the auditory cortex. Specifically, it has been suggested that the contributions of visual speech to the perception of an auditory speech signal (Sumby & Pollack, 1954) are the result of visual entrainment facilitating auditory entrainment (Schroeder, Lakatos, Kajikawa, Partan, & Puce, 2008).

A wealth of research has shown that children with SLI have processing deficits in the auditory domain (e.g., Corriveau, Pasquini, Goswami, 2007); however, investigations of visual processing in SLI are much more limited as compared to the research available for auditory processing in SLI. However, research has looked at the influence of visual speech cues on speech perception in SLI. Findings based on a McGurk effect paradigm indicate that both children and adults with SLI are significantly less influenced by visual speech when compared to typically developing peers (Boliek, Keintz, Norrix, & Obrzut, 2010; Norrix, Plante, & Vance, 2006; Norrix, Plante, Vance, & Boliek, 2007). This finding persists in children with SLI even when the McGurk stimuli are presented in noise (Meronen, Tiippana, Westerholm, &

Ahonen, 2013), which typically encourages more reliance on visual cues (Buchan, Paré, & Munhall, 2008). Limited research exists on the nature of temporal processing in the visual modality in SLI. Impaired visual entrainment, which would reflect a deficit in processing the temporal structure of a visual signal, could interfere with the ability of individuals with SLI to perceive redundant temporal information across the auditory and visual modalities. Again, this is critical for intersensory redundancy processing.

To date, research in SLI has established a deficit in detecting the temporal relationship between auditory and visual events (Kaganovich et al., 2014; Pons et al., 2012). It is unknown if intersensory redundancy processing is also impaired. Importantly, intersensory redundancy processing determines how the environment is navigated over the course of development and into adulthood. Furthermore, it is unknown whether the deficit in detecting a temporal relationship between auditory and visual events stems from an underlying deficit in auditory processing of temporal information or from an underlying deficit in visual processing of temporal information. The current set of studies will investigate the above questions in individuals with SLI.

Present Study

The current project examines intersensory facilitation in adults with and without SLI in order to investigate the nature of intersensory redundancy processing in SLI. Specifically, in Experiment 1, we ask, whether adults with SLI, as compared to adults with normal language (NL) experience similar patterns of intersensory facilitation for perception of a temporally redundant feature. In order to investigate intersensory facilitation, we looked at group performance across an audiovisual condition (i.e., intersensory redundancy) and two unisensory conditions (i.e., auditory only and visual only). The study design was based on previous work that investigated

intersensory redundancy processing in adults under intersensory redundancy and unisensory conditions (Gelfand et al., in prep., chpt. 1). Similar to previous work on intersensory facilitation, the current study will use reaction times (RTs) and accuracy measures to investigate intersensory facilitation effects in adults with and without SLI (Gelfand et al., in prep., chpt. 1; see Rowe, 1999, for a review). If reduced sensitivity to audiovisual synchrony (Kaganovich, et al., 2014; Pons et al., 2012) and temporal auditory processing deficits in SLI (Corriveau, Pasquini, & Goswami, 2007; Cumming, Wilson, & Goswami, 2015) are interfering with intersensory redundancy processing, then we predict more similar performance (i.e., smaller difference scores) across audiovisual and unisensory (auditory-only) conditions for the SLI group as compared to the NL group. If reduced sensitivity to audiovisual synchrony and a weaker reliance on visual information during audiovisual processing in adults with SLI (Norrix et al., 2006) are interfering with intersensory redundancy processing, then we predict more similar performance (i.e., smaller difference scores) across audiovisual and unisensory (visual-only) conditions for the SLI group as compared to the NL group.

Experiment 1

METHOD

Participants

A total of twenty-four monolingual English speaking college students were recruited from college campuses in the San Diego area. Participants were brought into the lab for two separate testing sessions. Each session was approximately 1.5 hours long. During these sessions the participants completed experimental tasks and

a series of diagnostic standardized assessment measures. Participants either received class credit or $5/session for their participation.

All participants reported normal or corrected vision and no history of fluency difficulty (e.g., stuttering), motor speech difficulty (e.g., apraxia of speech or dysarthria), attention deficit disorder (ADD) or attention deficit hyperactivity disorder (ADHD)[11], frank neurological impairment, language or learning disability, mental illness, or social difficulties (e.g., autism spectrum disorder). To ensure normal hearing, all participants were given a bilateral hearing screening at 500, 1000, 2000, and 4000 Hz at 25 dB HL (American National Standards Institute, 1996).[12]

Language Impaired and Typical Groups

To determine language ability, all participants were administered a battery of standardized language measures, developed by Fidler and colleagues designed to screen for presence of language impairment in adults (Fidler, Plante, & Vance, 2011). This battery included: 1) the spelling test from Fidler et al. (2011), 2) a modified version of the Token Test (Morice & McNicol, 1985), and 3) the Clinical Evaluation of Language Fundamentals, Fourth Edition, Word Definition subtest (CELF-4-WD; Semel, Wiig, & Secord, 2003). Scores from this battery were entered into an analysis described by Fidler et al. (2011) in order to determine if adults should be classified as having normal language or a language impairment. According to this analysis group membership is determined by the following formula: group membership score =

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[11] Despite our exclusion criteria, we collected data from one participant in the SLI group with a reported history of ADHD. The participant was retained for data analyses because removal of the participant did not significantly affect reported tests.
[12] Two participants (one from each group) failed the hearing screening at 500 Hz in one ear but were still included in the study since their hearing acuity was within normal limits bilaterally for the frequency range of experimental stimuli.

constant + [test1 x weight1] + [test2 x weight2] + [test3 x weight3].[13] If the analysis yielded a negative value, participants were classified as having typical language and, if the analysis yielded a positive value, participants were classified as having a language impairment.

Table 4.1 Group averages (standard deviation) for grouping criteria

	SLI (N=12)	NL (N=12)	p-value
Nonverbal IQ	97.33 (10.77)	95.42 (7.45)	.618
Fidler et al. (2011) Composite Language Score	.66 (.84)	-1.30 (.45)	<.001
Years of Education	14.50 (1.24)	14.67 (1.23)	.745
Maternal Education	15.67 (2.23)	15.67 (1.88)	1.00
Age (years)	22.74 (3.34)	23.49 (3.42)	.622

The SLI group included 12 college students (all female, M = 22.74 years, SD = 3.34) identified as language impaired according to their composite score, based on the Fidler et al. (2011) analysis described above (M = .66, SD = .84). The NL group included 12 college students (all female, M = 23.49 years, SD = 3.42) with language abilities at age-level expectations, based on the Fidler et al. (2011) analysis (M = -1.30, SD = .45). Groups were matched on gender, age, nonverbal intelligence quotient (IQ), years of education, and maternal education (see table 4.1)[14]. Maternal

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[13] Constant and weight values vary depending on group characteristics (e.g., known history of SLI) (see Fidler et al., 2011, for exact values). As recommended by Fidler et al. (2011) for use with a diverse research population, we used values from the "combined group" analysis.
[14] Participants included in the typical group were randomly selected and matched to participants in the SLI group from a total sample of 42 participants who took part in this project.

education was used as a measure of socioeconomic status (SES) (Luo, 2006).
Additionally, all participants demonstrated a nonverbal IQ within the normal range of
85 or greater, as measured by the Test of Nonverbal Intelligence, 4th Edition (TONI-
IV; Brown, Sherbenou, & Johnsen, 2010).

Stimuli

The auditory stimuli consisted of four different pure-tone pairs, which differed
only in the duration pattern of the tones. All tones were 1000 Hz pure tones presented
at 70 dB. Short tones were 75 ms long and long tones were 175 ms long. Four
different duration patterns were used in the study: (1) short-short (75 ms + 75 ms), (2)
short-long (75 ms + 175 ms), (3) long-long (175 ms + 175 ms), (4) long-short (175 ms
+ 75 ms). Three different duration lengths were used between tones of the tone pairs:
60 ms, 150 ms, and 300 ms. Auditory stimuli were created using Sound Studio
software.

The visual stimuli for the task consisted of three different shapes. These
included: a circle, a diamond, and a square. Each shape was bright yellow set against
a black background and height and width ranged from 75-90 pixels. Shapes were
centered at midline on the x-axis of the screen but presented 20% higher than the
midline on the y-axis of the screen. Shapes were presented above the center point of
the screen to ensure that fixation data was not confounded by a preference to stare at
the center of the screen. Shapes were varied across conditions in a fixed random
order; however, only one shape was used within any given condition. Shapes were
presented in duration pairs that were identical in duration and pattern to the tone
pairs. Visual stimuli were created using Adobe Photoshop CS4 (see Figure 4.1 for
examples).

Procedure

Participants were brought in for two testing sessions each lasting ~1.5 hours. Testing took place in experimental testing rooms on the SDSU campus in the School of Language, Speech, and Hearing building. The first session began with an explanation of consent forms, a general explanation of the testing session, and review of information provided in the background questionnaire, which was completed prior to the session. Participants then completed experimental tasks followed by standardized language and cognitive testing. The second session began with a reminder about informed consent and participants' rights followed by experimental testing, and then standardized language and cognitive testing.

Experimental Tasks

Participants were seated in a comfortable chair approximately 70 cm from a display monitor (1024 x 768 pixels). Tasks were presented on a PC computer using SR Research Eyelink Experiment Builder Software (SR Research Ltd, Mississauga, Ontario, Canada, 2011). Participants were given ~2 minute breaks in between tasks.

Synchronous Audiovisual Go/No-Go Task

The synchronous audiovisual task used a go/no-go task design. Participants were presented with one of two kinds of audiovisual target/non-target designs: either (1) short-short versus short-long or (2) long-long versus long-short (see Figure 4.1 for examples). These target/non-target designs were counterbalanced across participants. The short-short, short-long, and long-short stimuli served equally often as the target. The long-long pair was only used as a target for the single-modality tasks. In order to create synchronous audiovisual targets and non-targets, the

auditory and visual stimuli described above were presented concurrently and matched for onset and duration.

Participants were presented with 60 target trials (20 target trials at each of the 3 different duration lengths used between the two stimulus items of a stimulus pair: 60 ms, 150 ms, and 300 ms). Participants were presented with a total of 24 non-target trials (8 non-target trials at each of the 3 different duration lengths used between the two stimulus items of a stimulus pair: 60 ms, 150 ms, and 300 ms). Thus, 70% of the trials were target trials and 30% of the trials were non-target trials. This target to non-target ratio was used because a low no-go stimulus probability is said to increase task difficulty (Donkers & van Boxtel, 2004; Johnstone et al., 2007). Target and non-target trials were presented in a fixed random order. The amount of time between trials varied randomly between 1000 ms and 1200 ms.

Instructions for the task were presented on the screen while the experimenter read and explained the instructions to the participant. Participants were told that they would be presented with two different kinds of tone pairs. Two examples of each tone pair, one with a 60 ms duration between stimulus items of the tone pair and one with a 300 ms duration between stimulus items of the tone pair, were played for the participants. Participants were then told that one of the tone pairs was the target tone pair and asked to make a button response by pressing the space bar on the keyboard when hearing the target tone pair. Instructions were followed by six practice trials consisting of three target stimuli, one for each between stimulus items of a pair duration variation (60ms, 150ms, and 300ms) and three non-target stimuli, one for each between stimulus items of a pair duration variation, presented in a fixed random order. Participants were then reminded about which tone pair was the target tone pair

before beginning the experimental trials (see Figure 4.1 for examples of experimental trials). Auditory stimuli were presented through headphones and visual stimuli appeared on the screen during the practice and experimental trials.
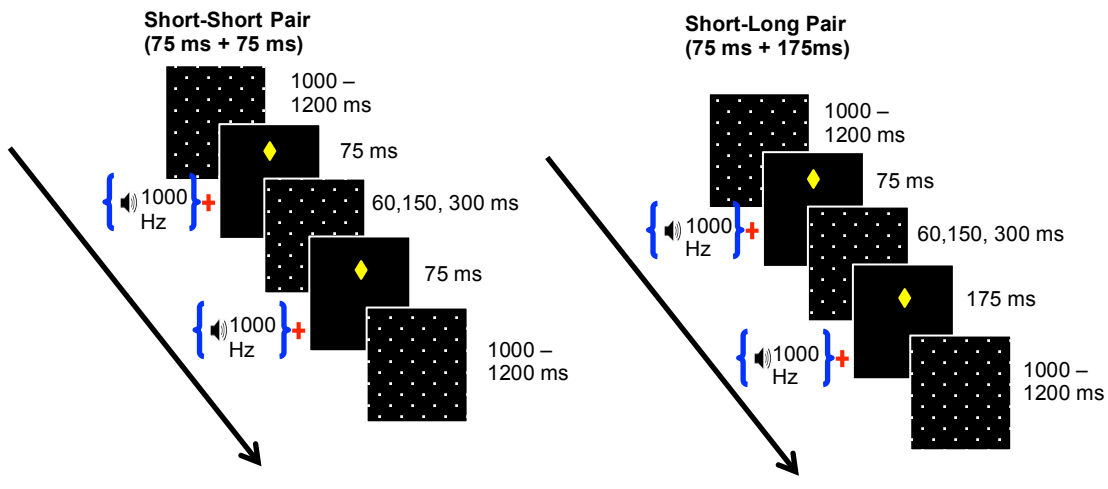
Figure 4.1 Example of one set of target/non-target pairs (short-short vs. short-long) for synchronous audiovisual task.

Visual-Only Go/No-Go Task

The design of the visual-only go/no-go task was identical to the audiovisual go/no-go task except for two design differences and one procedural difference. The first design difference was that only visual stimuli were presented for the visual-only go/no-go task. The second design difference was that only one target/non-target pair was used: long-long versus long-short (see Figure 4.2 for examples). Additionally, the long-long visual pair was always designated as the target pair. The reasoning behind this design variation stemmed from findings in the literature and our pilot data on the visual-only go/no-go task. Prior research has shown that temporal processing is superior in the auditory modality as compared to the visual modality (see Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010, for a review). Given this research and our pilot data suggesting that the visual-only go/no-go task was very challenging for

participants (e.g., well below chance accuracy), we selected the tone pair that was likely to be most easily perceived by the visual modality to serve as the target tone pair for all participants in the single modality tasks. Since participants completed all three tasks within the same session, we exclude the long-long pair as a possible target from the audiovisual synchrony go/no-go task in order to minimize practice effects. The procedural difference occurred during presentation of example stimuli. Rather than playing examples of tone-pairs for the participants, during the visual-only go/no-go task, participants were shown short video clip examples of the visual-only trials using an ipod touch. Similarly to the other two tasks, two examples of each visual pair were played. One example had a 60 ms between stimulus items of a visual pair duration and the other example had a 300 ms between stimulus items of a visual pair duration.
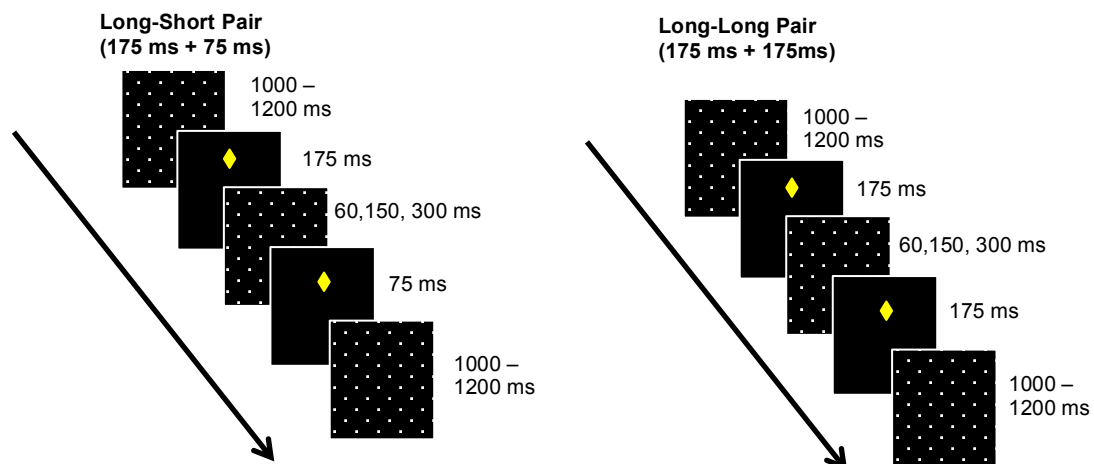
Figure 4.2 Example of one set of target/non-target pairs
(long-short vs. long-long) for visual-only task.

Auditory-Only Go/No-Go Task

The design of the auditory-only go/no-go task was identical to the audiovisual go/no-go task except for two design differences. First, only auditory stimuli were presented for the auditory-only go/no-go task. Participants remained seated in front of the computer screen in order to make keyboard responses; however, the computer screen remained entirely black for the duration of the task. The second design difference was that only one target/non-target pairing was used: long-long versus long-short (see Figure 4.3 for examples). Additionally, the long-long tone pair was always designated as the target pair. The reasoning for this design choice is described above.
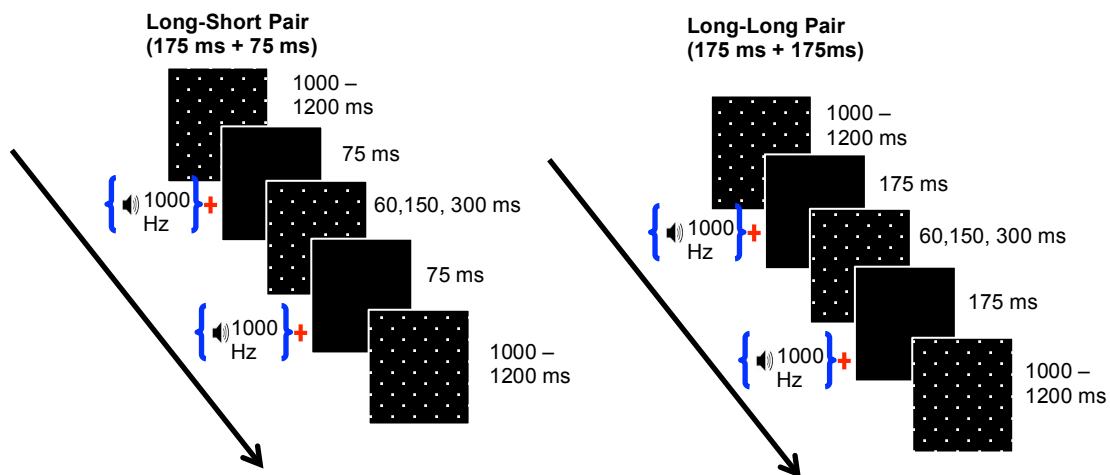
Figure 4.3 Example of one set of target/non-target pairs (long-short vs. long-long) for auditory-only task.

Data Analysis

Accuracy was calculated using d-prime (*d'*) (Green & Swets, 1966). Response bias was calculated using *C*. Response bias is an indicator of how liberal or how conservative responses are. A liberal response bias is consistent with a greater likelihood to identify a given stimulus item as a target item. A conservative response

bias is consistent with a greater likelihood to reject a given stimulus item as a target item. Alternate measures, beyond d' and C, exist for assessing performance accuracy and response bias. In particular, Pr (accuracy) and Br (bias) are similar to d' and C, respectively; however, these measures are based on a two-high threshold model rather than signal detection theory (Feenan & Snodgrass, 1990). Pr/Br and d'/C tend to trend together in terms of statistical findings except in cases where values are near asymptotic boundaries (Yonelinas & Parks, 2007). Presently, a consensus has not been reached on the best method of identifying discriminability. For that reason, in all cases where accuracy is reported in this work, all four measures (Pr, Br, d', and C) were calculated and statistical analyses were performed to evaluate the robustness of our findings. Average RTs for each participant for each task were also calculated. Average RTs were only based on correct button responses to target trials.

In order to effectively manage data analyses for our sample size, we reduced the number of condition comparisons by calculating difference scores for each behavioral measure across conditions and used these difference scores for our analyses. Thus, once d', C, Pr, Br and RT were calculated for each participant for each experimental task, two difference scores for each behavioral measure were calculated for each participant. One set of difference scores was calculated to determine the pattern of performance across the auditory-only task and the audiovisual synchrony task. This difference score was calculated by subtracting a participant's average score (e.g., d', C, Pr, Br or RT) during the auditory-only task from the participant's average score during the synchronous audiovisual task. The second set of difference scores was calculated to determine the pattern of performance across the visual-only task and the audiovisual synchrony task. This

difference score was calculated in a similar fashion (e.g., subtracting a participant's average score during the visual-only task from the participant's average score during the synchronous audiovisual task).

RESULTS

Difference scores calculated from data for three behavioral measures, accuracy, response bias, and RT, were analyzed to determine if results support our predicted group differences. Specifically, we predict that deficits in auditory and/or visual processing will interfere with intersensory redundancy processing and result in smaller difference scores for the SLI group as compared to the NL group. In order to test these predictions, separate analyses were run first to compare group difference scores generated from the audiovisual go/no-go task and the auditory-only go/no-go task and secondly to compare group difference scores generated from the audiovisual go/no-go task and the visual-only go/no-go task. All data analyses were carried out using non-parametric methods. Non-parametric methods are indicated when sample sizes are small (Siegel, 1957).

Accuracy

Average accuracy (*d'* and Pr) was calculated for each participant for each task. Difference scores for our two comparisons of interest were then created by: (1) subtracting average accuracy for the auditory-only task from average accuracy for the audiovisual task and (2) subtracting average accuracy for the visual-only task from average accuracy for the audiovisual task. We then compared accuracy difference scores across groups using a Mann-Whitney test. Accuracy audiovisual – auditory-only difference scores based on *d'* were significantly larger for the NL group (*Mdn* = -.79) as compared to the SLI group (*Mdn* = .29), *U* = 29.00, *z* = -2.48, *p* = .012, *r* = .51

(see Figure 4.4). Our findings suggest that the NL group showed greater differences in accuracy across the audiovisual and auditory-only tasks as compared to the SLI group. Given that accuracy during the auditory-only condition was subtracted from accuracy during the audiovisual condition, the negative median value seen for the NL group suggests that in general the NL group was more accurate during the auditory-only task. The positive median value seen for the SLI group suggests that in general the SLI group was slightly more accurate during the audiovisual task.
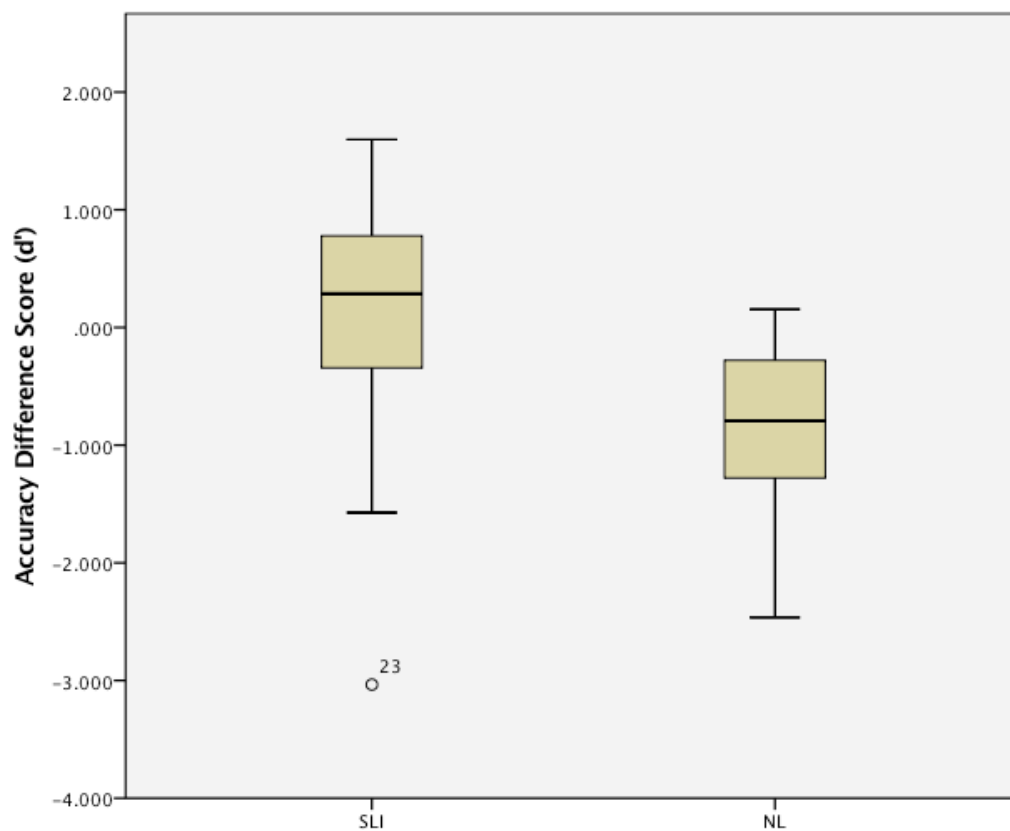
Figure 4.4 Experiment 1 NL vs. SLI: Audiovisual – Audio-only accuracy difference score (*d'*)

Accuracy audiovisual – auditory-only difference scores based on Pr were not significantly different for the NL group (*Mdn* = -.10) compared to the SLI group (*Mdn* = -.01), *U* = 56.50, *z* = -.90, *p* = .386, *r* = -.18 (see Figure 4.5). Based on Pr, group difference scores did not differ. The negative median values seen for both groups suggest that both groups performed slightly better in the auditory-only condition. Differences in Pr and *d'* findings will be discussed.
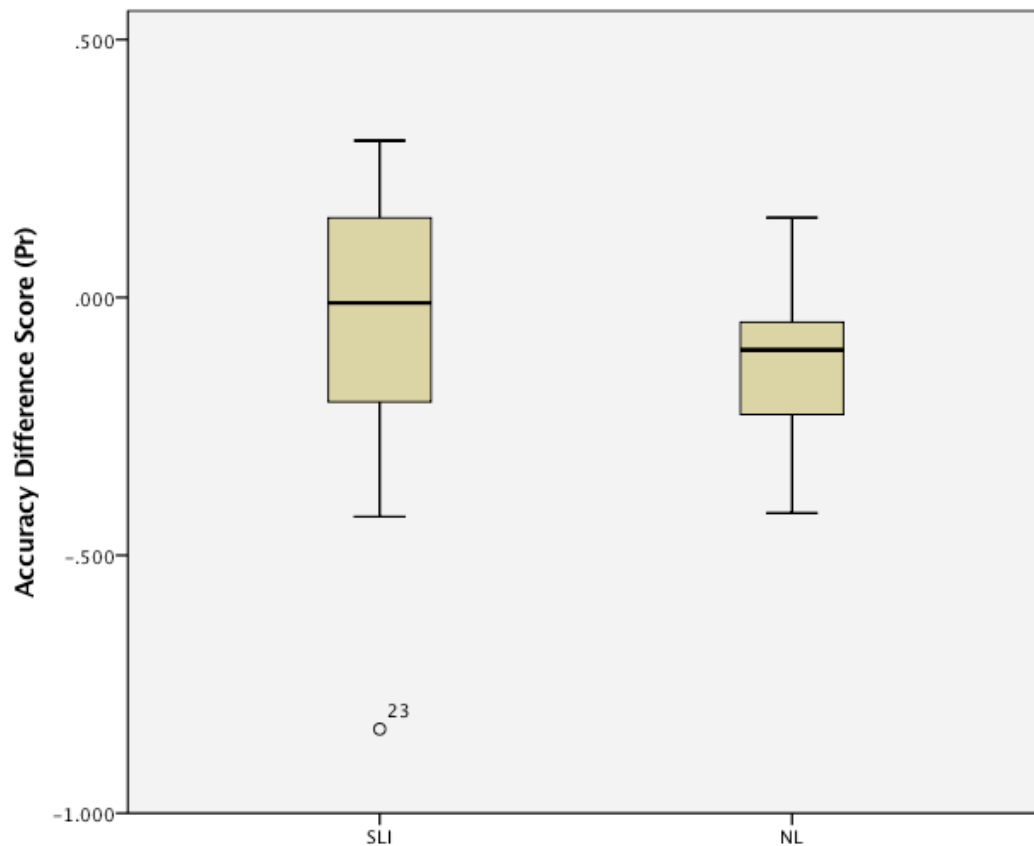
Figure 4.5 Experiment 1 NL vs. SLI: Audiovisual – Audio-only accuracy difference score (Pr)

Difference scores were also calculated for response bias. Response bias audiovisual – auditory-only difference scores based on *C* were not significantly different for the NL group (*Mdn* = .10) compared to the SLI group (*Mdn* = .53), *U* = 57.00, *z* = -1.44, *p* = .16, *r* = -.29. Response bias audiovisual – auditory-only

difference scores based on Br were not significantly different for the NL group (*Mdn* = -.08) compared to the SLI group (*Mdn* = -.30), *U* = 63.00, *z* = -.52, *p* = .619, *r* = -.11. Both findings indicate that response bias difference scores for the audiovisual – auditory-only conditions did not differ across groups.

Accuracy audiovisual – visual-only difference scores based on *d'* were not significantly different for the NL group (*Mdn* = 1.33) compared to the SLI group (*Mdn* = 1.17), *U* = 69.00, *z* = -.17, *p* = .887, *r* = -.04 (see Figure 4.6).
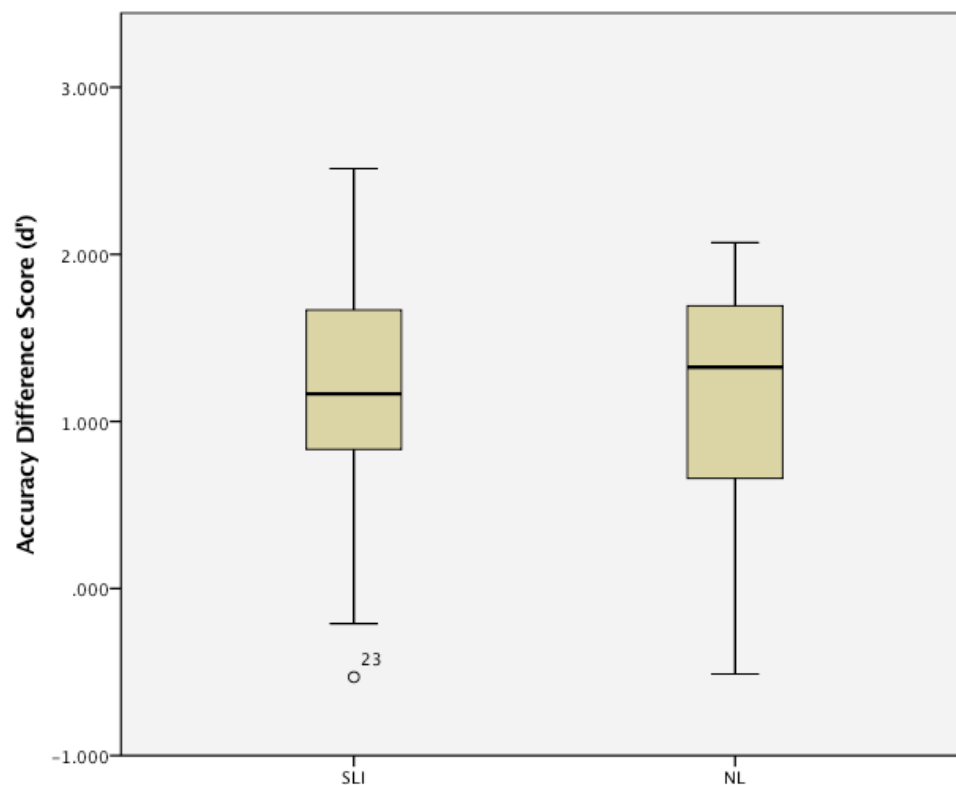
Figure 4.6 Experiment 1 NL vs. SLI: Audiovisual – Visual-only accuracy difference score (*d'*)

Accuracy audiovisual – visual-only difference scores based on Pr were not significantly different for the NL group (*Mdn* = .35) compared to the SLI group (*Mdn* = .26), *U* = 58.00, *z* = -.81, *p* = .434, *r* = -.17 (see Figure 4.7). Our groups did not differ in their pattern of accuracy performance across the audiovisual and visual-only tasks.

Furthermore, given the method used to calculate difference scores, the positive median value found for both groups suggests that, in general, both groups were more accurate during the audiovisual task than during the visual-only task.

Figure 4.7 Experiment 1 NL vs. SLI: Audiovisual – Visual-only accuracy difference score (Pr)

Again, difference scores were also calculated for response bias. Response bias audiovisual – visual-only difference scores based on *C* were not significantly different for the NL group (*Mdn* = .33) compared to the SLI group (*Mdn* = .69), *U* = 64.00, *z* = -.46, *p* = .671, *r* = -.09. Response bias audiovisual – visual-only difference scores based on Br were not significantly different for the NL group (*Mdn* = -.24) compared to the SLI group (*Mdn* = -.36), *U* = 62.00, *z* = -.58, *p* = .59, *r* = -.12. Both findings indicate that response bias difference scores for the audiovisual – visual-only conditions did not differ across groups.

Reaction Time

Average RT was calculated based on correct button responses during target trials. Once average RT was calculated for each participant, difference scores for our two comparisons of interest were generated by: (1) subtracting average RT during the auditory-only task from average RT during the audiovisual task and (2) subtracting average RT during the visual-only task from average RT during the audiovisual task. We then compared RT difference scores across groups using a Mann-Whitney test. RT audiovisual – auditory-only difference scores were not significantly different for the NL group (*Mdn* = -20.79) compared to the SLI group (*Mdn* = -13.55), *U* = 69.00, *z* = -.17, *p* = .887, *r* = -.04 (see Figure 4.8). Differences in
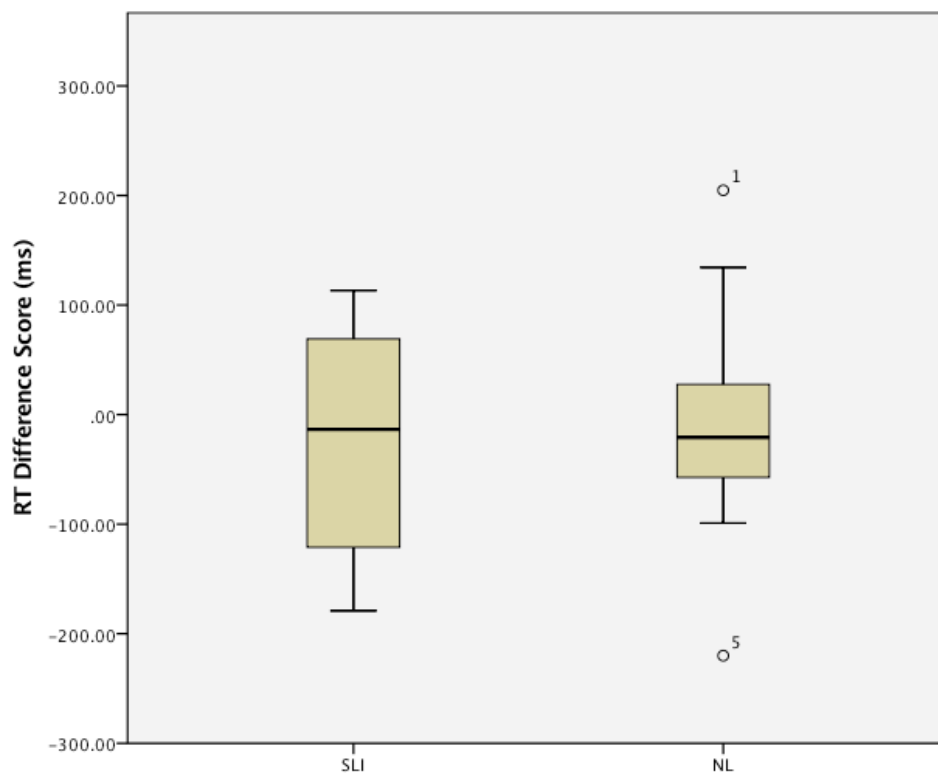
Figure 4.8 Experiment 1 NL vs. SLI: Audiovisual – Audio-only RT difference score

RTs across the audiovisual and auditory-only tasks were fairly similar across groups. Given the method used to calculate difference scores, the negative median difference score value in both groups, indicates that RTs were generally faster during the audiovisual task than during the auditory-only task, for both groups.

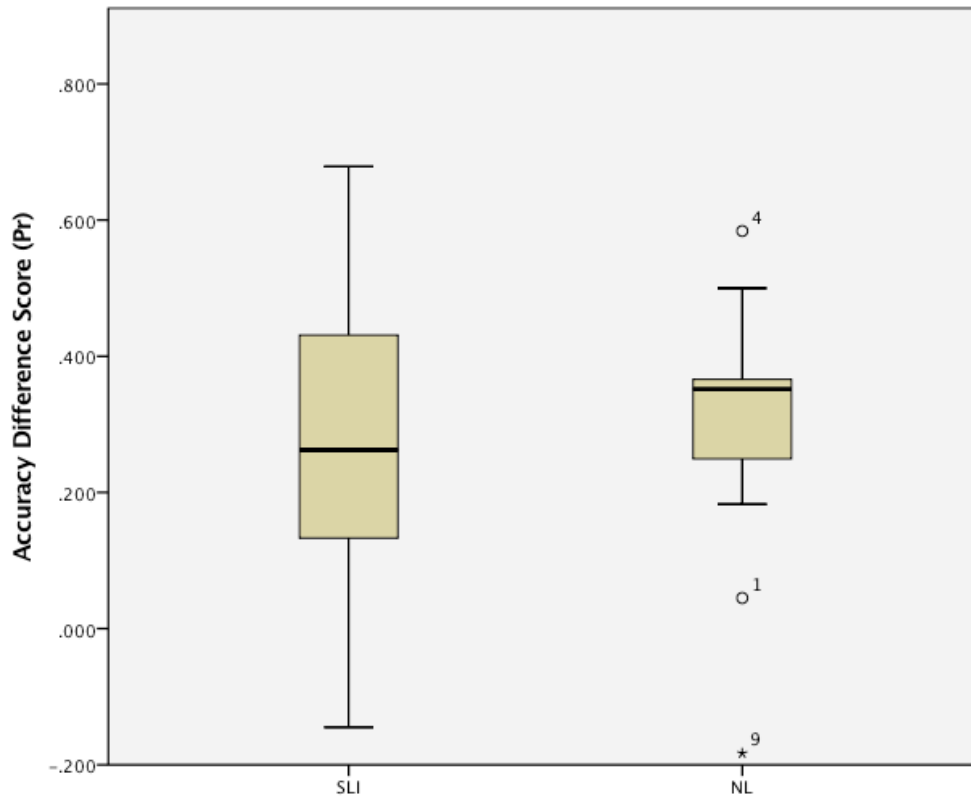Similarly, RT audiovisual – visual-only difference scores were not significantly different for the NL group (*Mdn* = -7.51) compared to the atypical group (*Mdn* = 7.61), *U* = 67.00, *z* = -.29, *p* = .799, *r* = -.06 (see Figure 4.9). Similarly to our other RT difference score comparison, differences in reaction times across the audiovisual and visual-only tasks were fairly similar across groups. Median values suggest that, in general, for the NL group RTs were slightly faster during the audiovisual condition than during the visual-only condition, and for the SLI group RTs were slightly faster during the visual-only condition than during the audiovisual condition.
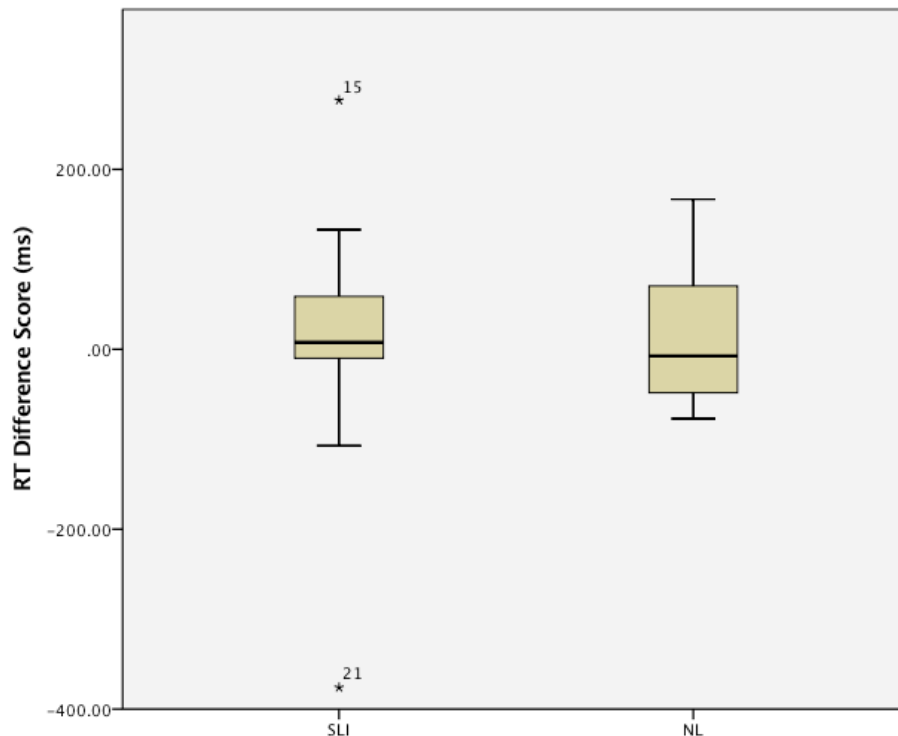
Figure 4.9 Experiment 1 NL vs. SLI: Audiovisual – Visual-only RT difference score

DISCUSSION

The overall goal of Experiment 1 was to investigate the interference of processing deficits in a single modality on intersensory redundancy processing in adults with SLI. To test this, we compared patterns of performance across multisensory (e.g., audiovisual) and unisensory (e.g., auditory-only and visual-only) conditions in adults with and without SLI. Evidence from the current study indicates differences in performance patterns between groups across the audiovisual and auditory-only conditions, but not across the audiovisual and visual-only conditions. These findings suggest that temporal auditory processing skills may be impaired in adults with SLI; however, these processing deficits may not interfere with intersensory redundancy processing.

Prior to further discussion of the findings, it is important to note the implications of using difference scores for our findings. Difference scores reflect patterns of performance across conditions. Thus, group comparisons based on difference scores provide information about similarity in general patterns of performance; however, these difference scores are not sensitive to fine-grained performance variation between groups. For example, based on accuracy, both the NL and SLI groups performed better on the audiovisual task relative to their performance during the visual-only task. This similar pattern of performance was reflected in the non-significant difference score findings for this comparison. However, in general the SLI group produced lower average accuracy scores on both tasks as compared to the NL group (see Table 4.2). Difference scores do not reflect these kinds of performance variations. Therefore, similarity in difference scores across groups indicates that the

groups demonstrate similar performance patterns across tasks, but they do not indicate that the groups perform equally well on the tasks.

Table 4.2 Experiment 1 group averages (standard deviation) for behavioral performance measures

		NL (N=12)	SLI (N=12)
Audiovisual	*Accuracy (d')*	2.26 (.76)	1.74 (.93)
	Accuracy (Pr)	.68 (.18)	.49 (.25)
	Bias (C)	.09 (.36)	.26 (.86)
	Bias (Br)	.44 (.23)	.30 (.33)
	RT	585.12 (52.86)	579.15 (145.01)
Auditory-only	*Accuracy (d')*	3.11 (1.01)	1.75 (.75)
	Accuracy (Pr)	.81 (.20)	.56 (.22)
	Bias (C)	-.01 (.38)	.01 (.72)
	Bias (Br)	.53 (.27)	.42 (24)
	RT	595.47 (111.57)	602.25 (86.62)
Visual-only	*Accuracy (d')*	1.12 (.43)	.60 (.28)
	Accuracy (Pr)	.39 (.13)	.22 (.10)
	Bias (C)	-.33 (.31)	-.12 (.36)
	Bias (Br)	.67 (.15)	.54 (.16)
	RT	574.63 (70.39)	574.54 (102.25)

Our results yielded a significant difference between groups when comparing accuracy difference scores across the audiovisual and auditory-only conditions, based on *d'* values but not Pr values. Therefore, results should be interpreted with

caution. Extreme accuracy scores (i.e., accuracy scores close to 1 or 0) and limitations of sample size may have contributed to the difference in Pr and *d'* findings. Based on our *d'* findings, careful inspection of groups' average accuracy performance during each task suggests that this finding is more indicative of difficulty in auditory processing in the SLI group, rather than difficulty in audiovisual processing. Results showed a negative median value for the NL group and a positive median value for the SLI group, which suggest that the groups were demonstrating different performance patterns across tasks. For the NL group, accuracy was generally higher during the auditory-only condition, but for the SLI group, accuracy was generally higher during the audiovisual condition. However, the pattern of groups' average accuracy across tasks reveals that average accuracy performance across tasks was fairly similar for the SLI group, whereas average accuracy was much higher during the auditory only condition for the NL group (see Table 4.2). Taking into consideration both the group difference score medians and group averages across tasks, the data indicate that our significant finding is driven by low accuracy performance in the SLI group during the auditory-only condition. The low accuracy performance during the auditory-only condition represents a marked deviation from the NL group's pattern of performance and led to a smaller difference in accuracy scores across conditions for the SLI group.

Trends in groups' performance based on average Pr values are very similar to those described above for *d'* values (see Table 4.2). Pr values suggest slightly better performance during the auditory-only condition for the SLI group than *d'* values for the same condition. This difference may be driving the difference seen in statistical findings. Nevertheless, if our findings based on Pr are reflective of the population,

then differences in performance across tasks were similar for both groups; however, even based on Pr values, the SLI group had lower overall average scores for each condition.

Superior accuracy performance during the auditory-only condition as compared to the audiovisual condition in our NL group of adults was unexpected, based on the predictions of the IRH and prior research demonstrating boosts in accuracy performance due to the presence of multisensory information (Frassinetti, Bolognini, & Ladavas, 2002; Lovelace, Stein, & Wallace, 2003; Rowe, 1999; Watkins & Feehrer, 1965). However, Gelfand et al. (in prep., chpt. 1) demonstrated similar findings in a larger group of typical adults, using the same task. As suggested by Gelfand et al. (in prep., chpt. 1), the superior performance in the auditory-only condition is likely a reflection of the inverse effectiveness principle (Meredith & Stein, 1983; 1986; Stanford, Quessy, & Stein, 2005; Stein & Meredith, 1993). Essentially, this principle explains that multisensory information most effectively boosts performance when performance is not especially strong for any of the unisensory components. In this case, performance based only on the unisensory auditory-only component was strong enough for the NL group to negate any possible performance benefits from the audiovisual condition.

The principle of inverse effectiveness also suggests that if performance based on a single sensory signal is at near maximum capacity, then the addition of a secondary sensory signal can actually interfere with performance. This idea explains the pattern of average accuracy performance across the audiovisual and auditory-only tasks for the NL group. However, the pattern of average accuracy performance for the SLI group is certainly not in line with the principle of inverse effectiveness

based on *d'* values and shows weak adherence to this principle based on Pr values. It may be the case that average accuracy scores across the audiovisual and auditory-only tasks reflect maximum performance capacity for the SLI group. If that is the case, then lack of strong interference (e.g., decrease in accuracy performance) from the inclusion of a secondary sensory stimulus during the audiovisual condition is a deviation both from the principle of inverse effectiveness and from the pattern seen in the NL group. It is possible that individuals with SLI are less influenced by visual information during audiovisual processing than typical peers, as has been suggested in previous work on audiovisual processing in SLI (Meronen et al., 2013; Norrix et al., 2006; Norrix, Plante, Vance, & Boliek, 2007).

Results from group accuracy difference score comparisons across the audiovisual and visual-only conditions suggest intact intersensory redundancy processing in SLI. Median accuracy difference scores for both groups were positive, indicating that both groups performed better (i.e., higher accuracy) during the audiovisual condition than during the visual-only condition. Furthermore, the non-significant finding reflects a similar boost in performance during the audiovisual condition for both groups, suggesting that adults with SLI are able to process and benefit from intersensory redundancy. Average accuracy performance for each group across conditions reflects this pattern, but also demonstrates higher accuracy scores for the NL group overall across conditions, as previously mentioned. Given our sample size, group x condition analyses were not conducted. Future research should investigate temporal visual processing in a larger group of adults with and without SLI to determine if the trend seen in our data, which suggests possible differences in processing temporal information visually, is substantiated.

The design of the current experiment was such that the target stimulus pair used for the visual-only and auditory-only tasks was never used as a target stimulus pair for the audiovisual task. This design choice was made in order to maximally manage practice effects and processing trade-offs. The challenge in designing the current experiment was to develop a set of tasks that sufficiently taxed the superior temporal processing skills of the auditory modality while not exceeding the inferior temporal processing skills of the visual modality. Results from Gelfand et al. (in prep., chpt. 1), based on this experimental design, indicated that no task yielded superior behavioral performance across all behavioral measures, which suggests that the slight variation in task design did not create substantial variation in task difficulty. However, future research on temporal processing, particularly as it relates to multisensory and unisensory comparisons, may explore alternative experimental designs to mitigate the challenge posed by processing trade-offs in the auditory and visual modalities.

To summarize, our data suggest that intersensory redundancy processing is intact in adults with SLI. Furthermore, if adults experience weaker temporal auditory processing abilities, then these weaker abilities do not necessarily interfere with intersensory redundancy processing in adults with SLI. Trends in our data warrant additional investigation of both temporal auditory and temporal visual processing abilities in SLI; however, much like temporal auditory processing abilities, there is no indication in our data that temporal visual processing abilities are impacting intersensory redundancy processing. Our current findings are inconsistent with findings from previous work indicating deficits in audiovisual processing in SLI (Boliek et al., 2010; Hayes, Tiippana, Nicol, Sams, & Kraus, 2003; Holloway, 1971; Meronen

et al., 2013; Norrix et al., 2006; Norrix, Plante, Vance, & Boliek, 2007). This previous work has exclusively investigated audiovisual processing in SLI during language-based tasks, and all but one of these studies have investigated audiovisual processing in children with SLI, but not adults with SLI. Design differences may be driving our divergent findings. If design differences, specifically the use of a non-linguistic task, are responsible for our divergent findings, then this would suggest that deficits in audiovisual processing may be less robust during non-linguistic tasks and in adult populations. However, the set of tasks used during the current study do not evoke robust intersensory facilitation effects (Gelfand et al., in prep., chpt. 1). Therefore, if deficits in audiovisual processing abilities during non-linguistic tasks are small in adults with SLI, then a more robust test of intersensory facilitation effects may tease out differences in intersensory redundancy processing abilities among adults with and without SLI.

Experiment 2

In Experiment 2, we further examined intersensory redundancy processing in SLI by assessing intersensory facilitation effects in adults with and without SLI during a more consistent test of intersensory facilitation (Gelfand et al., in prep., chpt. 2). Temporal synchrony among co-occurring sensory signals is a defining feature of intersensory redundancy. In fact, Bahrick & Lickliter (2012) suggest that temporal synchrony is the quintessential redundant feature that facilitates detection of nested redundant features (e.g., duration, or rhythm). Thus, manipulations of temporal synchrony across auditory and visual signals should impact the presence of intersensory facilitation effects. Indeed, Gelfand et al. (in prep., chpt. 2) found that synchronous audiovisual information facilitated faster reaction times as compared to

asynchronous audiovisual information. This particular test of intersensory redundancy processing is especially germane to the SLI population, given previous work demonstrating reduced sensitivity to audiovisual synchrony (Kaganovich et al., 2014; Pons et al., 2012). Since sensitivity to temporal synchrony is a reported area of weakness in SLI, a test of intersensory redundancy processing that specifically manipulates temporal synchrony may be more sensitive to differences in intersensory redundancy processing abilities among adults with and without SLI.

In Experiment 2, we used the same task from Gelfand et al. (in prep., chpt. 2) to compare performance in adults with and without SLI during temporally synchronous and temporally asynchronous audiovisual tasks. Manipulation of temporal synchrony may be a more sensitive test of intersensory redundancy processing in SLI, given reported deficits in sensitivity to audiovisual synchrony in SLI (Kaganovich et al., 2014; Pons et al., 2012). If intersensory redundancy processing is impaired due to weaker sensitivity to temporal synchrony (Kaganovich et al., 2014; Pons et al., 2012), then we predict that difference scores for both accuracy and RT performance measures will be smaller for adults with SLI as compared to NL adults. If intersensory redundancy processing remains intact, despite weaker sensitivity to temporal synchrony in SLI (Kaganovich et al., 2014; Pons et al., 2012), then we predict that difference scores for both accuracy and RT will be similar across groups.

Findings from Experiment 1 and findings from prior research on audiovisual processing in SLI point to the possibility that individuals with SLI are less reliant on visual information during audiovisual processing (Meronen et al., 2013; Norrix et al. 2006; Norrix et al., 2007). In order to address this possibility, we used an eye-tracking methodology to measure looking behavior during Experiment 2. Specifically, we

measured the proportion of time adults spent looking at the visual stimulus during each condition. Comparisons in normal language adults of looking behavior patterns during synchronous and asynchronous audiovisual tasks find greater looking during audiovisual synchrony as compared to audiovisual asynchrony (Gelfand et al., in prep. chpt. 2). If adults with SLI are behaviorally less reliant on visual information during audiovisual tasks, then we predict that adults with SLI will demonstrate similar looking behavior across conditions and thus have smaller difference scores as compared to the NL group. If the attenuated influence of visual information on audiovisual processing in adults with SLI is, instead, a result of downstream processing inefficiency, then we predict that adults with SLI and NL adults will produce similar difference scores.

METHODS

The same participants who participated in Experiment 1 also took part in Experiment 2. Tasks for Experiment 1 and Experiment 2 were completed on the same day during the first testing session. To examine the role of synchrony in intersensory redundancy processing abilities of adults with SLI, we compared the performance of adults with SLI to NL adults during the audiovisual synchrony condition from Experiment 1 and an asynchronous condition. Stimuli and general procedures were identical to Experiment 1; however, Experiment 2 consisted of a new asynchronous audiovisual condition. Procedure and design specifics related to eye-tracking methodology were not reported during Experiment 1 because eye-tracking data was not a variable of interest. However, procedure and design specifics related to eye-tracking methodology reported here hold for both the audiovisual

synchrony condition from Experiment 1, which will be used for analyses, and the new audiovisual asynchrony condition included in the current experiment.

Experimental Tasks

During tasks, participants were asked to place their chins and heads on and against a chinrest and headrest and to remain situated for the duration of the task. This apparatus is a feature of the EyeLink tower mount set-up and ensures stability and consistency of eye recordings within and across participants. Participants were given an opportunity to move and adjust positions between tasks. Each experimental task began with a 5-point manual calibration and validation phase during which participants were asked to look directly at a bull's-eye image, which appeared at five different locations on the screen. The calibration and validation tasks allow the eye-tracker to measure specific characteristics of the eye in order to accurately track and estimate the eye's position on the screen throughout the experimental tasks. Tasks were presented on a PC computer using SR Research Eyelink Experiment Builder Software (SR Research Ltd, Mississauga, Ontario, Canada, 2011). Participants were given ~2 minute breaks in between tasks.

Recording Eye Movements

Eye movement data was recorded at a rate of 1000 Hz using an SR Research Eyelink 2000 Eyetracker with the tower mount configuration (SR Research, Ltd). Eye movement data includes the following movement behaviors: fixations, blinks and saccades. Data was recorded every millisecond from trial onset to trial offset. Each event that occurred within a trial was tagged with a label (e.g., onset of first visual stimulus) that was then included in the data output file. This allowed for offline data analyses of trial events of interest.

Asynchronous Audiovisual Go/No-Go Task

The experimental design of this task was based on Gelfand et al. (in prep., chpt. 2). As previously described in the design of Experiment 1, two target/non-target pairings were used during the task: either (1) short-short vs. short-long or (2) long-long vs. long-short. During the asynchrony condition, the auditory and visual signals were selected from different pairings in order to ensure that the visual stimuli were not predictive of the auditory stimuli. For example, if a participant received an auditory signal comprised of short-short vs. short-long pairs as the target/non-target comparison, then the visual signal was comprised of long-long vs. long-short pairs (see Figure 4.10 for examples). Likewise, if a participant received an auditory signal
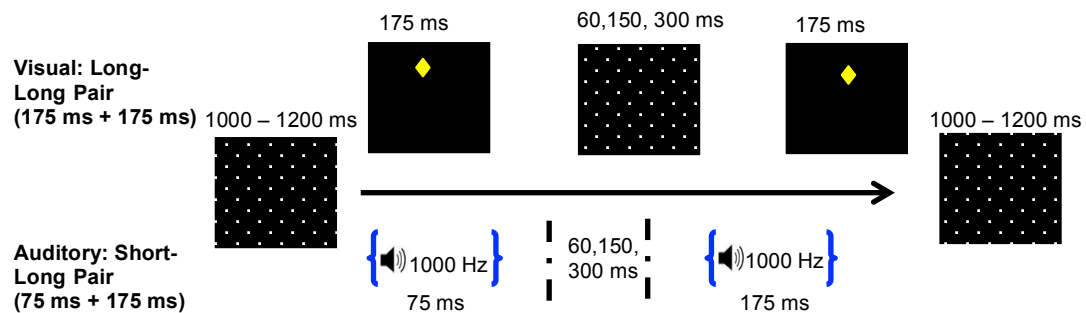
Figure 4.10 Asynchronous audiovisual task trial example of target tone and visual pair (audio: short-long, visual: long-long) in which both visual stimulus items for the visual stimulus pair appear.

comprised of long-long vs. long-short pairs as the target/non-target comparison, then the visual signal was comprised of short-short vs. short-long pairs (see Figure 4.11 for examples). In this way, the auditory and visual signals were matched for onset; however, duration patterns were never predictable between the two signals. Since these timing differences were slight and potentially fell within the time window where facilitation effects might persist (see Laurienti & Hugenschmitdt, 2012, for a review),

an additional design change was made to the presentation of the visual signal. For 25% of the trials, the first visual stimulus of the visual pair was removed, so that participants only saw the standard black background. For another 25% of the trials, the second visual stimulus of the visual pair was removed. Thus, for 50% of the trials, a single visual stimulus item appeared on the screen at some point during the presentation of the auditory stimulus pair (see Figure 4.11 for examples). For the remaining 50%, a visual stimulus pair (i.e., two visual stimulus items) was presented during the presentation of the auditory stimulus pair (see Figure 4.10 for examples).
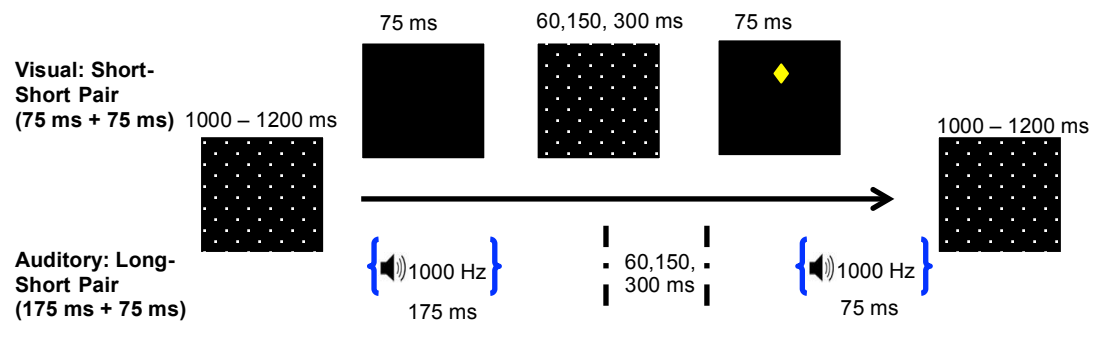
Figure 4.11 Asynchronous audiovisual task trial example of target tone and visual pair (audio: long-short, visual: short-short) in which only one visual stimulus item for the visual stimulus pair appears.

Data Analysis

Behavioral measures calculated for data analyses in Experiment 1 were also calculated for Experiment 2. These measures included d', C, Pr, Br and RT. An additional behavioral measure was calculated for both the synchronous condition from Experiment 1 and the new asynchronous condition included in Experiment 2 for use in data analysis for Experiment 2: average proportion of time spent looking at the visual stimulus out of total trial duration. Total trial duration was defined as beginning with the onset of the first visual stimulus and ending with the offset of the second

visual stimulus. All trials were included in the looking time analysis. Average proportion of time spent looking was determined based on eye movement data recordings generated by Eyelink's built-in software. Eyelink's built-in software may be used to analyze gaze position based on predefined regions of interest. In this case, the visual stimulus and immediate surrounding area were predefined as a region of interest (300 x 300 pixel square centered at the center point of the visual stimulus). Average gaze duration within this region of interest out of total trial duration was calculated to determine proportion of time spent looking at the visual stimulus for each participant. Data analyses were again based on difference scores. Groups' difference scores across conditions were compared for all behavioral measures.

RESULTS

Difference scores were calculated based on performance during the audiovisual synchronous condition from Experiment 1 and the audiovisual asynchronous condition from the current experiment. These difference scores were then used to compare performance across groups. We again used non-parametric methods for all data analyses (Siegel, 1957).

Accuracy

Average accuracy (operationalized as *d'* and Pr) was calculated for each participant for each condition. Difference scores were created by subtracting average accuracy scores during the asynchronous condition from average accuracy scores during the synchronous condition. Differences scores were then compared across groups using a Mann-Whitney test. Accuracy difference scores based on *d'* were larger for the NL group (*Mdn* = -.50) compared to the SLI group (*Mdn* = .26), *U* = 38.00, *z* = -1.96, *p* = .052, *r* = -.40 (see Figure 4.12). The NL group showed a greater

difference in accuracy across conditions and, based on reported median values, the direction of this difference was opposite from that of the SLI group. The negative median value for the NL group indicates that accuracy was higher during the asynchronous condition, whereas the positive median value for the SLI group indicates that accuracy was slightly higher during the synchronous condition.
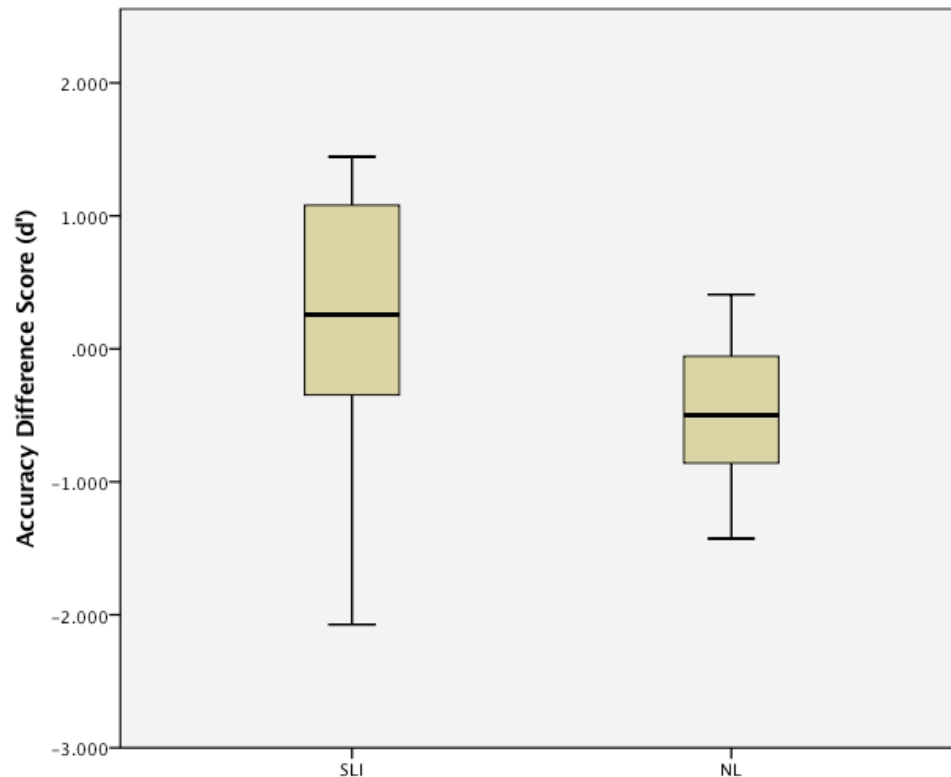
Figure 4.12 Experiment 2 NL vs. SLI: Synchronous audiovisual – Asynchronous audiovisual accuracy difference score (*d'*)

However, these results should be interpreted with caution given the difference in statistical findings based on analysis of Pr. Accuracy difference scores based on Pr were not significantly different for the NL group (*Mdn* = -.15) compared to the SLI group (*Mdn* = -.01), *U* = 45.50, *z* = -1.53, *p* = .131, *r* = -.31 (see Figure 4.13). In this case, results suggest that both groups demonstrated a similar pattern of accuracy performance across tasks. The negative median value seen for both groups, based

on Pr, instead suggests that both groups performed slightly better, during the asynchronous condition. The discrepancy in statistical findings between Pr and *d'* warrant cautious interpretation of these data.
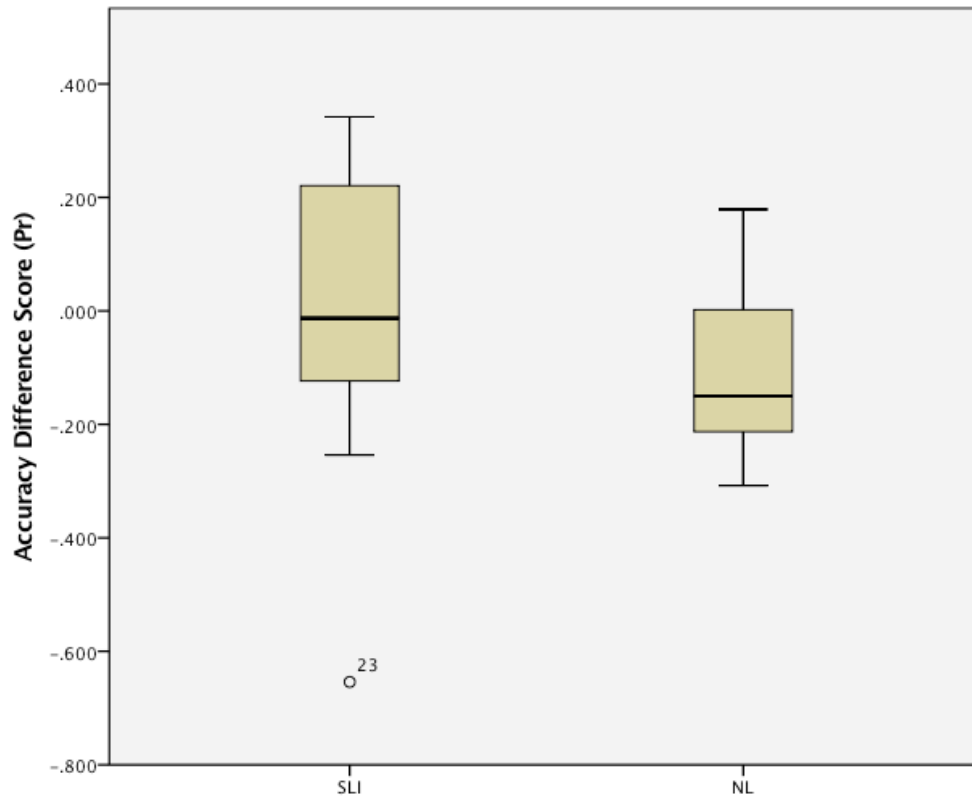
Figure 4.13 Experiment 2 NL vs. SLI: Synchronous audiovisual – Asynchronous audiovisual accuracy difference score (Pr)

Difference scores were also calculated for response bias (*C* and Br) in a similar fashion. Response bias difference scores based on *C* were not significantly different for the NL group (*Mdn* = -.13) compared to the SLI group (*Mdn* = .27), *U* = 46.00, *z* = -1.50, *p* = .143, *r* = -.31. Similarly, response bias difference scores based on Br were not significantly different for the NL group (*Mdn* = .14) compared to the SLI group (*Mdn* = -.17), *U* = 41.00, *z* = -1.79, *p* = .078, *r* = -.37. In both cases, results indicate that response bias difference scores did not differ across groups.

Reaction Time

Average RT was calculated based on correct button responses during target trials. Difference scores were generated by subtracting average RT during the asynchronous condition from average RT during the synchronous condition. We then compared RT difference scores across groups using a Mann-Whitney test. RT difference scores were not significantly different for the NL group (*Mdn* = -41.72) compared to the SLI group (*Mdn* = -15.11), *U* = 64.00, *z* = -.46, *p* = .671, *r* = -.09 (see Figure 4.14). The pattern of differences in RTs across tasks was fairly similar across groups. The negative median difference score value, seen for both groups, indicates that RTs were generally faster during the synchronous condition than during the asynchronous condition.
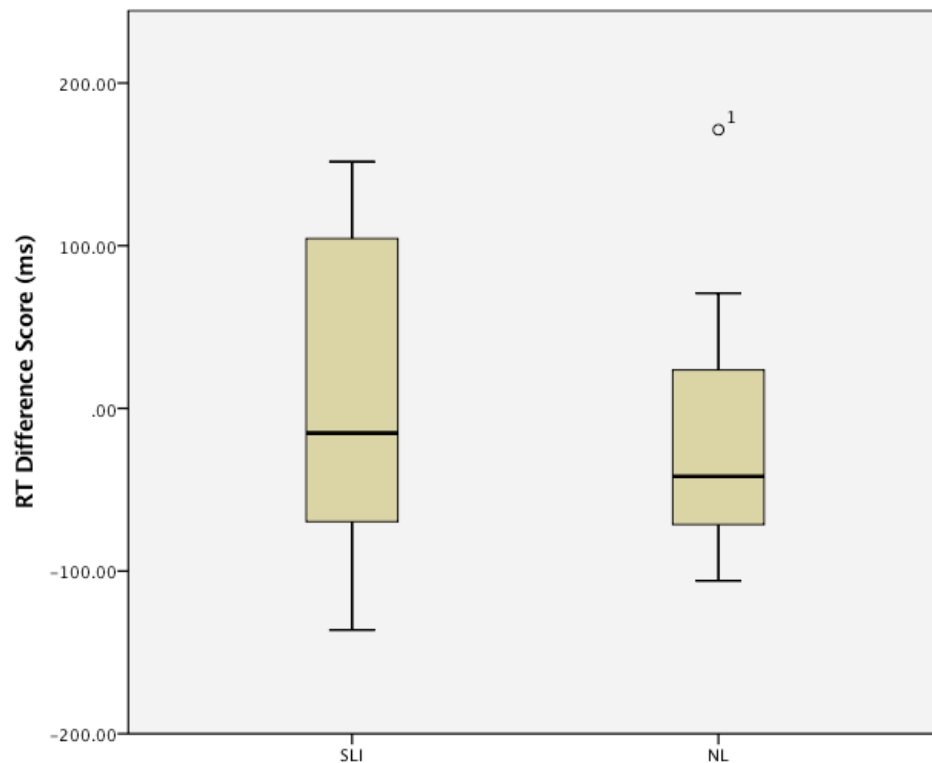
Figure 4.14 Experiment 2 NL vs. SLI: Synchronous audiovisual – Asynchronous audiovisual RT difference score

Proportion of Looking

Average proportion of time spent looking at the visual stimulus was calculated based on all trials. Difference scores were created by subtracting average proportion looking during the asynchronous condition from average proportion looking during the synchronous condition. Difference scores were compared across groups using a Mann-Whitney test. Difference scores for the proportion of time spent looking at the visual stimulus were not significantly different for the NL group (*Mdn* = .06) compared to the SLI group (*Mdn* = .09), *U* = 67.00, *z* = -.29, *p* = .788, *r* = -.06, (see Figure 4.15). Difference scores suggest that the pattern of looking behavior across tasks was similar for both groups. The positive median values, seen for both groups, indicate that proportion of looking was higher during the synchronous condition than during the asynchronous condition.
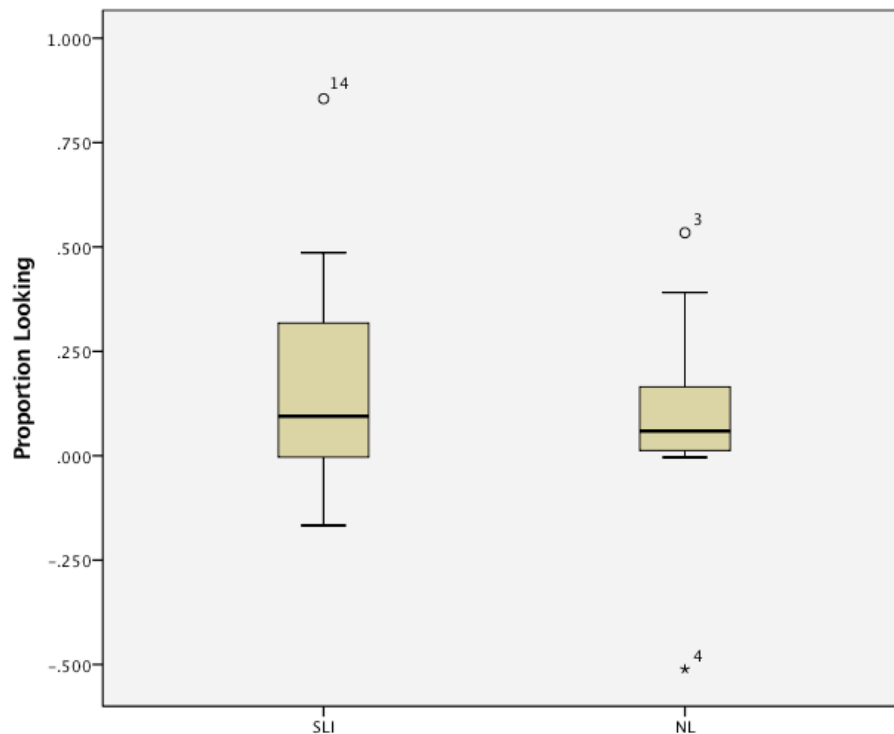
Figure 4.15 Experiment 2 NL vs. SLI: Synchronous audiovisual – Asynchronous audiovisual proportion looking difference score

DISCUSSION

The overall goal of Experiment 2 was to investigate the impact of audiovisual synchrony on intersensory redundancy processing in SLI. A secondary goal was to investigate implications from previous work, which suggest that attenuated reliance on visual information may contribute to deficits in audiovisual processing in SLI (Meronen et al., 2013; Norrix et al. 2006; Norrix et al., 2007). In order to investigate these questions, we used an eye-tracking methodology to compare patterns of behavioral and eye movement performance across synchronous and asynchronous audiovisual conditions in adults with and without SLI. Evidence from the current study largely suggests that adults with and without SLI demonstrate similar patterns of performance across synchronous and asynchronous tasks. The current findings indicate that reduced sensitivity to synchrony in SLI does not interfere with intersensory redundancy processing. Furthermore, the similarity in patterns of looking behavior across tasks for both groups suggests that the influence of audiovisual synchrony on patterns of visual attention allocation, as measured by overt eye movements, does not differentially affect adults with SLI. Groups' average performance during each condition (Table 4.3) will be used to clarify discussion of the data because difference scores are limited in their ability to describe data patterns (see Experiment 1 discussion for further explanation).

Results based on accuracy performance during Experiment 2 must be interpreted cautiously given the statistical variability across operational measures of accuracy (i.e., *d'* and Pr). The inconsistency in statistical significance across these measures suggests that if group differences in accuracy performance exist, the differences are small. Extreme accuracy scores (i.e., accuracy scores very close to 1

Table 4.3 Experiment 2 group averages (standard deviation) for behavioral performance measures

		NL (N=12)	SLI (N=12)
Synchronous Audiovisual	*Accuracy (d')*	2.26 (.76)	1.74 (.93)
	Accuracy (Pr)	.68 (.18)	.49 (.25)
	Bias (C)	.09 (.36)	.26 (.86)
	Bias (Br)	.44 (.23)	.30 (.33)
	RT	585.12 (52.86)	579.15 (145.01)
	Proportion Looking	.83 (.23)	.85 (.22)
Asynchronous Audiovisual	*Accuracy (d')*	2.74 (.60)	1.58 (.91)
	Accuracy (Pr)	.79 (.13)	.50 (.27)
	Bias (C)	.21 (.26)	.10 (.76)
	Bias (Br)	.33 (.18)	.39 (.27)
	RT	604.38 (69.78)	575.67 (98.01)
	Proportion Looking	.75 (.26)	.68 (.31)

or 0) and limitations of sample size likely contributed to the cause of this inconclusive finding. If our accuracy findings based on *d'* are an accurate reflection of population performance, then our findings would suggest that adults with SLI have more difficulty inhibiting visual misinformation than NL adults during audiovisual asynchrony. The pattern of performance based on group averages for each condition (see Table 4.3) indicates that NL adults actually performed slightly better in the asynchronous condition than in the synchronous condition, whereas adults with SLI preformed slightly better in the synchronous condition than in the asynchronous condition. If these findings hold, they might suggest that adults with SLI have more difficulty

inhibiting the misinformation contained in the visual signal during the asynchronous condition. However, it may be the case, instead, that our accuracy findings based on Pr are an accurate reflection of population performance. In this case, patterns of accuracy performance across tasks did not differ between groups, suggesting that synchronous and asynchronous information do not differently affect accuracy performance in adults with SLI as compared to typical adults. Group averages for both *d'* and Pr suggest that overall performance was higher for NL adults than adults with SLI. Findings based on RT performance also support the conclusion that manipulation of audiovisual synchrony does not differentially affect performance in adults with and without SLI. Overall average RTs for both groups were fairly similar.

The current experiment extends previous work on audiovisual processing in SLI by including measures of looking behavior. Interestingly, our looking behavior data shows similar patterns of looking to the visual stimulus across tasks for both groups. This finding was unexpected based on previous work suggesting that individuals with SLI are less reliant on visual information during audiovisual tasks as compared to typical peers (Meronen et al., 2013; Norrix et al. 2006; Norrix et al., 2007). Furthermore, proportion of looking averages across groups were fairly similar (see Table 4.3). However, while adults with and without SLI evidence similar proportions of looking and similar looking behavior patterns across conditions, looking behavior is not necessarily indicative of downstream visual processing ability or efficiency. Groups' averages for performance measures during the visual-only condition from Experiment 1 suggest that the visual processing abilities of adults with SLI may be weaker than NL adults. Research indicating weaker reliance on visual information during audiovisual tasks in SLI has largely investigated audiovisual

processing during linguistic tasks (Meronen et al., 2013; Norrix et al. 2006; Norrix et al., 2007). It may be the case that individuals with SLI are more reliant on visual information during non-linguistic audiovisual tasks. Variations in complexity across linguistic and non-linguistic tasks may also be a contributing factor.

Our looking behavior findings also suggest that adults with SLI are equally sensitive to audiovisual synchrony. Typical adults spend less time looking at asynchronous audiovisual information as compared to synchronous audiovisual information (Gelfand et al., in prep., chpt. 2). Looking behavior averages across conditions reflect this pattern for the both the NL group and the SLI group. Similarity in difference scores across groups indicates that the groups do, in fact, exhibit similar looking behavior patterns across conditions. If adults with SLI were less sensitive to audiovisual synchrony, then we would have expected similar looking behavior averages across conditions and thus smaller difference scores for the SLI group as compared to the NL group. Our looking behavior findings contradict previous findings of reduced sensitivity to audiovisual synchrony in SLI (Kaganovich et al., 2014; Pons et al., 2012). To date, sensitivity to audiovisual synchrony in SLI has only been investigated in children. The development of audiovisual processing skills follows a protracted trajectory (Desjardins, Rogers, & Werker, 1997; Hillock, Powers, & Wallace, 2011; Lewkowicz, Minar, Tift, & Brandon, 2015; Massaro, Thompson, Barron, & Laren, 1986; McGurk & MacDonald, 1976). It is possible that audiovisual processing skills mature at a slower rate in SLI, but by adulthood, difference in sensitivity to audiovisual synchrony resolve.

Conclusions based on the current experiment are somewhat limited by our accuracy findings. Furthermore, our unexpected looking behavior findings warrant

further investigation to determine if the similarity in allocation of visual attention in adults with and without SLI is consistent across tasks. There are two methods that would allow us to clarify our accuracy findings and determine if differences exist in accuracy performance across adults with and without SLI. The first possible approach is to increase our sample size. The second possible approach is to magnify any group differences in performance ability by increasing the difficulty of the task such that intersensory redundancy processing abilities are additionally taxed. A more difficult and taxing test could also be used to accentuate the contributions of visual processing to intersensory redundancy processing. Thus, unlike the first approach, the second approach would allow us to further examine the broad reliability of our looking behavior findings.

Experiment 3

In Experiment 3, we aimed to clarify and expand our findings from Experiment 2 by again investigating performance across synchronous and asynchronous audiovisual tasks in adults with and without SLI. However, Experiment 3 employed more demanding audiovisual tasks shown to be more sensitive to the effects of intersensory redundancy processing (Gelfand, in prep., chpt. 2). Specifically, during Experiment 3, we increased task demands by using the same tasks used during Experiment 2, but degraded listening conditions. Research in typical adults has shown that the availability of redundant visual cues can improve performance under degraded listening conditions (Barutchu et al., 2010; Dodd, 1977; Erber, 1971; Sumby & Pollack, 1954) and cause shifts in gaze patterns such that adults increase duration of fixation to the redundant visual signal (Buchan et al., 2008). Essentially, degrading the quality of the auditory signal encourages greater reliance on redundant

visual signals. Using conditions that heavily influence reliance on visual information and looking behavior patterns in typical adults may reveal any existing differences in reliance on visual information in SLI. Furthermore, degrading the auditory signal creates a condition under which intersensory facilitation effects are intensified (Gelfand et al., in prep., chpt. 2), and this may help to tease out any existing group differences.

If small differences in intersensory redundancy processing abilities exist in adults with SLI, then we predict that the more taxing tasks used in Experiment 3 will result in smaller difference scores across all performance measures (accuracy and RT) for the SLI group compared to the NL group. Additionally, if reliance on visual information is attenuated in SLI, then use of conditions that motivate visual reliance may result in smaller looking proportion difference scores for the SLI group compared to the NL group.

METHODS

The same participants who participated in Experiments 1 and 2 also participated in Experiment 3. After participating in Experiments 1 and 2, participants were brought back and took part in Experiment 3 during a separate session run on a different day. During Experiment 3, participants took part in two experimental tasks: 1) a synchronous audiovisual go/no-go task, which was identical to the synchronous audiovisual go/no-go task from Experiment 1, aside from a volume modification to the auditory stimuli, and 2) an asynchronous audiovisual go/no-go task, which was identical to the asynchronous audiovisual go/no-go task from Experiment 2, aside from a volume modification to the auditory stimuli. Volume was modified in order to degrade the quality of the auditory single. We reduced volume so that all auditory

stimuli were presented at 35 dB as compared to 70 dB in Experiments 1 & 2. Except for the volume modification to the auditory stimuli, designs and procedures for these two conditions were identical to the designs and procedures used during Experiments 1 and 2.

Data Analysis

All four behavioral measures examined in Experiment 2 (*d'*, *C*, Pr, Br, RT, and proportion of time looking at the visual stimulus) were also calculated and analyzed for Experiment 3.

RESULTS

Difference scores based on the synchronous and asynchronous conditions were calculated for all behavioral measures and used to compare performance across groups. We again used non-parametric methods for all data analyses (Siegel, 1957).

Accuracy

Average accuracy (operationalized as *d'* and Pr) was calculated for each participant for each condition. Difference scores were created by subtracting average accuracy scores during the asynchronous condition from average accuracy scores during the synchronous condition. Difference scores were then compared across groups using a Mann-Whitney test. Accuracy difference scores based on *d'* were not significantly different for the NL group (*Mdn* = .66) than for the SLI group (*Mdn* = -.02), *U* = 46.50, *z* = -1.47, *p* = .143, *r* = -.30 (see Figure 4.16). These findings indicate that both groups demonstrated similar patterns of accuracy performance across tasks. The positive median value seen for the NL group indicates that accuracy was slightly higher during the synchronous condition, whereas the negative median value

seen for the SLI group indicates that accuracy was slightly lower during the synchronous condition. However, these differences across tasks were small enough that accuracy performance across conditions was fairly similar for both groups.
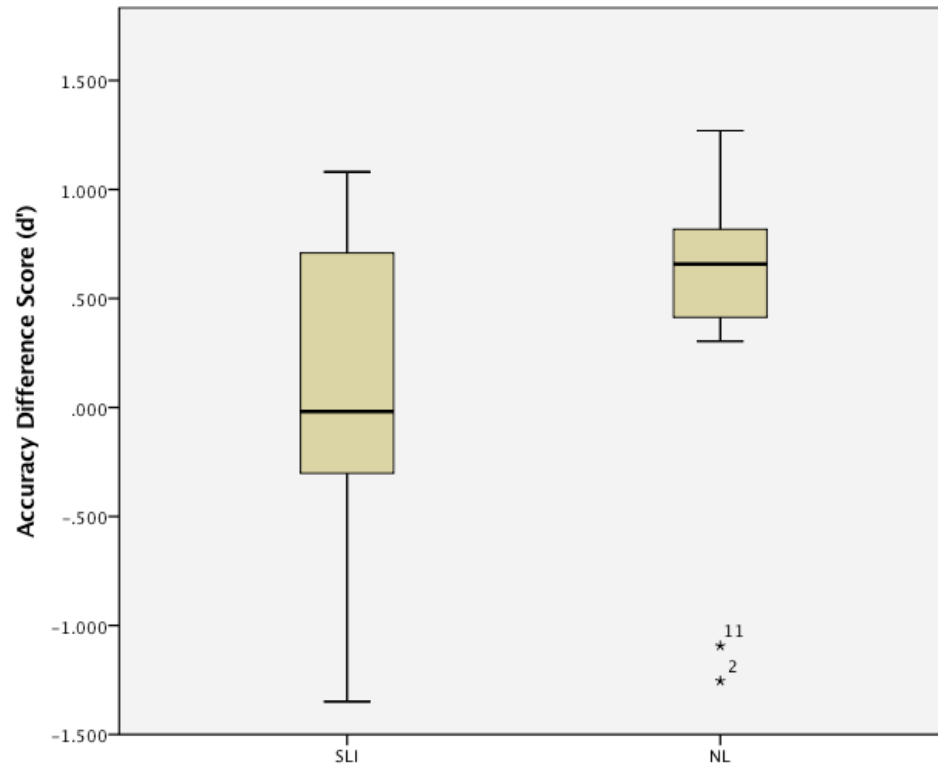
Figure 4.16 Experiment 3 NL vs. SLI: Synchronous audiovisual – Asynchronous audiovisual accuracy difference score (*d'*)

Accuracy difference scores based on Pr were not significantly different for the NL group (*Mdn* = .10) compared to the SLI group (*Mdn* = .01), *U* = 53.00, *z* = -1.10, *p* = .291, *r* = -.22 (see Figure 4.17). Much like the *d'* analysis, these scores indicate that both groups demonstrated similar patterns of accuracy performance across tasks. In this case, both groups had slightly positive median values, suggesting that both groups performed slightly better in the synchronous condition.

Response bias difference scores based on *C* were not significantly different for the NL group (*Mdn* = -.03) compared to the SLI group (*Mdn* = .05), *U* = 63.00, *z* =

-.52, *p* = .630, *r* = -.12. Response bias difference scores based on Br were not significantly different for the NL group (*Mdn* = .05) compared to the SLI group (*Mdn* = -.01), *U* = 71.00, *z* = -.06, *p* = .977, *r* = -.01. Results indicate that response bias difference scores were similar across groups.
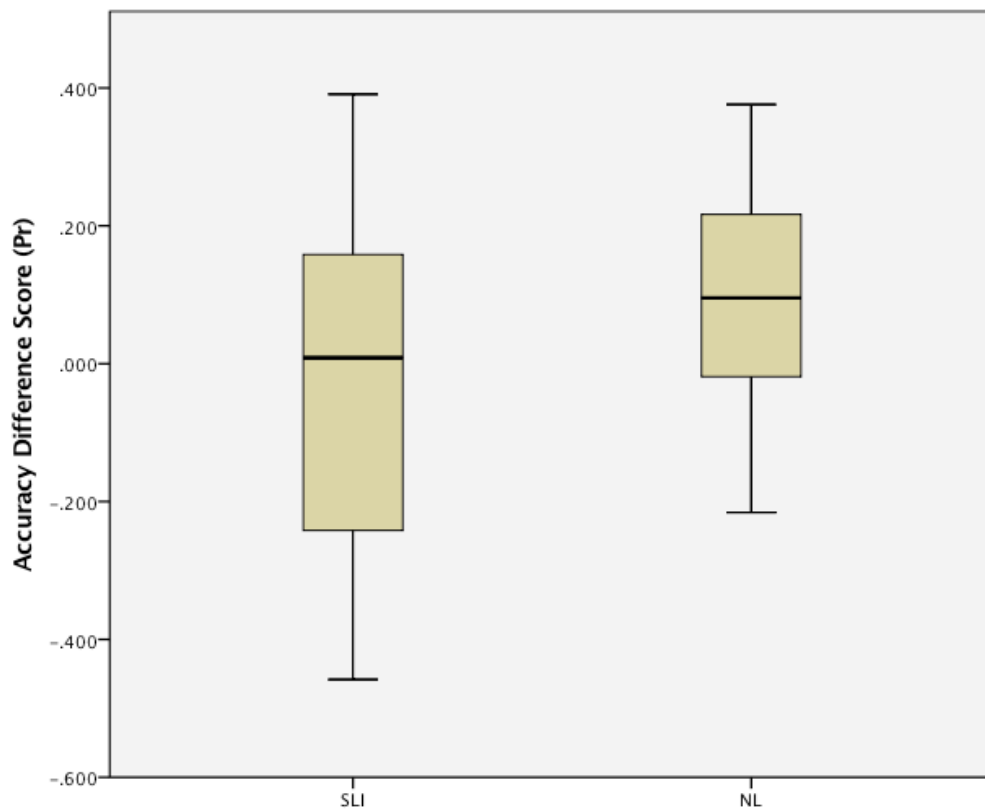
Figure 4.17 Experiment 3 NL vs. SLI: Synchronous audiovisual – Asynchronous audiovisual accuracy difference score (Pr)

Reaction Time

Average RT was calculated based on correct button responses during target trials. Difference scores were generated by subtracting average RT during the asynchronous condition from average RT during the synchronous condition. We then compared RT difference scores across groups using a Mann-Whitney test. RT difference scores were not significantly different for the NL group (*Mdn* = -14.45)

compared to the SLI group (*Mdn* = -64.93), *U* = 43.00, *z* = -1.67, *p* = .101, *r* = -.34

(see Figure 4.18). The pattern of RT performance across tasks was fairly similar for

both groups. The negative median difference score value, seen for both groups,

indicates that RTs were generally faster during the synchronous condition than during

the asynchronous condition.
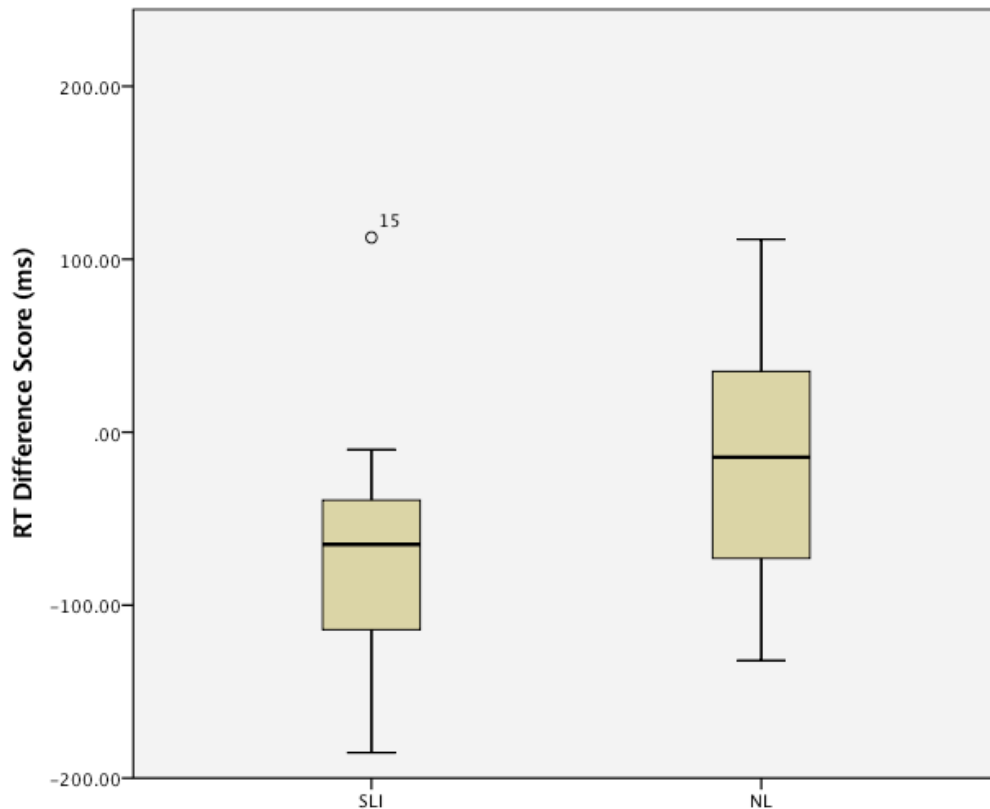
Figure 4.18 Experiment 3 NL vs. SLI: Synchronous audiovisual – Asynchronous audiovisual RT difference score

Proportion of Looking

Average proportion of time spent looking at the visual stimulus was calculated

based on all trials. Difference scores were created by subtracting average proportion

looking during the asynchronous condition from average proportion looking during the

synchronous condition. Difference scores were compared across groups using a

Mann-Whitney test. Difference scores for the proportion of time spent looking at the visual stimulus were not significantly different for the NL group (*Mdn* = .23) compared to the SLI group (*Mdn* = .12), *U* = 59.00, *z* = -.75, *p* = .478, *r* = -.15, (see Figure 4.19). Difference scores suggest that the pattern of looking behavior across tasks was similar for both groups. The positive median values, seen for both groups, indicate that proportion of looking was higher during the synchronous condition than during the asynchronous condition.
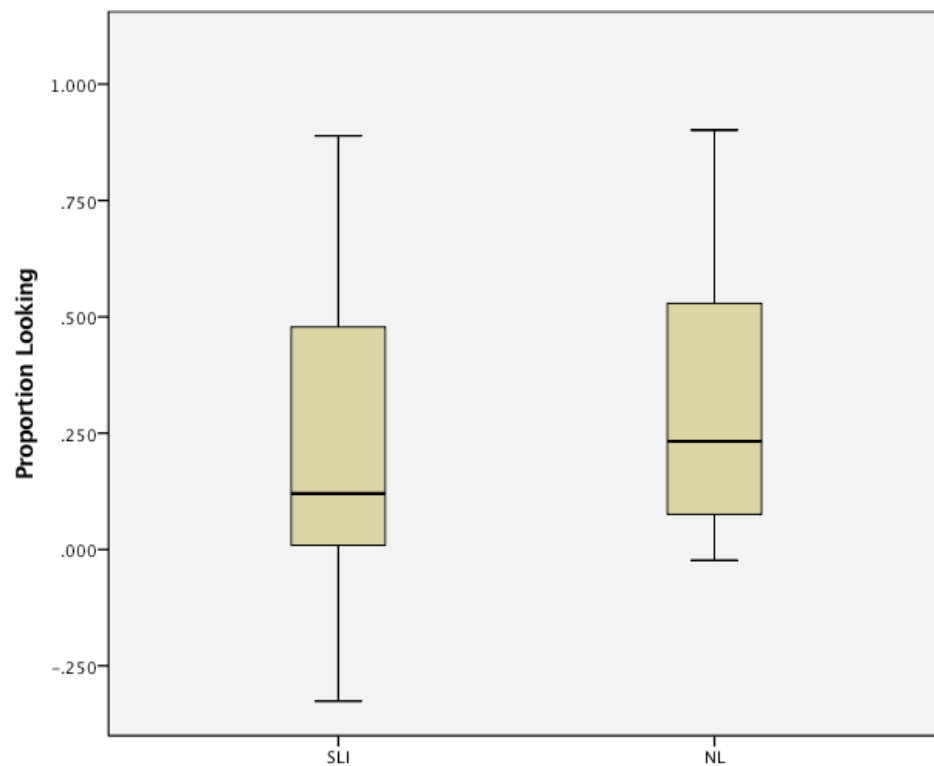
Figure 4.19 Experiment 3 NL vs. SLI: Synchronous audiovisual – Asynchronous audiovisual proportion looking difference score

DISCUSSION

The goal of Experiment 3 was to further clarify our findings from Experiment 2 about intersensory redundancy processing and looking behavior during audiovisual tasks in SLI. We used an eye-tracking methodology to compare patterns of

performance in adults with and without SLI across synchronous and asynchronous tasks under degraded listening conditions. Evidence from the current study clarified findings from Experiment 2 and confirmed that adults with and without SLI do not differ in performance patterns across synchronous and asynchronous tasks. The current findings suggest that intersensory redundancy processing is intact in adults with SLI, reduced sensitivity to audiovisual synchrony may not persist in adults with SLI, and reliance on visual information to support auditory processing may be relatively similar in adults with and without SLI.

In Experiment 3, we taxed audiovisual processing skills by degrading the auditory signal in order to increase reliance on redundant visual cues. In doing so, potential group differences present in Experiment 2 disappeared. Our findings from Experiment 3 suggest that indications of group differences in Experiment 2 were likely not reliable. Despite differences in auditory processing skills seen during Experiment 1, results from Experiment 3 suggest that adults with SLI are still able to effectively utilize redundant visual information to facilitate performance in a manner similar to NL adults. Additionally, adults with and without SLI demonstrate similar looking behavior patterns across tasks. However, while analysis of difference scores indicates that patterns of behavioral performance across tasks are similar for both groups, from descriptive inspection of performance score averages (see Table 4.4) for each group in each task, it is clear that the NL group, in general, produced higher accuracy scores than the SLI group. Averages for RTs and looking proportion were fairly similar across groups.

Table 4.4 Experiment 3 group averages (standard deviation) for behavioral performance measures

		NL (N=12)	SLI (N=12)
Synchronous Audiovisual	*Accuracy (d')*	2.73 (.80)	1.82 (.84)
	Accuracy (Pr)	.76 (.14)	.54 (.23)
	Bias (C)	.03 (.44)	.33 (.52)
	Bias (Br)	.49 (.30)	.37 (.27)
	RT	586.28 (102.92)	584.65 (89.65)
	Proportion Looking	.76 (.35)	.76 (.29)
Asynchronous Audiovisual	*Accuracy (d')*	2.30 (.94)	1.77 (.77)
	Accuracy (Pr)	.68 (.22)	.55 (.21)
	Bias (C)	.08 (.37)	.28 (.39)
	Bias (Br)	.45 (.25)	.34 (.24)
	RT	603.68 (93.75)	653.37 (84.86)
	Proportion Looking	.44 (.34)	.54 (.33)

GENERAL DISCUSSION

The overall goal of our study was to investigate intersensory redundancy processing in college-aged adults with SLI. Secondary goals included investigating the contributions of auditory and visual processing skills to intersensory redundancy processing skills in adults with SLI (Experiment 1) and investigating looking behavior in adults with and without SLI during audiovisual tasks (Experiments 2 & 3). Specifically, across all three experiments, we looked at how patterns of performance change in adults with and without SLI when redundant auditory and visual cues are available. We used three different manipulations to assess differences in performance patterns: 1) performance patterns across multisensory (i.e.,

synchronous audiovisual) and unisensory (i.e., auditory-only and visual-only) tasks (Experiment 1), 2) performance patterns across synchronous and asynchronous audiovisual tasks (Experiment 2) and 3) performance patterns across synchronous and asynchronous audiovisual tasks with a degraded auditory signal (Experiment 3). Generally, our results suggest that despite possible evidence for weak processing skills in the auditory modality, adults with SLI demonstrate similar patterns of performance across tasks where redundant and non-redundant audiovisual information is available, as compared to NL adults.

As has previously been discussed, when considering and interpreting results from the current study, it is important to keep in mind that findings were based on difference scores, which in some cases may not have adequately reflected all performance differences between groups. For example, groups' average accuracy for each condition of Experiment 3 suggests that during both the synchronous and asynchronous tasks, the SLI group in general produced lower accuracy scores than the NL group (see Table 4.4). If the within group difference in accuracy performance across tasks was similar for both groups, then analyses based on differences scores would indicate that group performance was similar, as was the case for Experiment 3; however, this finding does not account for any group differences in overall performance ability (e.g., the SLI group generally exhibiting lower performance ability). We chose to base analyses on difference scores for this study for two reasons: 1) to minimize comparisons given our sample size and 2) because our primary goal was to compare performance facilitation. Given our primary goal, comparisons of within group differences across tasks were more reflective of our research interest than comparisons of general group performance or group

performance on individual tasks. As a result, findings from the current study are not directly comparable to findings in the extant literature, which suggest weaker performance on audiovisual tasks in individuals with SLI (Boliek et al., 2010; Hayes et al., 2003; Holloway, 1971; Kaganovich et al., 2014; Meronen et al., 2013; Norrix at al., 2006; Norrix et al., 2007; Pons et al., 2012).

In some respects, findings from the current study do deviate from findings in the extant literature for reasons above and beyond data analysis choices; however, these deviations should be interpreted with caution. For example, the similar pattern of performance across synchronous and asynchronous audiovisual tasks in adults with and without SLI suggests that adults with SLI are not less sensitive to audiovisual synchrony. While this finding contradicts previous work, previous work on sensitivity to synchrony in SLI has only investigated this phenomenon in children and is additionally limited by the number of available studies (Kaganovich et al., 2014; Pons et al., 2012). The trajectory of development for audiovisual processing skills is protracted during typical development (Desjardins et al., 1997; Hillock et al., 2011; Lewkowicz et al., 2015; Massaro et al., 1986; McGurk & MacDonald, 1976). Thus, it may be the case that audiovisual processing abilities mature even more slowly in SLI; however, by adulthood, audiovisual processing abilities are similar in adults with and without SLI. Relatedly, previous work on the developmental trajectory of auditory processing skills in SLI has suggested that auditory processing abilities may mature more slowly in SLI (Bishop & McArthur, 2005; 2004; McArthur & Bishop, 2004). Results from Experiment 1 of the current study suggest that processing of temporal aspects of an auditory signal may continue to be an area of impairment in SLI into adulthood. To date, research on auditory processing skills in adults is limited and the

auditory processing skills targeted in the current study differed from previous work. It may be the case that some deficits in auditory processing resolve by adulthood, while other deficits continue to affect adults with SLI. More work is needed to investigate the reliability of temporal auditory processing findings in adults with SLI.

Despite our findings that auditory processing abilities may be impaired in adults with SLI, our results also suggest that audiovisual processing, as it relates to intersensory facilitation, remains intact in SLI. Previous work has hypothesized that deficits in visual entrainment may impair audiovisual processing (Power et al., 2012). However, findings from the current study suggest that, if deficits in visual processing exist in SLI, these deficits are not interfering with audiovisual processing. The current study cannot speak directly to the nature of visual processing abilities in adults with SLI compared to NL adults, because groups were not compared based on performance during individual tasks. Descriptively, higher accuracy was seen for adults with NL as compared to adults with SLI during the visual-only task included in Experiment 1. Nevertheless, findings from Experiment 3 and the audiovisual – visual-only comparisons from Experiment 1 suggest that adults with and without SLI still experience similar patterns of intersensory facilitation.

Additionally, research is needed to determine if the current findings extend to linguistic tasks, modality combinations beyond the auditory and visual modalities, and pediatric populations. If it remains the case that individuals with SLI benefit from access to redundant cues from multiple modalities relative to their own performance in a single modality, then the clinical implications for intervention strategies and treatment techniques are compelling. Should the current findings represent a consistent finding in SLI, then treatment techniques in SLI will need to consider

implementation of multisensory approaches in order to increase access to redundant

multisensory information, and thus to additionally support perceptual processing.

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CHAPTER 5: GENERAL DISCUSSION & FUTURE DIRECTIONS

The goal of this dissertation is to bring together two areas of research, multisensory processing and language impairment, to both advance our understanding of multisensory processing in adults and to investigate how multisensory processing affects language ability. The previous chapters offer unique contributions to research, each on their own. However, these chapters also present highly related studies that serve to inform each other. Considered as a whole, the research included in this dissertation identifies and begins to offer insights into gaps in the multisensory processing literature. The research also demonstrates the need to move beyond one-dimensional, unisensory approaches to research on language impairment. In this chapter, I will review the contributions and implications of the research findings from each of the studies discussed in this dissertation. I will then consider all of the findings together and discuss implications for future research. In particular, I will discuss the implications of these findings for future clinical research and, importantly, clinical practice.

At the outset of this dissertation, in Chapter 1, I reviewed three areas of research in an effort to bring together converging and informative findings from disparate areas of research: 1) basic findings from multisensory processing research in adults, 2) multisensory contributions to development with a particular focus on mechanisms and language development, and 3) the state of multisensory processing research in SLI. From a comprehensive review of these areas of research, I concluded that additional research was necessary in order to better define certain parameters of multisensory processing in typical adults, and prior to investigating

multisensory processing in adults with SLI. The studies that followed were designed to address areas of need.

EXPERIMENTAL STUDIES

MULTISENSORY VS. UNISENSORY PERFORMANCE IN TYPICAL ADULTS

In Chapter 2, we examined intersensory facilitation effects under the guidelines of prediction 4 of the IRH, which makes specific predictions about intersensory facilitation in *adults* (Bahrick & Lickliter, 2012). We looked at performance during a go/no-go task in multisensory (i.e., audiovisual) and unisensory (i.e., audio-only or visual-only) conditions. Target and non-target items consisted of tone and shape pairs, which varied in duration lengths (e.g., long-long or long-short). We evaluated both accuracy (*d'* and *C*) and reaction times for evidence of facilitation effects and compared performance in the audiovisual condition to performance in each unisensory condition. Our findings provided inconsistent evidence for prediction 4 of the IRH. Intersensory facilitation effects were evident when comparing reaction times in the audiovisual condition and the auditory-only condition (i.e., reaction times were faster during the audiovisual condition). Facilitation effects were also evident when comparing accuracy in the audiovisual condition and the visual-only condition (i.e., accuracy was higher in the audiovisual condition). However, inconsistent with the predictions of the IRH, we found higher accuracy in the auditory-only condition than in the audiovisual condition and reaction times were equivalent across the visual-only and audiovisual conditions.

Based on the modality appropriateness hypothesis, we explained that higher accuracy in the auditory-only condition might have been the result of ceiling effects in the processing ability of the auditory modality. Superior processing ability in a single

modality mitigates multisensory facilitation effects, according to the hypothesis (Meredith & Stein, 1983; 1986; Stanford, Quessy, & Stein, 2005; Stein & Meredith, 1993). However, the modality appropriateness hypothesis, as it is laid out, does not entirely account for our findings; in Chapter 2, some (i.e., accuracy), but not all (i.e., reaction time) facilitation effects were attenuated when comparing performance in the auditory-only and audiovisual conditions. Similarly, comparison of behavioral performance in the visual-only and audiovisual conditions, evidenced facilitation effects for some behavioral measures (i.e., accuracy), but not others (i.e., reaction time).

The similarity in reaction time findings across the audiovisual and visual-only conditions was explained in terms of participants' sense about the difficulty of the visual-only task and further supported by response bias data. During the experimental session, most participants commented on the challenging nature of the visual-only task and often also commented on their sense of their own poor performance. Lower confidence may have lead to less thoughtful, and therefore speedier, responses. Response bias data indicated that participants demonstrated a significantly more liberal response bias in the visual-only condition than in the audiovisual condition, which additionally supports the possibility that participants may have been less thoughtful and less intentional about their responses in the visual-only condition.

Considering each condition comparison and each behavioral measure individually, it is possible to identify plausible accounts for findings inconsistent with the IRH. However, considering findings from all behavioral measures across condition comparisons as a whole, it is not clear why facilitation effects were only evident for some behavioral measures, and further, why the facilitated behavior varied across

condition comparisons. What is driving this inconsistency in facilitation effects across measures and conditions? What does inconsistency in facilitation effects reflect? For example, does the presence of facilitation effects in accuracy indicate a stronger or different variant of intersensory facilitation than the presence of facilitation effects in reaction times? Furthermore, among various behavioral measures, which measures more consistently evidence intersensory facilitation effects?

It is very possible that the inconsistency in facilitation effects across behavioral measures and conditions seen in Chapter 2 is related to trade-offs that exist between speed and accuracy in human performance. Furthermore, it is possible that we can predict where facilitation effects are most likely to appear for any given comparison, based on some of the ideas laid out by the modality appropriateness hypothesis. It makes sense that facilitation effects were detectable in reaction times when comparing performance in the audiovisual condition to performance in the auditory-only condition, given that the auditory modality is particularly adept (i.e., accurate) at perceiving temporal information. Therefore, whereas there was little room for improvement in accuracy from the auditory-only condition to the audiovisual condition, there was much more room for improvement in reaction time. Similarly, it makes sense that facilitation effects were more likely to appear in accuracy when comparing performance in the audiovisual condition to performance in the visual-only condition, given that the visual modality is particularly weak (i.e., not especially accurate) when processing temporal information. Therefore, in contrast to reaction time, there was room for improvement in accuracy from the visual-only condition to the audiovisual condition. While the above are plausible explanations for the pattern of data seen in Chapter 2, ultimately what became clear, based on our findings in

Chapter 2, is that our understanding of how various combinations of sensory information (e.g., multisensory or unisensory) affect performance and the underlying meaning of that variability remains incomplete.

INFLUENCES ON INTERSENSORY FACILIATION EFFECTS IN TYPICAL ADULTS

In Chapter 3 we continued our investigation of intersensory facilitation effects, based on factors laid out in prediction 4 of the IRH. Through a series of experiments, we investigated the influences of timing, predictive value and signal quality on multisensory facilitation. We compared performance across synchronous and asynchronous audiovisual go/no-go tasks in which timing, predictive value and signal quality were manipulated. Performance comparisons were based on three behavioral measures: accuracy (*d'* and *C*), reaction time and looking behavior (i.e., proportion of time spent looking at the visual stimulus). We included a measure of looking behavior to test the IRH's prediction that intersensory redundancy (i.e., synchrony) recruits selective attention.

Inconsistent with the IRH, in all three experiments, accuracy was similar across conditions, suggesting that intersensory redundancy may not facilitate accuracy in synchronous versus asynchronous contexts. Alternatively, it is possible that accuracy is an insensitive measure for detecting intersensory facilitation effects, when comparing across multisensory conditions, and therefore accuracy is unaffected by manipulations of predictive value and signal quality. However, consistent with the IRH and across all three experiments, reaction times consistently evidenced intersensory facilitation effects, such that reaction times were faster in synchronous conditions (intersensory redundancy conditions) than in comparison conditions, in which intersensory redundancy cues were not present in the stimuli.

Unlike our accuracy findings, this finding suggests that intersensory redundancy facilitates reaction times in synchronous versus asynchronous contexts, even when the predictive value and signal quality are manipulated. Further, reaction time may be the most robust and sensitive behavioral measure of intersensory facilitation effects, particularly when comparing across multisensory conditions. Lastly, also consistent with the IRH, our looking behavior data suggested that looking behavior is also sensitive to the presence of intersensory redundancy. Our looking behavior data indicated higher proportions of time spent looking at the visual stimuli during synchronous conditions (intersensory redundancy conditions) as compared to asynchronous conditions.

Our first experimental manipulation in Chapter 3 compared performance on a synchronous audiovisual condition to performance on an asynchronous audiovisual condition with high predictive value. During the asynchronous condition, both the auditory and visual stimuli presented the same pattern of information; however, the auditory stimuli followed the visual stimuli by a constant time-offset of 400 ms. In this way, the pattern of the preceding visual stimuli was highly predictive of the pattern of the subsequent auditory stimuli. Additionally, the consistency in time offset made the approximate presentation time of the auditory stimuli highly predictable. Our findings suggested that, while synchronous audiovisual information facilitated reaction time performance and encouraged a higher proportion of time spent looking at the visual stimulus, the high predictive value present in the asynchronous condition might have facilitated higher accuracy in that condition compared to the synchronous condition.

However, thinking about our findings from Experiment 1 in light of our findings from Chapter 2, an alternative explanation arises. Our findings from Experiment 1

pattern identically to our findings from Chapter 2, in which we compared performance in an auditory-only condition to performance in an audiovisual condition. In both cases, reaction time was faster in the synchronous condition but accuracy was higher in the comparison condition (i.e., audio-only condition for Chapter 2, asynchronous condition for Experiment 2). It is possible that our findings from Experiment 1 had nothing to do with the predictive value of the preceding visual stimuli, but instead simply provided enough separation between the auditory and visual stimuli that participants were essentially performing an auditory-only task. Our looking behavior findings provide additional support for this alternative explanation. Looking behavior findings indicated that participants spent less time (proportionally) looking at the visual stimuli during the asynchronous condition, suggesting that participants may have been apathetic to the visual signal. Future research could begin to investigate these alternative explanations by, for example, testing independent manipulations of the predictive-value of the visual stimuli and the amount of time between the offset of the visual stimuli and the onset of the auditory.

We included a second experiment in Chapter 3 to investigate intersensory facilitation effects under conditions of audiovisual synchrony and asynchrony in the absence of predictive pattern and predictive timing information in the asynchronous condition, which also rectified the possible unintentional creation of an auditory-only like task in the asynchronous condition. During Experiment 2, differences in accuracy performance disappeared, but, inconsistent with the IRH, facilitation effects did not manifest in accuracy performance. On the other hand, consistent with the IRH, intersensory facilitation effects were seen in reaction times, with faster reaction times in the synchronous condition than in the asynchronous condition. While our looking

behavior data did not yield significant differences, it did indicate a strong trend, consistent with the IRH, of a higher proportion of looking time to the visual stimuli during the synchronous condition (p = .062). Our looking behavior data was explained in the following way: the less overtly asynchronous nature of the audiovisual stimuli (as compared to Experiment 1) during the asynchronous condition in Experiment 2 may have caused participants to spend more time looking at the visual stimuli, particularly early in the experiment, in order to determine the usefulness of the visual stimuli. One could test this hypothesis by using a time-course analysis to compare looking behavior over time (i.e., across trials) across various conditions where synchrony is manipulated in a graded fashion. When asynchrony is harder to discern, participants may spend a greater amount of time looking at a visual stimulus early in an experiment and then looking behavior may decrease over time (i.e., across trials not within trials). As asynchrony becomes more overt, looking behavior may look more consistent across trials. While our second experiment confirms that either the predictive value of the visual stimuli or simply the amount of time separation between the auditory and visual stimuli was responsible for the accuracy finding in Experiment 1, future work will need to independently manipulate these two variables to determine which is driving our accuracy findings.

Our initial goal in designing Experiments 1 and 2 was to investigate the importance of timing for intersensory facilitation effects. It became clear in designing both Experiments 1 and 2 that creating asynchrony in order to investigate the effects of timing on intersensory facilitation was not a straightforward process. A number of factors required careful consideration. For example, it was clear from Experiment 1 that a large separation in time between the presentation of the auditory and visual

stimuli was not an effective method of creating asynchrony, given the potential for predictive information and the potential for creating a condition that mimicked an auditory-only task. Thus, it seemed as though smaller timing differences would be a more effective approach for creating asynchrony. However, previous research has shown that multisensory processing effects persist for stimuli separated by as much as 200 ms (see Laurienti & Hugenschmidt, 2012, for a review). Therefore, it seemed as though the most effective way to create asynchrony was to both reduce the timing difference between auditory and visual stimuli and to reduce pattern likeness between auditory and visual stimuli (i.e., different patterns were used in each modality), in order to limit the likelihood that auditory and visual stimuli would be perceived as coherent. It is certainly worth considering whether a change in pattern likeness qualitatively alters the condition such that it can no longer be classified as truly asynchronous. The task for future work is to determine how best to define asynchrony and, if a change in pattern likeness is determined to be outside the bounds of how asynchrony is defined, then determine how best to test the affects of asynchrony on multisensory processing.

During the third experiment in Chapter 3, in which we degraded the quality of the auditory signal, the facilitative influence of synchronous audiovisual information was again seen in both reaction times and looking behavior when compared to performance in an asynchronous condition similar to the one used in Experiment 2. Taken together, our looking behavior findings across Experiments 2 and 3 suggest that degrading signal quality may increase participants' ability to efficiently determine the usefulness of a secondary sensory stimulus, since analysis of looking behavior

difference changed from a strong trend in Experiment 2 to a significant difference in Experiment 3.

Overall, our findings from Chapter 3 suggest that intersensory facilitation effects manifest in different behaviors dependent upon context, but generally, facilitation effects are more likely to appear in reaction times than in accuracy. Furthermore, timing, predictive value, and signal quality are all factors that influence the strength of facilitation effects and which behavioral response will be facilitated. For example, larger timing differences, as seen in Experiment 1, may influence variability in how facilitation effects manifest and how signal quality may influence the robustness of intersensory facilitation effects. The experiments included in Chapter 3 were not initially designed to tease apart the influence of timing versus predictive value on intersensory facilitation effects. Nevertheless, our findings have important ramifications for the IRH, given that temporal synchrony is an essential ingredient for intersensory redundancy processing according to the IRH. Furthermore, as yet, the IRH does not make specific predictions about how intersensory facilitation effects should manifest in behavioral measures in various contexts. For example, it is possible that temporal synchrony is much more essential early in development for accuracy facilitation effects (Bahrick & Lickliter, 2012), but then, as perceivers become more experienced and gain more expertise, accuracy performance is less susceptible to variations in the temporal structure of coordinated stimuli. Indeed, there is evidence that the time window for processing multisensory signals as associated signals varies across ages and becomes wider at later stages of development (Diederich, Colonius, & Schomburg, 2008; Laurienti & Hugenschmidt, 2012). In short, more research is needed to identify which behaviors are facilitated by multisensory

stimuli and under what conditions. Additionally, future research should investigate whether our findings that facilitation effects most consistently appear in reaction times hold across additional experimental manipulations. Perhaps, much like our previous suggestion, the processing strengths of individual modalities within any experimental manipulation may dictate how facilitation effects manifest in performance.

INTERSENSORY FACILITATION IN ADULTS WITH AND WITHOUT SLI

In Chapter 4 across a series of experiments, we investigated intersensory facilitation effects in adults with and without SLI. We looked at facilitation effects in multisensory versus unisensory comparisons, synchronous versus asynchronous comparisons, and under degraded signal conditions. Due to a small sample size, we reduced the number of comparisons for statistical analyses by comparing groups based on difference scores across conditions on the same three behavioral measures investigated in typical adults in Chapter 3: accuracy, reaction time, and looking behavior. Our results indicated that across all comparisons across all experimental manipulations, adults with SLI demonstrated the same patterns of behavioral performance as typical adults, except in the case of accuracy performance across the synchronous audiovisual and auditory-only tasks. Despite finding a significant difference in patterns of accuracy performance across the audiovisual and auditory-only tasks for our two groups, we noted that this finding must be interpreted with caution, because our analysis only reached statistical significance when accuracy was operationalized as *d'*; not when accuracy was operationalized as Pr. Nevertheless, should this difference in patterns of performance hold in future investigations, our results suggest that adults with SLI may continue to experience impaired auditory processing. However, possible impairments in auditory processing

do not seem to interfere with intersensory redundancy processing and subsequent facilitation effects.

By comparing groups based on difference scores, we were able to look at differences in patterns of performance across groups across tasks, rather than performance differences on individual tasks. This method allowed us a unique opportunity to evaluate how multisensory information influenced performance in each group relative to each group's own performance on a baseline, or comparison task, and then to compare the change from baseline across groups. As a result, we were able to determine that adults with SLI experience similar intersensory facilitation effects, suggesting that multisensory processing may not persist as an area of deficit once individuals with SLI reach adulthood. The trade-off, however, is that comparisons of difference scores overlook performance differences across groups on individual tasks. Though our data indicated similar patterns of performance across most tasks, our findings should not be taken as an indication that groups' performance on individual tasks was equivalent. In fact, when looking at group averages across tasks, it is evident that adults with SLI, for the most part, evidenced lower average scores on most behavioral measures compared to the typical group. Previous research in SLI indicating differences in multisensory processing have largely compared groups' performance on individual tasks, and, based on findings indicating group differences, have determined that individuals with SLI demonstrate difficulty in multisensory processing (Boliek, Keintz, Norrix, & Obrzut, 2010; Kaganovich, Schumaker, Leonard, Gustafson, & Macias, 2014; Meronen, Tiippana, Westerholm, & Ahonen, 2013; Norrix, Plante, & Vance, 2006; Norrix, Plante, Vance, & Boliek, 2007; Pons, Andreu, Sanz-Torrent, Buil-Legaz, & Lewkowicz, 2012).

However, as discussed, our findings suggest that comparing groups' performance on individual tasks may not be the best approach for assessing multisensory processing abilities in individuals with and without SLI. Difference scores, or at least an analysis methodology which allows for a within group comparison between some baseline or comparison task and a complementary multisensory task, may be more reflective of multisensory processing abilities in SLI (as compared to typical peers).

Our findings indicate that more research on multisensory processing, particularly as multisensory processing changes over the course of development, is warranted in SLI. If individuals with SLI do benefit from multisensory information relative to their own performance when they do not have access to multisensory information, then multisensory approaches to treatment design could prove fruitful for this population. The potential utility of multisensory approaches to treatment are particularly relevant if auditory processing deficits continue to affect individuals with SLI across the lifespan, as our findings possibly suggest.

GENERAL IMPRESSIONS & REMAINING QUESTIONS

In designing the above described studies, it became increasingly more evident that developing a multisensory research design poses a number of challenges. Challenges exist due to gaps in our knowledge about how various external factors work together to influence multisensory processing. For example, it is common knowledge within the multisensory processing literature that certain sensory systems possess superior processing abilities for certain kinds of information. Specifically, as has been addressed a number of times throughout this dissertation, the auditory modality is far superior for processing temporal information as compared to the visual modality; the visual modality exceeds the auditory modality in its ability to process

spatial information (Battaglia, Jacobs, & Aslin, 2003; Hirsh & Sherrick, 1961; see Shams, Kamitani, & Shimojo, 2004; Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010, for reviews; Welch & Warren, 1980). Furthermore, the superior processing abilities of individual modalities can ultimately interfere with intersensory facilitation (Meredith & Stein, 1983; 1986; Stanford et al., 2005); Stein & Meredith, 1993). As a result, it becomes very difficult to design stimuli and research paradigms that balance what we know about intersensory facilitation, with what we know about the processing capacity of individual modalities, and further, with what we know about the inverse relationship between intersensory facilitation and unisensory processing capacity.

With respect to the studies included in this dissertation, typical adult auditory processing skills were highly proficient at processing and perceiving the stimuli used across these studies. This proficiency may have had an impact on some intersensory facilitation effects. However and unfortunately, typical adult visual processing skills were very poor at processing and perceiving the stimuli used across these studies and, thus, it became necessary to strike a balance between the skill sets of each of these modalities. Furthermore, design choices were influenced by the inclusion of adults with SLI in this research. A specific goal of ours was to keep stimulus and research design simple, to limit contamination of our findings by additional known deficits in SLI (e.g., working memory capacity and implicit learning) (Archibald & Gathercole, 2006; Ullman & Pierpont, 2005). Previous research on multisensory facilitation has been successful with even simpler research designs; however, in the majority of those studies, multisensory facilitation effects were estimated based on reaction times only. Apart from our one finding that reaction times were similar across

the synchronous audiovisual condition and visual-only condition (Chapter 2), which we plausibly explained based on shifts in response bias and/or related to the processing weakness of the visual modality, faster reaction time during conditions reflecting intersensory redundancy, as compared to during alternative conditions, was the most consistent finding throughout this dissertation. However, had we only based our investigation on reaction times, the challenge in designing these studies and the potential challenge for designing future multisensory research may have been overlooked.

It is also possible that we could have managed design challenges by increasing the complexity of our task rather than simply making it more perceptually challenging. Along the lines of the IRH hypothesis, in theory, increasing the complexity of the task may have bolstered facilitation effects (e.g., facilitated accuracy and/or reaction time) without sacrificing unwanted cost from weaker processing in certain individual modalities. As was discussed in previous chapters, we did increase task complexity, as compared to the much more basic detection tasks used in previous research (Diederich & Colonius, 2004; Frassinetti, Bolognini, & Ladavas, 2002; Gielen, Schmidt, & Van Den Heuvel, 1983; Hershenson, 1962; Lovelace, Stein, & Wallace, 2003; see Rowe, 1999, for a review; Watkins & Feehrer, 1965). However, as mentioned earlier, we specifically attempted to design a challenging but still achievable task based on the abilities of our SLI population, which limited the ways in which we could increase the level of difficulty of the tasks used. It is clear from our findings that additional work is needed in typical adults, to further characterize the nature of the interaction between task difficulty, processing abilities of individual modalities, and the subsequent effects on intersensory facilitation.

As discussed in the studies presented in Chapters 2 and 3 of this dissertation, the extant literature on multisensory processing in adults, intersensory redundancy processing in particular, has failed to investigate intersensory redundancy processing across a range of behavioral measures within the same task. As a result, our knowledge about what sort of "performance" is facilitated when researchers refer to intersensory or multisensory facilitation is limited. Furthermore, what variability in facilitation across behavioral measures means is, as yet, unknown. Further investigation of these remaining questions in typical adults would be valuable, so that we may better understand how sensory input interacts with behavioral output. More importantly, however, further investigation would be valuable in light of the possible clinical implications of the research included in this dissertation. For example, if individuals with SLI are able to improve their performance when given access to redundantly specified information from a variety of sensory sources, then it would be beneficial to know if we are more likely to facilitate speed performance (i.e., faster reaction times) or accuracy performance, and further, if there are speed-accuracy trade-offs when facilitating performance. Having a sense of these impact factors would eventually inform clinical implementation decisions.

CLINICAL IMPLICATIONS: RESEARCH & PRACTICE

Contemplating how our findings fit with what we know about multisensory processing in SLI and the normal developmental trajectory of multisensory processing abilities paves the way for future clinical research. In particular, two remaining questions warrant further investigation in order for this work to be more directly clinically informative. The first question that future work should tackle is why our findings from Chapter 4, which indicated similar patterns of audiovisual processing

across groups, differ from previous research suggesting that individuals with SLI have more difficulty processing audiovisual information (Boliek et al., 2010; Kaganovich et al., 2014; Meronen et al., 2013; Norrix et al., 2006; Norrix et al., 2007; Pons et al., 2012). There are number of possible reasons for this difference in findings. For the most part, prior research on audiovisual processing in SLI has investigated audiovisual processing using much more complex stimuli, as compared to our very simplistic pure-tone and simple visual graphic design (Boliek et al., 2010; Meronen et al., 2013; Norrix et al., 2006; Norrix et al., 2007; Pons et al., 2012). An increase in the complexity of the stimuli alone might have altered our findings. Per the predictions of the IRH, increasing the complexity of the stimuli might result in even more robust intersensory facilitation effects in typical adults. If this is an area of mild impairment in adults with SLI, more complex stimuli might widen the performance gap between groups and result in groups demonstrating different patterns of performance.

Furthermore, previous research has largely investigated audiovisual processing using speech stimuli (Boliek et al., 2010; Meronen et al., 2013; Norrix et al., 2006; Norrix et al., 2007; Pons et al., 2012). It may be the case that deficits in audiovisual processing abilities are more evident in individuals with SLI, during linguistic tasks. At the moment, one cannot disentangle complexity of stimuli from linguistic versus non-linguistic design in order to determine which, if any, might be driving a difference in our findings compared to the findings in the extant literature. Future research would need to disentangle these two variables, to determine if either one contributes to changes in audiovisual processing abilities in individuals with SLI. If our findings hold across manipulations of complexity and use of linguistic and non-linguistic design, then we can begin to design clinical intervention approaches that

capitalize on the added processing benefits of having access to multisensory information. If our results vary across manipulations of complexity and linguistic and non-linguistic design, then the circumstances under which multisensory information may be useful will be more limited and potentially less useful for clinical practice. Importantly, these findings may also inform us about circumstances under which multisensory information is actually detrimental to performance. This too could inform how sensory information is utilized in clinical practice.

Most of the research looking at audiovisual processing in individuals with SLI has been carried out in children (Boliek et al., 2010; Kaganovich et al., 2014; Meronen et al., 2013; Norrix et al., 2007; Pons et al., 2012). It is possible, given the protracted developmental trajectory of multisensory processing abilities (Desjardins, Rogers, & Werker, 1997; Hillock, Powers, & Wallace, 2011; Lewkowicz, Minar, Tift, & Brandon, 2015; Massaro, Thompson, Barron, & Laren, 1986; McGurk & MacDonald, 1976), that differences in audiovisual processing abilities mature more slowly in individuals with SLI, but eventually resolve by adulthood. In fact, this possibility leads to our second remaining question, which warrants further investigation in future work. Only one other study in the literature has investigated audiovisual processing abilities in adults with SLI and, unlike our findings, that study found differences between adults with and without SLI (Norrix et al., 2006). However, this difference should be considered cautiously given that Norrix et al. (2006) were investigating multisensory integration, not intersensory redundancy processing, a form of cross-modal matching (see Chapter 1 for a detailed discussion about the difference between these two forms of multisensory processing). Thus, not only is additional work needed to determine if multisensory processing abilities do eventually resolve in individuals with

SLI, but also, whether or not some multisensory processing abilities are more consistently impaired (e.g., multisensory integration) than others (e.g., cross-modal matching/intersensory redundancy). Should research find that multisensory processing improves over time, then clinical intervention may find it useful to incorporate more multisensory strategies with older individuals with SLI. Alternatively, it may be worth investigating whether intervention can improve multisensory processing abilities in individuals with SLI earlier, such that individuals with SLI, at younger ages, are able to benefit from multisensory information both in treatment and in the natural environment.

It is clear from prior research, and the contributions of the current work, that important and relevant questions remain about the nature of multisensory processing in SLI. These are questions worth investigating, given the valuable contributions of multisensory processing to perceptual and linguistic development (see Bremner, Lewkowicz, & Spence, 2012, for a review) and the potential utility of multisensory approaches to clinical treatment.

FUTURE DIRECTIONS

Throughout this dissertation, and this chapter in particular, a number of questions have been identified as areas for continued research. Broadly, our remaining questions may be grouped into two categories: 1) remaining questions within typical populations and 2) remaining questions within individuals with SLI. Within typical adult populations, more research is needed to characterize the nature of intersensory facilitation in terms of the conditions under which intersensory facilitation occurs and the processing and behaviors that are facilitated by the presence of intersensory redundancy. For example, Chapters 2 and 3 of this

dissertation suggest that the strength of processing in individual modalities, timing, predictive value, and signal quality all potentially impact intersensory facilitation to varying degrees. Furthermore, Chapters 2 and 3 indicate that facilitation effects are not necessarily consistent across all behavioral measures; however, what drives variable patterns of behavioral facilitation and what variable patterns of behavioral facilitation are reflective of in terms of processing, remain unclear. We know from previous work that multisensory processing follows a protracted developmental trajectory well into adolescence (Desjardins et al., 1997; Hillock et al., 2011; Lewkowicz et al., 2015; Massaro et al., 1986; McGurk & MacDonald, 1976). Thus, it will be important to not only investigate and characterize intersensory facilitation in typical adults, but also in school-aged children and adolescents; these two populations have received the least amount of attention from multisensory processing research.

A better understanding of intersensory facilitation in typical individuals across age groups will help to inform research on multisensory processing in SLI. For instance, the research discussed in Chapter 4 suggests that adults with SLI may experience behavioral facilitation from intersensory redundancy and thus benefit from redundantly-specified multisensory information. Future work not only needs to determine if this finding can be replicated and replicated in a range of contexts, but also to determine if individuals with SLI only begin to show more typical patterns of intersensory facilitation in later stages of development (i.e., adulthood). Finding that individuals with SLI demonstrate more typical patterns of facilitation at later stages of development would not only parallel other data suggesting slower rates of maturation for certain abilities in SLI (Bishop & McArthur, 2005; 2004; McArthur & Bishop, 2004),

but would also guide treatment research and eventually treatment practice. For example, if multisensory processing and sensitivity to intersensory redundancy matures more slowly in SLI, could treatment increase the rate of maturation through an increase in exposure to intersensory redundancy? Or would treatment best serve individuals with SLI by focusing on individual modality processing early in development, then switching to a more multisensory approach at later ages? Lastly, our findings from Chapter 4 potentially suggest that deficits in individual modality processing may not have downstream effects on multisensory processing, or at least not intersensory redundancy processing. This finding raises questions for both typical and atypical research on multisensory processing. Specifically, one might wonder what processing skills are necessary or must remain intact in order for intersensory redundancy processing, and perhaps more generally, multisensory processing, to remain intact. For example, if an ability to process rhythmic information is impaired in the auditory modality, as suggested by some recent work in SLI (Corriveau & Goswami, 2009; Corriveau, Pasquini, & Goswami, 2007; Cumming, Wilson, & Goswami, 2015), could intersensory facilitation still occur? Would intersensory facilitation only occur in some environments (i.e., environments where rhythm was not the redundant feature) and not others? Alternatively, one might wonder what information must be present in sensory signals in order for intersensory redundancy processing to occur. For example, how distorted or degraded might a signal be before intersensory facilitation effects begin to disappear?

This dissertation set out to investigate intersensory redundancy processing in adults with and without SLI, based on some hypothesized parameters on intersensory redundancy, and in an attempt to better understand the value of intersensory

redundancy processing and its potentially diffuse effects in individuals with SLI. In doing so, we have made only a start, in what promises to be an intriguing and informative area of research. How do humans use the various sensory signals present in the environment to process, learn about, and navigate the world, particularly with respect to language development? Furthermore, this dissertation makes a strong case for a multisensory approach to research in disordered populations, particularly SLI. A multisensory approach to research is much more representative of a child's natural, every day learning environment and therefore may provide better insight into the nature of the disorder and the consequences for those individuals, and into valuable ecological treatment methodology.

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