Abstract

AN INVESTIGATION OF AUDITORY AND VISUAL TEMPORAL PROCESSING IN CHILDREN WITH READING DISORDERS

by

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Several lines of research have revealed a relationship between reading disorders (RD) and auditory temporal processing deficits. That is, subtle, yet rapid changes within an acoustic message are more difficult for individuals with RD to perceive than for those individuals with normal reading abilities, which negatively impacts accurate speech perception and, in turn, phonological processing and decoding abilities (Cestnick & Jerger, 2000; De Jong et al, 2000; Fink et al., 2006; Walker et al., 2006). However, researchers investigating a pansensory temporal processing deficit theory of RD have found conflicting evidence supporting the relationship between visual temporal processing and reading, specifically in regards to the magnocellular deficit theory of dyslexia (Chase & Jenner, 1993; Farmer & Klein, 1993; Lehmkuhle et al., 1993; Lovegrove, 1993). The purpose of the current study was to further investigate the relationship between pansensory processing deficits and subtypes of reading disorders. Participants included 27 children (ages 10-13) divided into three reading ability groups (i.e., normal reading, dysphonetic, and dysphoneidetic) based on performance the

Woodcock Reading Mastery Test-Revised and the *WRMT-R and Word/Nonword Test*. Experimental tasks included gap detection, duration discrimination, and duration temporal order judgment tasks presented in both the auditory and visual modalities. When controlling for verbal ability (*PPVT-IVT*), due to significant group differences, both RD groups (dysphonetic and dysphoneidetic deficits) demonstrated a poorer performance when compared to the control group on both the within- and between-channel gap paradigms of the auditory gap detection task. No significant differences were found between normal, dysphonetic, and dysphoneidetic readers on any of the visual temporal processing tasks. The current study failed to support the pansensory deficit of RD when reading groups were dichotomized across experimental tasks. However, when considering reading abilities as a continuum several significant correlations between performance on auditory and visual experimental tasks and reading decoding standardized measures were found suggesting that pansensory temporal processing is strongly associated with reading abilities. Results suggest that auditory temporal processing abilities are closely linked to phonological decoding skills in addition to sight-word recognition abilities for the young adolescents having reading disorders.

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By
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CHAPTER I

LITERATURE REVIEW

Introduction to the Literature

The prevalence of reading disability in school-aged children ranges from approximately 3 to 9 percent, with some reports estimated as high as 17%, and accounts for almost 75 percent of referrals for learning disability (Lehmkuhle, Garzia, Turner, Hash, & Baro, 1993; Temple, 2002). Reading disorders (RD), or dyslexia, manifest as uneven development of reading and spelling achievement when compared to the individual's age and normal IQ, impaired phonological and visual/lexical processing abilities, and poor performance on tasks assessing rapid automatized naming (Bellis, 2003; Torgeson, Wagner, & Raschotte, 1994; Wolf & Bowers, 1999). These deficits, in turn, inhibit the achievement of automatic and fluent reading, which often leads to secondary deficits in comprehension (Catts & Kamhi, 1999). In attempts to explain the causes of RD, researchers have taken a wide approach to examining several theories or hypotheses regarding reading disorders, from neurobiological bases of developmental reading disorder, language development and processing, to sensory temporal processing deficits. Neuroimaging and behavioral research studies have provided evidence to support inter-hemispheric differences in reading between normal and poor readers as well as have identified subtypes of RD based on specific deficits in accessing the mental lexicon (Joseph, Noble, & Eden, 2001; Lovegrove, 1993; Shaywitz & Shaywitz, 2005; Temple, 2002; Wolf & Bowers, 1999). Current researchers continue to investigate the causative role of auditory and visual processing deficits on RD, attempting to identify predictive variables on reading achievement (Bellis, 2003; Catts, Fey, Tomblin, & Zhang, 2002; Chase & Jenner, 1993; Torgeson et al., 1994).

Researchers have investigated the association between phonological processing and temporal processing in the auditory and visual fields, striving to answer the question of whether reading disorders are language specific or stem from a generalized temporal processing disorder (Ben-Artzi, Fostick, & Babkoff, 2004). Several hypotheses regarding the relationship between sensory deficits and reading disorders have been posited including an auditory temporal processing hypothesis and a visual temporal processing hypothesis. The auditory temporal processing hypothesis assumes that underlying deficits in the ability to correctly identify and discriminate rapid yet subtle temporal cues in an acoustic signal leads to difficulty with phonological awareness and decoding abilities. Thus, deficits in auditory temporal processing may manifest as the inability to segment acoustic events into individual phonetic units. At present, evidence exists supporting the argument that RD stems from not only core deficits in phonological processing and naming speed but is associated with an auditory temporal processing deficit as well (Shaywitz & Shaywitz, 2005; Wolf & Bowers, 1999). Another hypothesis, the visual temporal processing hypothesis, suggests that disturbances existing in the magnocellular pathway result in decreased sensitivity to rapid transitions of visual stimuli. It has been suggested that readers with visual processing deficits are unable to achieve automaticity and fluency in reading and/or decoding due to improper coding of letter position, impaired whole-word pattern recognition, or poor visual attention (Au & Lovegrove, 2007; Lovegrove, 1993; Ramus, 2003; Samuels, 1987). Lassus-Sangosse, N'guyen-Morel, and Valdois (2008) argued that while auditory deficits alone play a role in RD, visual deficits may occur as another expression of a sensory temporal processing deficit but would have no impact on reading achievement. Thus, only a handful of studies indicate a relationship between visual temporal processing and RD. Due to these equivocal findings, the hypothesis that RD stems from a pansensory temporal processing deficit currently remains debated (Bretherton & Holmes, 2003; Farmer & Klein, 1993; Heim, Freeman, Eulitz, & Elbert, 2001).

This literature review focuses on several models of reading development, which will attempt to link reading abilities to underlying phonological processing and visual/lexical skills and to auditory and visual temporal processing capabilities. Behavioral and neuroanatomical studies are reviewed to highlight differences in phonological and orthographic processing abilities between normal readers and individuals with RD. Neuroimaging studies in conjunction with evoked-related potential measures provide evidence supporting timing differences in the brain regions activated during temporal processing and reading tasks. Auditory and visual temporal processing abilities in normal readers and individuals with RD are also reviewed to provide evidence that subtypes of reading disorder exhibit deficits in one or both of these processing abilities. Theories regarding a general temporal processing deficit are also explored.

Sensory Systems

Auditory Temporal Processing

Auditory temporal processing refers to the ability of the auditory system to receive and analyze temporal cues within an acoustic signal. The ability to perceive the temporal properties of a signal, such as duration, sequence, or rhythm is crucial for the localization of sounds in the environment, perception of voice onset time (VOT), sequencing series of stimuli, and discriminating duration and frequency patterns all of which are critical skills in the understanding of spoken language (Bellis, 2003; Chermak & Musiek, 1997; Hirsh, 1959; Mody, Studdert-Kennedy, & Brady, 1997). However, temporal processing also involves the process of identifying or discriminating rapidly changing stimuli, or the perception of rate (Mody, et al., 1997). Several general models have been developed to describe auditory processing based on hierarchical stages: detection, perceptual analysis, and higher-level cognitive capabilities, all of which allow the listener to correctly extract and interpret meaning (Chermak & Musiek, 1997). Thus, hearing is not solely based on the identification and discrimination of sounds, but on the successful analysis of the information embedded in the signal (Phillips, 1999). Deficits in auditory temporal processing and patterning manifest themselves as difficulty in recognizing acoustic contours and exhibiting poor reading (Bellis, 2003). Various measures of temporal processing, including both behavioral and electrophysiological, have been utilized to identify possible deficits in the coding of temporal stimuli. Included among these measures are gap detection, word recognition in noise, and temporal order judgment tasks.

It has been suggested that gap detection tasks offer a closer look at the speech perception process. The inability to detect subtle changes in an acoustic signal has been assumed to interfere with the identification of phonological cues during speech perception (Boets, Wouters, van Wieringen, & Ghesquiere, 2006; Phillips, 1999).

Speech perception requires attention to the temporal characteristics of speech, such as voice onset time, formant structures and transitional properties. These temporal characteristics provide cues necessary for phonological decoding. Gap detection tasks measure the listener's ability to detect continuity changes in a signal by assessing the timing mechanism of the auditory system. A typical gap detection paradigm consists of the insertion of a silent period in ongoing stimuli. Two typical gap detection paradigms are used to measure auditory temporal acuity: (1) within-channel and (2) between-channel. Within-channel paradigms consist of leading and trailing markers of a gap with the same acoustic features. Since the acoustic features of the stimuli are similar, the same set of peripheral auditory neurons is stimulated. Therefore, a judgment made of temporal order is "actually the detection of discontinuity in the activity aroused in the neural or perceptual channel(s) representing stimulus content" (Phillips, 1999, p. 345). In contrast, between-channel stimuli have leading and trailing markers that differ between one or more of the acoustic dimensions, such as duration or frequency. Thus, a judgment of temporal order is based on the "relative timing of the offset of the activity in the channel representing the leading marker and the onset of the activity in the channel activated by the trailing marker" (Phillips, 1999, p. 346). Therefore, gap detection tasks not only assess temporal order judgment based on the effects of manipulating the leading and trailing markers, but the timing mechanism of the auditory system is also assessed when the inter-stimulus interval (ISI) between markers is manipulated as well.

Several researchers have investigated the effects of ISI and the acoustic nature of the stimulus on the perception of temporal cues (Hirsh, 1959; Phillips, 1999; Wright, Lombardino, King, Puranik, Leonard, & Merzenich, 1997). Hirsh (1959) studied the effects of interstimulus intervals in gap detection tasks. Based on the premise that speech sounds must be discriminated from one another and judged in regards to order, Hirsh investigated three effects of interstimulus interval time and auditory perception. Hirsh found that two milliseconds (ms) was the minimum amount of time required to detect two separate sounds instead of one and that this minimum amount of time was independent of the frequency or complexity of the signal. As for the third effect, Hirsh found that in order for the normal listeners to correctly judge temporal order, or identify which sound came first, the interstimulus interval had to increase to approximately 17 ms, therefore, the minimum interstimulus interval required to detect one versus two signals is not enough time to correctly perceive temporal order.

With regard to the effects of interstimulus intervals and gap paradigm on auditory processing, Phillips (1999) suggested that the between-channel paradigm might more closely imitate temporal processing during normal speech perception due to the fact that gaps of two ms do not occur in human speech and that this paradigm more closely resembled VOT in spoken language. Through several studies examining the effects of interstimulus intervals during the between-channel paradigm, Phillips and colleagues (1997, 1999, 2000) found that normal gap detection thresholds were consistently longer in the between-channel paradigm. This gap detection threshold has been found to correspond to the “perceptual boundary between voiced and voiceless consonants” (Bellis, 2003). This finding indicates that disorders in processing the between-channel paradigm may offer insight into VOT characteristics and rapid auditory processing (Phillips, 1999).

Elangovan (2005) investigated the role of auditory mechanisms in phonetic distinctions. Specifically, he explored the hypothesis that a between-channel gap detection paradigm would better demonstrate the psychoacoustic relationship to categorical VOT perception than a within-channel paradigm. Participants included 10 native English-speaking adults, 10 native Spanish-speaking adults, and 10 bilingual (English-Spanish) speaking adults. Behavioral gap detection and VOT perception tasks were utilized. Elangovan found that the between-channel gap paradigm was better correlated to categorical VOT perception as the between-channel gap detection paradigm mimics the acoustic dimensions of speech.

Temporal processing involves both temporal resolution and temporal integration. Studies investigating temporal resolution and integration abilities have used various test paradigms, including forward and backward masking, gap detection, and continuous and interrupted noise. Masking paradigms have provided evidence of a “release from masking” phenomenon that provides listeners with a certain advantage in word recognition. Specifically, the release from masking phenomenon improves word recognition performance in interrupted noise conditions than in the continuous noise conditions (Stuart, 2005). This performance difference is assumed to be due to the ability of the auditory system to catch “glimpses” of speech information during the interruptions in noise. Thus, the listener is able to patch together the fragments of the signal and use their knowledge of language to correctly identify the signal.

Stuart (2005) conducted a study to investigate the development of temporal resolution in normal-hearing school-aged children by examining word recognition scores in quiet, continuous, and interrupted noise. Previous studies have reported that temporal resolution in children is not as good as adults, which may be due to maturation effects. Five groups of fifteen children, grouped according to age from 6-7years, 8-9 years, 10-11 years, 12-13 years, and 14-15 years, and one group of young adult women participated in the study. All participants had normal hearing from 250-8000 Hz and normal middle ear function. All participants had negative history of speech, language, and learning disorders. The stimuli consisted of Northwestern University-Children's Perception of Speech (NU-CHIPs) monosyllabic words, presented at 30 dB sensation level (SL) above speech recognition thresholds. The lists were presented in quiet and in both interrupted and continuous noise conditions, in which the signal-to-noise ratio was 10, 0, -10, or –20 dB. Participants were instructed to repeat the words presented. It was hypothesized that word recognition performance would be poorer for children than adults, that word recognition performance would be poorer in the noise conditions, and finally, that performance would reach adult-like sooner in quiet conditions than with competing noise.

Results confirmed the hypotheses that children did perform poorer than adults in word recognition performance, especially in the competing noise conditions, and that the older the child, the more adult-like the word recognition performance in the quiet condition (Stuart, 2005). This was found to occur around the age of 10 years. Poor performance on word recognition in the noise conditions by the younger groups may be explained by their limited linguistic knowledge combined with immature temporal resolution capabilities. Poorer performance in both interrupted and continuous noise conditions in the younger children may also be attributed to developing temporal resolution ability. Thus, while younger children perform poorer on temporal resolution tasks, their auditory systems are not selectively impaired but are as yet inefficient for processing signals in competing noise (Stuart, 2005).

In another study conducted by Stuart et al. (2006), the researchers compared word recognition performance of normal hearing preschool children in interrupted and continuous noise paradigms to that of a normal adult listener. Sixteen preschool children with normal hearing participated in the study. NU-CHIPS monosyllabic words were presented in either interrupted or continuous noise to the children and responses were scored as percent correct. A three-factor mixed analysis of variance (ANOVA) was utilized to analyze differences between group (adult vs. child), signal to noise ratio, and noise condition (interrupted vs. continuous). Result indicated that word recognition performance was better in the interrupted noise condition, which confirmed previous results by Stuart (2005). They also found that while children performed poorer than adults, children as young as four or five years performed better in the interrupted noise condition. Stuart et al. (2006) cited research indicating that temporal resolution abilities should mature to adult-like by age twelve years of age. Thus, it was concluded that younger auditory systems are not impaired in any way, but are less efficient in temporal resolution abilities than in older children and adults. Taking this into consideration, it was suggested that temporal resolution abilities could successfully be assessed in preschool aged children using word recognition in noise paradigms. Earlier identification would thus lead to earlier diagnosis and intervention of auditory processing deficit.

Temporal order judgments are considered a more complex form of auditory processing than detection. It has been suggested that the ability to sequence events may serve as the basis for higher-level cognitive processes, such as speech and language processing (Fink, Ulbrich, Churan, & Wittmann, 2006). Evidence suggests that both the right and left temporal lobes have specified auditory processing functions and that these functions aid in the ability to correctly order sequences of events. The left temporal lobe is responsible for serial ordering of acoustic stimuli whereas the right temporal lobe is primarily responsible for the recognition of temporal pattern (Musiek, Pinheiro, & Wilson, 1980). The perception and verbal report of temporal order or patterning requires the interactive function of both temporal lobes. Musiek, et al. (1980) investigated the effects of commissurotomy on temporal patterning tasks. Three participants were studied approximately 10 days after surgery. One participant was tested before surgery, ten days after surgery, and again one year after surgery. Participants had normal pure tone thresholds (250-8000 Hz), normal speech reception thresholds, and normal word recognition scores. Thirty frequency and 30 intensity pattern lists were randomly presented to each ear individually. Two of the three tones were the same and the third differed in either intensity or frequency. The patient had to respond with either “high” or low” and “soft” or “loud.” The stimuli were presented in a second experiment where the patient had to hum the pattern. The researchers found that all three subjects exhibited poor verbal sequencing performance on both the frequency and intensity tasks, following right ear presentation which was poorer than the left ear presentation. However, performance on the humming task was significantly better than for verbal sequencing.

As previously stated, the left temporal lobe is responsible for the verbal sequencing of pattern and the right hemisphere is responsible for pattern perception. Thus, verbal sequencing first requires the perception of pattern by the right hemisphere, the transfer of that information across the corpus callosum, and the processing of that information by the left hemisphere for linguistic labeling (Bellis, 2003). With a commissurotomy, pattern information is unable to reach the left hemisphere, which explains why the patients were unable to verbally sequence the stimuli but were able to correctly hum the pattern. The researchers concluded that, independently, neither hemisphere could adequately process the verbal sequencing of intensity and frequency patterns (Musiek et al., 1980). Thus, frequency pattern tasks are sensitive to interhemispheric dysfunction. Temporal order deficits inhibit the ability to correctly sequence successive stimuli or discriminate acoustic patterns of speech resulting in decoding breakdowns or the ability to segment sequences of acoustic events into individual phonemic units. The ability to match phonemic units to their lexical counterparts is essential for fluent and automatic reading (Chermak & Musiek, 1997).

Auditory Temporal Processing and Reading Disorders

Temporal processing tasks provide significant insight with regards to children diagnosed with language disorders and RD. Two hypotheses have been developed regarding impaired speech perception and subsequent phonological processing impairments. The first is that speech perception is speech-specific and is thus related to a deficit in verbal working memory. Under this hypothesis, it is assumed that poor readers have more difficulty "identifying phonetically similar, though phonologically contrastive" speech stimuli, exhibited poorer performance in word recognition in noise conditions, and had shorter verbal memory spans (Mody, et al., 1997, p. 201). The second hypothesis assumes that impaired speech perception is due to a temporal processing deficit and may be nonlinguistic in nature. Tallal (1980) hypothesized that an auditory processing disorder may result in the inability to discriminate rapidly presented speech and nonspeech stimuli. It might be expected that the more difficulty children experienced in processing brief acoustic stimuli, the more difficulty they would have in overall speech perception and subsequently in learning to read. In other words, difficulty in speech perception may be related to the inability to quickly and efficiently make grapheme to phoneme conversions (Lachmann, Berti, Kujala, & Schroger, 2004). It has been suggested that the underlying cause of reading disorders is due to phonological processing deficits; therefore, breakdowns occurring in auditory temporal processing degrade acoustic signals thus forming the root of phonological processing deficits in dyslexic children (Klein, 2002; Talcott, Witton, Hebb, Stoodley, Wastwood, France, Hansen, & Stein, 2002).

Mody, Studdert-Kennedy, and Brady (1997) tested the speech-specific and auditory temporal processing hypotheses in normal and reading impaired children to determine which hypothesis could most accurately be associated with impairments in speech perception. Three experiments were conducted in this study. The first experiment sought to identify good and poor readers based on performance using a /ba/-/da/ temporal order judgment task modeled after Tallal (1980) and to then determine if these difficulties still persisted in a discrimination task in which the syllables were readily identifiable. The researchers hypothesized that if the difficulties vanished during the discrimination task, then the errors observed in the temporal order task may be due to difficulties identifying the syllables rather than judging temporal order. The second experiment served as a nonspeech stimuli discrimination control. The researchers claimed that if poor readers displayed difficulties discriminating nonspeech stimuli, then it could be assumed that the difficulties may be due to an auditory temporal processing deficit of rapidly changing stimuli. However, if the difficulties in discrimination were not observed, then it could be concluded that difficulties in discrimination are phonetic and thus specific to speech. Finally, the third experiment compared good and poor readers on sensitivity to transitional information. Forty second-grade children (age 7-9 years) participated in the study. All children underwent pre-experimental testing, consisting of the Word Attack and Word Identification subtests of the Woodcock-Johnson Reading Mastery Test-Revised (Woodcock, 1987), the Peabody Picture Vocabulary Test-Revised (Dunn & Dunn, 1981), and the Block Design subtest of the Wechsler Intelligence Scale for Children-Revised (Wechsler, 1974). All stimuli were presented through supra-aural headphones at a comfortable listening level. Results from all three experiments did not lend support for an auditory temporal processing disorder in regards to speech perception. In experiment 1, poor readers exhibited difficulties with /ba/-/da/ temporal order, but did not exhibit these same difficulties in the discrimination task. These results supported the researchers’ hypothesis that poor readers can judge temporal order accurately if they can identify the correct items. Thus, difficulties with temporal order judgment of /ba/-/da/ is phonological. In the second experiment, no significant difference was found between good and poor readers on the nonspeech discrimination task. While in experiment one, there was a strong effect of ISI on discrimination of speech stimuli, there was no effect of ISI on nonspeech stimuli. Thus, difficulty with /ba/-/da/ is specific to speech and cannot be attributed to auditory temporal processing. Finally, in the third experiment, results showed that poor readers were not less sensitive to transitional information than good readers. Again, this confirmed the hypothesis that difficulties in speech perception are speech specific rather than due to deficits in auditory temporal processing (Mody, et al., 1997).

However, Wright, Lombardino, King, Puranik, Leonard, and Merzenich (1997) provided evidence supporting the argument that breakdowns in auditory temporal processing degrade acoustic signals in speech resulting in the inability to hear "acoustic distinctions among successive brief sounds in speech" (p. 176) and that such degradation may result in developmental language impairments. The researchers reported that children with specific language impairment have severe auditory perceptual deficits in processing brief rather than longer durational auditory stimuli. These researchers measured detection thresholds for a brief tone presented before, during, and after two different masking paradigms in eight children diagnosed with specific language impairment and eight children with normal language development. Wright et al. (1997) revealed that the children with normal language development were able to detect the presence of a tone both preceding and following the presentation of noise, but not when the tone was presented simultaneously with the noise. In contrast, the specific language impairment group needed a higher tone level in order to detect its presence in all conditions. It was also found that backward masking (when the tone was presented before the noise) hampered detection performance as much as when the tone was presented before or during the noise for the specific language impairment group. When the researchers presented a brief tone with notched noise, the performance of the specific language impaired group improved as compared to the continuous noise paradigm. That is, the language-impaired group was better able to detect the presence of a tone presented before the notched noise. Wright et al. (1997) summarized that children with specific language impairment "are severely impaired in their ability to (1) separate a brief sound from a rapidly following sound of similar frequency, and (2) enhance the detection of a brief tone by exploiting a frequency difference between the tone and a longer co-occurring or preceding masking sound" (p. 177). This evidence supports a previous study cited (Bradley & Bryant, 1978) in which children with reading difficulties were found to be poor at discriminating words that differed in their initial sound.

In another study supporting the argument for an auditory temporal processing disorder in reading disorder, Rey, De Martino, Espesser, and Habib (2002) investigated difficulties experienced by poor readers with consonant cluster ordering. The study was designed to examine whether a deficit exists in the ordering of two different syllable structures, such as consonant-consonant-vowel (CCV) or consonant-vowel-consonant-vowel (CVCV); to find a possible link between temporal order judgment and event duration; and to investigate whether a temporal deficit is related to phonological impairment. Three experiments were conducted on children with phonological processing deficits (age 9-13 years) and 10 normal readers (age 11-13 year). The first experiment investigated whether consonant order in a CCV syllable was difficult for children with a reading disorder. The second experiment compared consonant ordering in CCV and CVCV sequences, in which the consonant clusters in both sequences were of the same duration. Finally, the third experiment tested whether temporal duration of the consonants influenced performance on temporal order judgments. Performances on all tasks in each experiment revealed significant differences in performance between normal and impaired readers. Individuals with reading disorder consistently exhibited poorer performance on order judgments in all experiments. These findings did not support Mody et al.'s (1997) claim that temporal order impairment is due to phonetic similarity of stimuli rather than auditory temporal processing, but rather supported Tallal's claim of an auditory processing deficit. That is, phonological awareness deficits in individuals with RD may be the result of an inability to order brief acoustic events (Rey et al., 2002).

In a study conducted by Walker, Givens, Cranford, Holbert, and Walker (2006), the relationship between auditory processing of tonal stimuli and word recognition abilities in children was investigated. Previous research indicated that poor lexical readers exhibited more difficulty processing rapidly presented tonal stimuli while poor nonlexical readers exhibited a global deficit in the recollection of tones regardless of presentation speed or response mode (Cestnick & Jerger, 2000). Therefore, Walker et al. investigated not only performance on pitch pattern discrimination tasks but also duration discrimination tasks as well. Eighteen normal hearing children (mean age 10 years) identified as either normal reading or dyslexic, based on decoding skills and receptive language tasks, participated in the study. The pitch pattern and duration pattern tasks were administered and results indicated that dyslexic children performed poorer on both the pitch and duration pattern discrimination tasks than the normal reading children. The results confirm and support previous evidence that indicate the existence of an auditory temporal ordering disorder in dyslexic individuals.

Finally, Boets, Wouters, van Wieringen, and Ghesquiere (2006) conducted a study investigating the relationship between auditory temporal processing and phonological processing and to determine if genetically high-risk children for reading disorder perform differently (poorer) on both phonological and auditory temporal processing tasks than low-risk children. Sixty-two five-year-old children participated in the study. Thirty-one children were identified as high-risk based on a questionnaires investigating the reading and spelling disabilities of family members and on the development of the child. The other 31 participants were considered low-risk due to answers provided on the same questionnaires. Phonological awareness and auditory temporal processing tasks were administered. Phonological skills were assessed using phonological awareness tasks (sound identity, rhyme fluency), verbal short-term memory tasks (digit span forward and nonword repetition), and rapid naming tasks. Productive and receptive letter knowledge was also assessed because previous literature has shown these tasks to be good predictors of literacy development (Boets et al., 2006). For the auditory tasks, gap-detection, frequency modulation (FM) detection, and tone in noise detection tasks were utilized. All auditory tasks were presented monaurally at 70 dB SPL over calibrated supra-aural headphones. For the auditory temporal tasks, a three-interval forced choice oddball paradigm was used. The participant was instructed to indicate which stimulus was different from the others. A two-down, one-up staircase procedure was used to calculate 70.7% correct responses and thresholds were calculated as the geometric mean of the values in the last four reversals. All data were collected between the second and fourth month of the last year of kindergarten.

Boets et al. (2006) revealed that the high-risk children tended to perform poorer on almost all phonological tasks than the normal children, although some of these performance differences did not reach significance. For the auditory tasks, there was no significant group effect for gap-detection, FM detection, or tone-in-noise detection; however, there was a significant effect of threshold run for all three of the auditory tasks. When examining the relationship between phonological and auditory skills, the researchers found that for the total group the FM detection and tone-in-noise detection were significantly related to variables assessing phonological awareness skills. FM detection was the only auditory task related to letter knowledge. However, for the high-risk group, only tone-in-noise detection was significantly related to phonological awareness. The researchers concluded that a specific aspect of auditory temporal processing might not be related to phonological awareness, since gap-detection was not related to any phonological awareness task, but rather the nontemporal tone-in-noise task. They further suggested that accurate phase-locking systems might be more related to phonological processing due to the finding that deviant auditory spectral processing was more closely related to phonological processing skills. Boets et al. neither confirmed nor negated the auditory temporal processing hypothesis of reading disorder.

While several behavioral studies have been conducted to investigate the link between auditory temporal processing and reading impairment, other researchers have utilized electrophysiological measures (Alonso-Búa, Diaz, & Ferraces, 2006; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998; Sharma, Purdy, Newall, Wheldall, Beamon, & Dillon, 2006). One electrophysiological measure typically used is the mismatch negativity (MMN). This measure is best suited to examine automatic central auditory processing (Schulte-Körne et al., 1998). The MMN is a component of the evoked related potential that is elicited by any discernible change in an acoustic sequence and is thought to reflect behavioral acoustic discrimination (Schulte-Körne et al., 1998; Alonso-Búa et al., 2006; Sharma et al., 2006). The MMN has been used to investigate whether reading impairment is related to a speech-specific deficit or a deficit in auditory temporal processing.

Schulte-Körne, et al. (1998) investigated whether a relationship exists between reading disorder and central auditory processing. To determine if speech perception deficits were preattentive and automatic, the researchers utilized an oddball paradigm using both tonal and speech stimuli. MMN responses were recorded. The researchers hypothesized that the MMN would be attenuated for speech stimuli only in the dyslexic readers. Nineteen children with spelling disability (mean age 12.5) and 15 normal reading children participated in the study. The children with spelling disability were defined as having lower word decoding ability than the controls. All auditory stimuli were presented binaurally through headphones. Tonal stimuli consisted of a standard tone of 1000 Hz and a deviant tone of 1050 Hz. Tones were 90 ms in duration and were presented in pseudorandom order. Speech stimuli consisted of a standard /da/ and a deviant /ba/, adopted from Heinz and Stark (1996). Participants were instructed to attend to a silent video and were asked several questions on topics of the movies after EEG recording.

Schulte-Körne et al. (1998) revealed no significant effects for tonal stimuli between groups, while there was significant effect for speech stimuli. That is, children with RD exhibited attenuated MMN responses for speech stimuli but not for tonal stimuli. These results are supported by results from Alonso-Búa, et al. (2006) who found no significant differences between normal and impaired readers in MMN amplitude. However, they did find a significant delay in MMN latency for the linguistic stimuli for both groups. Reduced discriminatory ability for linguistic stimuli suggests a specific phonological deficit in children with RD. These results support the argument that speech perception deficits are, indeed, speech specific and not due to an auditory temporal processing disorder.

However, a study conducted by Sharma, et al. (2006) showed that reading impairment might stem from an underlying auditory processing disorder. Comparing behavioral phonological and audiological performance to MMN responses, the researchers examined whether children with reading impairment show auditory processing deficits for both speech and nonspeech stimuli. They hypothesized that children with reading impairment would show attenuated MMN responses as compared to normal reading children. Twenty-one children (mean age 10.4) served as controls while 15 children with RD (mean age 10.9) were placed in the experimental group.

Children with RD were identified as having reading scores two years behind their chronological ages and showed no evidence of attention, language or cognitive deficits. Children were tested using the Wheldall Assessment of Reading Passages (WARP), which measures reading fluency and Coltheart and Castle's *Word/Nonword Test*, which measures regular and irregular words, and nonwords. Four behavioral tests were used to assess auditory processing: dichotic digits test version 2, frequency pattern test, random gap detection, and ipsilateral speech-in-noise, with a presentation level of 60 dB HL under supra-aural headphones. For the frequency pattern test and the speech-in-noise test, stimuli were presented to the right and left ears separately. For the gap detection task and the dichotic digits test, stimuli were presented binaurally. In the electrophysiological test battery, six deviant stimuli were delivered monaurally to the right ear. An oddball paradigm was used where the standard stimuli for tones was a 1000 Hz tone and two deviant tones of 1100 Hz and 1500 Hz. The standard chord stimuli was a combination of 1000, 1100, and 1500 Hz tones and the two deviant chords were 1000 and 1100 Hz tones presented simultaneously and 1000 and 1500 Hz tones presented simultaneously. And finally, the standard speech stimuli were /da/ and /ga/ with /a/ pronounced similar to the word "hard" and for the deviant the /a/ was spoken as a low back vowel (as in "hard" without the /r/). For the MMN recordings, P1, N250 peak latencies and amplitudes were measured for both standard and deviant stimuli.

Sharma et al. (2006) found that the reading disabled group had poorer reading fluency and accuracy scores as well as poorer nonword reading scores than normal reading children. The control group performed well on all behavioral auditory tests while the reading disabled group showed deficits on at least one of the four auditory tests, specifically the frequency pattern test. Additionally, the researchers also found that MMN responses were more consistently present with the speech stimuli; however MMN responses were too inconsistent to be used as a clinical tool for diagnosing auditory processing deficits. The researchers concluded that there is no clear relationship between MMN and auditory processing disorder. This could be due to poor reliability of the behavioral results or the small number of trials in the behavioral paradigm. However, a significant number of children with RD exhibited difficulty with the frequency pattern test, which is a complex task requiring "frequency discrimination, rapid auditory processing, temporal sequencing, and linguistic labeling" (Sharma et al., 2006, p. 1141). Thus, poor temporal discrimination may account for poor speech perception and subsequent phonological processing. Children with reading impairment who showed problems with nonword reading always showed evidence for an auditory processing disorder. The researchers then concluded that poor phonological awareness might be due to poor auditory temporal processing.

In summary, the inability to detect subtle changes in acoustic stimuli has been linked to phonological processing deficits in reading disabled children (Sharma et al., 2006; Tallal, 1980; Walker et al., 2006; Wright et al., 1997). Breakdowns in the most basic level of auditory temporal processing, detection, result in the inability to decode individual phonological elements in speech, thereby inhibiting the ability to make correct grapheme to phoneme correlations. It has been suggested that decoding deficits occurring at the lowest level of processing impedes higher-level processes such as comprehension (Shaywitz & Shaywitz, 2005). In addition, interhemispheric dysfunction can affect the ability of the listener to correctly judge temporal order or pattern. It has also been suggested that within the human brain exists a time organization system that is independent of a “peripheral and central modality-specific system,” thus leading to the argument that temporal processing deficits not only occur in the auditory system, but in the visual system as well (Bellis, 2003). It has been argued that visual temporal processing deficits may lead to the inability to retain visual information and the ability to rapidly process sequences of letters (Boden & Brodeur, 1999). Thus, it is important to review research focusing on the relationship between visual temporal processing and decoding.

Visual Temporal Processing and Reading Disorders

Until recently, previous research revealed that normal reading and reading impaired individuals did not differ systematically in visual processing and it was thus a common assumption that visual processing deficits were not attributable to reading disorder (Lovegrove, 1993). However, over the past two decades, research has found visual abnormalities associated with reading disorder, specifically involving the magnocellular system. Anatomical studies investigating the visual pathway have revealed that the visual system is comprised of two separate yet parallel pathways (Cestnick& Coltheart, 1999; Lehmkuhle, et al., 1993; Lovegrove, 1993). The magnocellular pathway is predominately a flicker- or motion-detecting system, is more sensitive to rapidly changing stimuli and is mediated via magnocellular lateral geniculate neurons to the occipital and parietal lobes. On the other hand, the parvocellular system is predominately a detailed pattern system, is more sensitive to slow moving stimuli, color and hue, and mediated via the parvocellular lateral geniculate neurons to the occipital and temporal lobes (Cestnick & Coltheart, 1999; Evans, Drasdo, & Richards, 1996; Lovegrove, 1993). Since the magnocellular system is primarily a motion detection system, it has been suggested that slower visual processing and longer visual persistence at lower spatial frequencies observed in individuals with reading disorder is due to a deficit affecting the magnocellular system (Eden, Van Meter, Rumsey, & Zeffiro, 1996). In other words, a specific deficit to the magnocellular pathway may underlie several characteristic errors associated with reading impairment.

The magnocellular theory of reading impairment holds that reading involves a series of brief fixations separated by saccadic eye movements (Skottun, 2000). The theory also holds that the parvocellular system is suppressed by the magnocellular system. This suppression serves to prevent information processed during one fixation from lingering into the next fixation. Failure of the magnocellular system to suppress the parvocellular system may cause visual confusion, specifically confusing neighboring letters while reading (Skottun, 2000; Stein & Walsh, 1997). However, whether the function of these two systems is causal or associative to reading impairment is still unclear. Thus, several behavioral, electrophysiological, and neuroimaging studies have been conducted to investigate the role of the magnocellular system and its relationship to reading impairment.

As mentioned above, the lower level components of the visual system are comprised of two parallel pathways: the magnocellular and parvocellular (Borsting, Ridder, Dudeck, Kelly, Matsui, & Motoyama, 1996). Evidence of a magnocellular deficit in reading impaired individuals comes from several behavioral studies, which have employed three main tasks: contrast sensitivity to both static and flickering stimuli, coherent motion, and the Ternus task. Contrast sensitivity tasks have been used to assess the magnocellular system because it has been shown that reading impaired individuals have reduced sensitivity to lower spatial frequencies and higher temporal frequencies (Borsting et al., 1996; Conlon, Sanders, & Zapart, 2004; Demb, Boynton, Best, & Heeger, 1998; Evans, et al., 1996; Greatrex & Drasdo, 1995).

In a study conducted by Borsting, et al. (1996), spatial contrast sensitivity was assessed in reading impaired adults subtyped as either dyseidetic or dysphoneidetic. These two subtypes were chosen because dyseidetic reading disorder is hypothesized to stem from visual processing deficits and dysphoneidetic reading disorder was chosen because it represents the most severe type of reading disorder and will therefore result in the most significant difference on visual processing tasks. Twenty-six participants (mean age 35 years) were divided into three groups: normal, dyseidetic, and dysphoneidetic. Each subject had to meet visual acuity and intelligence criterion. Dyslexic subtypes were determined by performance on the Adult Dyslexia Test (Griffin, Christenson & Walton, 1990). The visual stimuli consisted of vertically oriented sinusoidal gratings displayed on a monitor and were viewed binocularly. A two-alternative, forced-choice technique was used and a modified staircase method was used to determine threshold. Six spatial frequencies were employed (0.5, 1.0, 2.0, 4.0, 8.0, 12.0 c/deg) and gratings drifted at two temporal frequencies (1 and 10 Hz). Borsting et al. (1996) found that individuals classified as dyseidetic did not perform significantly different from those of normal individuals on the spatial contrast sensitivity tasks at any frequency, which did not confirm the hypothesis that dyseidesia stems from visual processing deficits. However, the dysphoneidetic individuals showed reduced sensitivity to low spatial frequency at 10 Hz, which confirms the hypothesis that a magnocellular deficit is related to a subtype of reading disorder.

In another study conducted by Demb, et al. (1998), contrast sensitivity and motion discrimination performance was compared to determine if reading skill is related to magnocellular pathway function. Five individuals with reading disorder (mean age 22.2 years) and five control subjects (mean age 26.8 years) participated in the study. Participants were administered five reading tests: the reading and spelling subtests of the Wide Range Achievement Test (WRAT 3), the word-attack subtest of the Woodcock-Johnson, and the reading rate and comprehension measures of the Nelson-Denny. Speed discrimination was measured using a two-interval, forced choice double staircase procedure. Stimuli were moving 0.4 c/deg sine-wave gratings at low mean luminance (5 cd/m^2). Participants were instructed to report which of the two stimuli moved faster. Contrast detection thresholds were measured using a similar method and stimuli were the same as those in the speed discrimination task. The researchers found that the motion discrimination task was a better indicator of reading impairment than contrast detection. The researchers suggested that when assessing the magnocellular pathway in individuals with reading disorder, motion discrimination tasks should be included in the test battery.

A review by Skottun (2000) highlighted several potential problems interpreting results from early research using contrast sensitivity tasks. That is, several early studies investigating the relationship between reading impairment and a magnocellular deficit have produced results that do not match predictions for a magnocellular deficit. Skottun (2000) makes the distinction concerning the difference between spatial and temporal contrast sensitivity. A contrast sensitivity curve exists to help predict deficits in the magno- or parvocellular systems. The curve represents the "sensitivity of whichever of the two systems is the more sensitive at any given spatial and temporal frequency" (Skottun, 2000, p.112). Using this curve, one could predict that a deficit in the magnocellular system exists if reduced sensitivity is observed below 1.5 c/deg. On the other hand, one would expect a parvocellular deficit if reduced sensitivity was observed above 1.5 c/deg. However, a number of earlier studies failed to produce results that could clearly be interpreted as a magnocellular deficit. That is, these researchers found that performance on contrast sensitivity tasks was less sensitive to higher spatial frequencies (above 1.5 c/deg) than lower spatial frequencies for individuals with reading disorder. Using the contrast sensitivity curve, these results do not predict a magnocellular deficit, but rather a parvocellular deficit.

While a number of studies failed to produce unambiguous results concerning a magnocellular deficit, other studies employing both static and flickering gratings have produced results more consistent with this deficit (Cornelisson, Hansen, Hutton, Evangelinou, & Stein, 1998; Borsting et al., 1996; Demb et al., 1998). When flickering stimuli (20 Hz) were used at low gratings of 0.5, 1.5, and 2 c/deg, the researchers found that reading impaired individuals' sensitivity was reduced with increases in temporal frequency, which is in agreement with the magnocellular deficit of reading impairment (Skottun, 2000).

Skottun (2000) offered possible explanations as to why results on contrast sensitivity tasks did not reconcile with predictions of a magnocellular deficit. One such explanation is that the criterion for a magnocellular deficit is reduced sensitivity below 1.5 c/deg. None of the studies he reviewed met this criterion. In fact, most of the studies found reduced sensitivity at medium or higher spatial frequencies, which is more consistent with a parvocellular deficit. If the criteria were more relaxed so that it included medium spatial frequencies, more results from these earlier studies would be consistent with a magnocellular deficit. However, if higher spatial frequencies were included it would be difficult to tease out a magnocellular deficit from a parvocellular deficit (Skottun, 2000). Several improvements were suggested by Skottun (2000) for future research using contrast sensitivity, such as the use of "Gaussian blob" to reduce sharp edges during the flicker cycle, masking stimulus transients (which reduces sensitivity of the magnocellular system), and using a dark screen during flickering rather than a luminance-matched surround because low luminance emphasizes the magnocellular pathway to the cortex.

Williams, Stuart, Castles, and McAnnally (2003) conducted a study investigating the relationship between a magnocellular deficit and subgroups of reading impairment. Twenty individuals with reading impairment and 23 normal reading children (age 8-12 years) participated in the study. The children with reading impairment were further classified as having phonological deficits, visual/lexical deficits, or a combination of deficits. The visual stimulus consisted of a Gaussian blob flickering sinusoidally at 8.33 Hz for 1 second, which measured the magnocellular system. The stimulus used as a measure for the parvocellular system was a moderately high spatial frequency (8 c/deg), which was presented for 1 second. Thresholds were determined using a modified three-down, one-up two-alternative, forced-choice staircase procedure to obtain a 79% correct threshold. Each trial consisted of two intervals, the first of which was paired with a 2500 Hz tone and the second, which was paired with a 400 Hz tone. The stimulus was presented either during the first or second interval. The participant was instructed to verbally indicate in which interval the stimulus was presented. The researchers found no significant difference in performance between normal readers and all three subgroups of reading impairment in both static and flickering contrast sensitivity tasks. They hypothesized that the lack of a magnocellular deficit could be explained by a lack of specific damage to the magnocellular system in their sample of reading impaired children (Williams et al., 2003). However, this leaves the question of whether a relationship exists between a magnocellular deficit and reading impairment unanswered. Several other behavioral studies have employed coherent motion tasks to determine if a relationship exists between reading impairment and a magnocellular deficit.

While contrast sensitivity tasks have been useful in examining the function of the magnocellular and parvocellular pathways during reading, another task, the coherent motion task, has also been utilized. As mentioned previously, deficits in visual processing can lead to letter confusion during reading. Cornelissen, Hansen, Hutton, Evangelinou, and Stein (1998) proposed that impaired magnocellular function, specifically, leads to letter transposition while reading, which may explain difficulties experienced by reading impaired individuals. That is, a magnocellular deficit may cause letters or parts of letters to be lost, duplicated, or scrambled during reading. They hypothesized that a positive correlation should exist between impaired performance on motion coherence tasks and letter errors in reading impaired individuals, thus supporting the magnocellular deficit of reading impairment. Sixty children (mean age 10.5 years) participated in the study and had normal to corrected-normal visual acuity. AH1 X & Y Tests of Perceptual Reasoning (Heim et al., 1977) and the Non-reading Intelligence Tests (NRIT) level 3 (Young, 1996) were used to assess IQ. The children's' reading age was assessed using the British Ability Scales (BAS) single word reading accuracy test and phonological awareness was assessed using two subtest of the Phonological Awareness Battery (Educational Psychology Publishing, UCL, 1995): the rhyme test and the spoonerism test. Experimental tasks included a word list based on the BAS reading age and a coherent motion task. The coherent motion task consisted of random dot kinematograms. Two black rectangular patches contained 300 randomly arranged white dots each. Each trial lasted 2300 ms and coherent motion appeared randomly in one of the two patches. "Coherently moving dots lived for only two consecutive animation frames (total of 58 ms) before being reborn in a new, randomly selected position on the patch" (Cornelissen et al., 1998, p.475). Thresholds were determined using a two-alternative, forced choice method. Results revealed a non-linear, positive relationship between coherent motion thresholds and letter errors made by reading impaired children.

The researchers also found that those children with intermediate phonological skills made more letter errors than those children who had very poor or very good phonological skills. However, since there was no significant correlation between performance on phonological tasks and coherent motion, the researchers hypothesize that this performance was independent of magnocellular function. The results of this study reveal a positive correlation between reading errors and magnocellular function, thus suggesting component skills in reading may be affected by deficits in the magnocellular pathway (Cornelissen et al., 1998).

In another study of coherent motion, Talcott, Hansen, Assoku, and Stein (2000) predicted poorer performance of coherent motion sensitivity in reading impaired individuals as compared to normal readers, especially at low and intermediate dot densities where information is more limited. Participants consisted of 10 adults diagnosed with RD (mean age 25.2 years) and 10 normal reading adults (mean age 22.2 years). All adults with reading impairment had been previously diagnosed by clinical or educational psychologists based on their literacy skills and cognitive abilities. The stimuli consisted of random dot kinematograms. Each dot had a lifetime of four animation frames, after which they would reappear in random location thus giving the appearance of coherent motion. The subjects were instructed to indicate in which patch coherent motion was perceived. Thresholds were determined using a one-up, one-down, two-alternative, forced-choice, single staircase procedure. Both the effects of dot density and stimulus duration were analyzed. Stimulus durations consisted of 4, 9, 18, and 36 animation frames, which corresponded to 200, 451, 902, and 1804 ms, respectively. Dot density consisted of patched containing either 75, 150, 300, or 600 dots, which corresponded to a dot density of 1.5, 3.1, 6.1, and 12.2 dots/deg^2, respectively. The researchers found that coherent motion sensitivity in reading impaired individuals was significantly reduced than controls for both the stimulus duration and dot density experiments. These findings support the hypothesis of poor global motion processing in developmental reading disorder. However, the reading impaired group was less sensitive to motion at each stimulus duration tested. The researchers found that this finding is not consistent with previous research indicating that reading impaired individuals are less sensitive primarily to short duration stimuli. Thus, results from Talcott et al. (2000) "demonstrates that the visual deficit is more related to their poor integration of the changes in time that are characteristic of dynamic visual stimuli than to more generalized detection deficits for stimuli with limited presentation durations" (p. 942).

A technique, called the Ternus task, has also been used to assess the magno- and parvocellular systems. Developed in 1938 by Ternus, the tasks allows for illusions of movement to be created. The squares, aligned horizontally, are presented and then re-presented on a screen. When the interstimulus interval is approximately 50 ms or more, the three squares appear to move backwards and forwards as a group, whereas if the interstimulus interval is 50 ms or shorter, the squares appear to move one by one, also known as apparent element movement (Cestnick & Coltheart, 1999). Breitmeyer & Ritter (1986) argue that apparent element movement depends upon the parvocellular system and group movement depends on the magnocellular system.

Cestnick and Coltheart (1999) investigated the relationship between exception word reading and nonword reading to a visual deficit observed during the Ternus task. The purpose of the study was to determine if a correlation existed between exception word reading and group movement. The researchers hypothesized that if exception word reading was associated with group movement, then there would also be an association to nonword reading and group movement. However, if the exception word reading variable were partialled out, then the correlation between nonword reading and group movement would disappear (Cestnick & Coltheart). Forty-three individuals with reading impairment and 44 normal readers participated in the study. Participants were selected from primary schools throughout Sydney, Australia. The Ternus display consisted of three squares on a dark background. Apparent movement was measured at 12 interstimulus intervals: 8.3, 16.6, 24.9, 33.2, 41.5, 49.8, 58.1, 66.4, 74.7, 83.0, 91.3, and 99.6 ms. Each individual display had a duration of 50 ms and there were 20 trials per interstimulus interval, thus resulting in a total of 240 trials. The participants were instructed to stare at a cross while the squares were flashed above or below it and make a judgment if three squares were moving ("three moving") or if one square was moving ("one jumping").

The researchers discovered that the reading impaired readers performed worse on the Ternus task than did normal readers. To determine if different groups of reading impairment display different patterns of performance on the Ternus task, Cestnick and Coltheart (1999) subtracted the number of nonwords read correctly from the number of irregular words read correctly from all 80 participants. Positive values indicated phonological reading disorder and negative values indicated surface reading disorder. Only pure phonological dyslexics (10 children) and pure surface dyslexics (3 children) were chosen for reanalysis of performance on the Ternus task. When compared with phonological dyslexics, surface dyslexics produced less group movement at short interstimulus intervals and more group movement at longer interstimulus intervals. When compared to normal readers, the phonological dyslexics displayed poorer performance on the Ternus task than the surface dyslexics. The researches suggested that, "evidence for heterogeneity is clear" (Cestnick & Coltheart, 1999, p. 242). That is, only some individuals with developmental reading disorder perform abnormally on Ternus tasks (i.e. specifically phonological dyslexics) whereas others do not. Positive correlations were found between poor performance on the Ternus task and nonword reading skills.

Electrophysiological studies have also been used to assess visual pathway function by measuring latency and amplitude of responses in normal and reading impaired individuals. Based on behavioral studies, it has been hypothesized that reading impaired individuals would display longer latencies and shorter amplitudes on low-level visual tasks than normal readers. That is, since reading impaired individuals showed reduced sensitivity to rapidly changing dynamic visual stimuli, it is assumed that the visual system in the reading impaired is characterized by longer integration time and/or longer visual persistence (Breznitz & Misra, 2003).

Lehmkuhle, et al. (1993) conducted an electrophysiological study comparing magnocellular visual pathway function in normal reading and in reading disordered children. The researchers hoped to support the hypothesis that the function of the magnocellular pathway in reading-disabled children was reduced as compared to normal reading individuals. Visual evoked potentials were recorded in children 8-11 years old using flicker fusion tasks. Similar to auditory gap detection tasks, flicker fusion tasks assess the timing mechanism of the visual system and its ability to detect one versus two flashes of light and thresholds are measured in ms. The critical finding of the visual evoked potential measures was that individuals with RD had longer latencies and were attenuated as compared to the normal reading children. The results supported the hypothesis of a magnocellular pathway deficit in reading disabled individuals involving a slowing of response in this pathway. It has been speculated by Livingstone et al. (1991) that the magnocells in the lateral geniculate nucleus (LGN) are smaller and more disorganized in individuals with reading disability and that smaller magnocells may affect visual processing speed.

Due to conflicting evidence in studies utilizing visual evoked potential measures to support the existence of a magnocellular deficit in individuals with RD (Galaburda and Livingstone, 1993; Lehmkuhle et al., 1993), the role of the parvocellular and magnocellular deficit in reading impairment was investigated in another study conducted by Farrag, Khedr, and Abel-Naser (2002). Fifty-two children with reading impairment and 41 controls participated in the study. All children with reading disorder were selected based on IQ and scores on Wechsler Intelligent Scale for Children-Revised and Wide Range Achievement Test. All children were in the fourth grade of elementary school. Visual stimuli consisted of black and white checkerboard patterns displayed on a screen. The participants were instructed to fix their gaze on a dot in the center of the screen. The latency and amplitude of the first positive (P100) were measured. Results showed that the latency of the VEP for high contrast and 3-Hz stimulus rate was significantly shorter than normal readers, while no significant difference was observed for amplitude. No significant difference in either latency or amplitude was observed between groups for low contrast stimuli. However, when comparing low and high contrast in the same group, the children with reading impairment showed significantly reduced amplitude under low contrast than normal readers. No significant differences in latency or amplitude were observed between the reading impaired group and normal readers under rapid and slow stimulation rates. Results from this study were in agreement with previous studies that found no magnocellular deficit in reading impaired individuals. In fact, the researchers suggested that it is the magnocellular system that is suppressed during saccadic suppression, which is, again, contradictory to the magnocellular theory. The findings indicated normal functioning of the magnocellular system, suggesting that a deficit exists in the parvocellular system (Farrag et al., 2002).

Neuroimaging studies have also been conducted to further the argument for a magnocellular deficit in reading impairment. Anatomical studies in postmortem brains have revealed abnormalities in the magnocellular layers of the lateral geniculate nucleus (Eden et al., 1996). These abnormalities include smaller and disorganized magnocellular neuron cell bodies. Behavioral and electrophysiological studies have found conflicting evidence for diminished sensitivity to rapidly changing stimuli (Farrag et al., 2002; Lehmkuhle et al., 1993, Lovegrove, 1993; Skottun, 2000). In light of these results, it is proposed that impaired activation in MT/V5 during motion perception will be seen during neuroimaging, thus adding support to the magnocellular deficit.

Eden, Van Meter, Rumsey, and Zeffiro (1996) used fMRI to study visual motion processing in men with normal reading ability and those with RD. A stimulus velocity judgment task was used to measure behavioral visual motion perception in dyslexic men. Blood-oxygenation level dependent (BOLD) contrast signals were measured while viewing one of the three stimuli. BOLD signals were compared between the two groups of men during a low-contrast coherent motion task. The results revealed difference in activation of the area MT/V5 between the individuals with normal and impaired reading ability. That is, the control group exhibited activation in the MT/V5 area, which has been reported to show particular sensitivity to coherent motion, whereas there was no activation in the men with RD. The researchers suggested that the lack of activation in this area may be due to “disrupted interaction of the motion processing areas that usually require exquisite temporal synchronization” (Eden et al., 1996, p. 114). Another interpretation is that abnormalities in the visual system may be one component of a disorder that has abnormalities from other systems associated with it. In the case of reading impairment, this interpretation suggests a global temporal deficit.

Research conducted on both auditory and visual temporal processing have revealed that individuals with reading disorder exhibit poorer performance on detection and processing speed tasks than normal readers (Hirsh, 1959; Lehmkuhle et al., 1993; Lovegrove, 1993; Phillips, 1999; Talcott et al., 2000; Talcott et al., 2002; Tallal, 1980; Walker et al., 2002). Talcott et al. (2000) found that individuals with reading disorder were less sensitive to dynamic visual stimuli, such as rapid motion changes, and that this reduced sensitivity may relate to poor integration of changes in time. Similarly, these readers performed poorer on auditory temporal order tasks, which may also reflect reduced sensitivity to changes in the temporal spectrum of the signal. Lovegrove (1993) suggested a relationship between combined deficits of both the auditory and visual systems and phonological processing abilities. That is, it may be possible that some individuals with RD have problems processing rapidly presented stimuli in several modalities (i.e. auditory and visual), reflecting a hypothesized general timing deficit associated with RD, which is further supported by Livingstone et al. (1991).

Auditory/ Visual Temporal Processing

Due to the emergence of data indicating a visual temporal processing deficit associated with reading disorder (Lehmkuhle et al. 1993; Lovegrove, 1993), a hypothesis has been formulated suggesting that individuals with reading disorder have temporal processing deficits in both the auditory and visual modalities (Ben-Artzi et al., 2005). Talcott, Gram, Ingelghem, Witton, Stein, and Toennessen (2003) conducted a study investigating dynamic visual and auditory stimuli in children who were native speakers of Norwegian. The purpose of this study was to determine if sensory temporal processing deficits were exhibited by children who speak a language with more regular orthography as compared to children who speak a language reflecting more irregular orthography, such as English. Employing an auditory frequency modulated (FM) tone task and a visual coherent motion task, the researchers found that the Norwegian children also demonstrated poor auditory and visual temporal processing based on poor performance on auditory and visual detection tasks. Since the Norwegian language has a more regular orthography, it was concluded that poor performance on dynamic auditory and visual tasks is characteristic of most disabled readers, regardless of native language.

Several studies have been conducted examining cross-modal temporal processing abilities in normal readers and those with RD (Farmer & Klein, 1993; Heim et al., 2001; Ingelghem, Wieringen, Wouters, Vandenbussche, Onghena, & Ghesquiere, 2001; Rose, Feldman, Jankowski, and Futterweit, 1999) in attempts to determine a relationship between auditory versus visual temporal processing abilities and phonological versus visual/lexical decoding (Bretherton & Holmes, 2003; Cestnick, 2001; Walker et al., 2002). However, research investigating auditory and visual temporal processing using analogous tasks to assess temporal resolution has either found evidence of a general processing deficit or found no association between visual processing and reading ability (Bretherton & Holmes, 2003; Farmer & Klein, 1993; Heim et al., 2001)

Ingelghem, et al. (2001) assessed detection abilities (lowest level of temporal processing), by means of psychophysical threshold tests for gap detection in the auditory system and for double flash detection in the visual system, in order to determine the existence of a general temporal processing deficit. Participants included 20 children age 10 years to 12 years. Ten were identified with developmental reading disorder and were age-matched to 10 participants with normal reading abilities. All participants had normal IQ and no auditory or ophthalmologic abnormalities. A gap detection task was employed to assess auditory temporal processing and a double flash detection task was employed to assess visual temporal processing. The researchers used the double flash detection task as analogous to the gap detection task due to the ability of both tasks to measure the timing mechanism of each system and the ability to determine interstimulus interval thresholds. The children were instructed to verbally report which interval, the first or second, contained the target (gap) stimulus. The threshold corresponding to 70.7% correct was recorded for both tasks. Results for the gap detection and double flash tasks indicated that the children with reading impairment had higher detection thresholds than the normal reading children, indicating slower processing speeds of rapidly presented stimuli in both the visual and auditory modalities. The researchers confirmed the hypothesis that auditory and visual temporal processing deficits may be an underlying distal cause of reading disorder. In other words, reading disorder is a symptom of global temporal processing deficits (Ben-Artzi et al., 2005). The researchers also concluded that the results supported the hypothesis of a general temporal processing deficit in dyslexic individuals (Ingelghem et al., 2001).

Rose, et al. (1999) conducted a study supporting the hypothesis of a general temporal processing deficit in individuals with RD. Ninety children, age 11 to 12 years, participated in the study and were identified with normal hearing and normal or corrected-normal vision. Forty-eight children were classified as normal readers and the remaining 33 children as poor readers. Two temporal processing tasks were administered to assess both auditory and visual processing abilities. In task one, four conditions (two intramodal and two cross modal) were employed to assess auditory and visual processing of temporal patterns. The conditions were presented as auditory-auditory, visual-visual, auditory-visual, or visual-auditory. Auditory patterns consisted of three to six tones and visual patterns consisted of three to six light flashes. The children were instructed to indicate if the patterns were same or different. For task two, the auditory and visual patterns were held constant and were brief in duration. Again, intramodal and cross-modal conditions were used. All patterns contained interstimulus pauses of 500 ms in duration and one extended pause of about 1000 ms that occurred after the first or second stimulus presentation. Children were instructed to determine if the patterns were same or different. The researchers found that poor readers performed poorer on all temporal patterns whether they were auditory or visual, suggesting that the inability to recognize temporal patterns regardless of modality was related to RD (Rose et al., 1999).

Investigating the relationship between cross-modal processing deficits and reading ability, Cestnick (2001) compared temporal processing abilities among two subgroups of reading disordered populations: phonological (poor nonlexical readers) and surface dyslexics (poor lexical readers). She showed that individuals with phonological reading disorder performed poorer on both the auditory and visual temporal processing tasks than did the individuals with surface reading disorder and that their performance were correlated with one another. Cestnick (2001) hypothesized that “simultaneous deficits to the magnocellular pathways in both visual and auditory systems could mimic the behavioral cross-modality temporal processing difficulties observed in the phonological dyslexics” (p. 324). Thus, cross-modal deficits exist in phonological reading disorder but not in surface reading disorder.

While several studies have found a relationship between auditory and visual temporal processing and phonological decoding and visual/lexical processing, few studies have examined this relationship when nonwords and irregular words were presented singly or in contiguity. Au and Lovegrove (2007) investigated auditory and visual temporal processes involved in reading irregular words and nonwords by normal readers when the words were presented in two presentation paradigms: singly and in contiguity as a series of six words. As mentioned previously throughout the literature review, it has been suggested that auditory processing is thought to be associated with phonological decoding abilities, thus affecting nonword reading ability. Likewise, it has been suggested that visual temporal processing plays a role in visual/lexical processing, thus affecting the ability to read irregular words and rapidly transition from one word to the next. For this study, the researchers also examined how well various visual processes accounted for reading of nonwords and irregular words singly and in contiguity. Seventy-nine English-speaking young adults participated in the study. The auditory and visual tasks utilized in the study included visual flicker contrast sensitivity task, a visual temporal order judgment (TOJ) task, visible persistence flicker fusion task, auditory gap detection task, and an auditory TOJ task. The reading tasks consisted of two lists of 30 irregular words each selected from Castles and Coltheart (1993) and from the National Adult Reading Test (NART) and two lists of 30 nonwords each selected from Castles and Coltheart (1993) and the *WRMT-R*. Significant correlations were found between the visual and the irregular word reading measures and between the auditory and nonword reading measures. Regression analyses also indicated that the auditory temporal processing tasks predicted nonword reading for both the single and in contiguity presentation modes. These results support that notion that different subtypes of RD exhibit selective temporal processing deficits in different modalities.

In another study investigating the hypothesis of a general temporal processing deficit, Farmer and Klein (1993) investigated whether poor performance on visual and auditory temporal tasks would be correlated with each other and with reading and phonemic awareness tasks. Twenty children identified as dyslexic, age 14 years, 20 age-matched normal readers (age 14 years), and 20 younger normal reading children, age 8.8 years, participated in the stud study. Three auditory tasks were administered: a click fusion task to measure the smallest interstimulus interval required to differentiate the clicks, a temporal order judgment task, and a tone sequence matching task. Analogous visual tasks using light flashes, two meaningless symbols, and a sequence of four light flashes were also administered. The researchers found that children with reading disorder required longer interstimulus intervals to correctly perceive and identify individual auditory clicks and were less accurate at perceiving the order of acoustic stimuli. However, the children with RD did not perform significantly poorer than normal readers on the visual flash detection task, nor were they less accurate at determining order of visual stimuli. These results indicate the presence of an auditory processing disorder, supporting Tallal’s (1980) hypothesis of an auditory processing disorder in reading disorder, but did not indicate the presence of a visual processing deficit although a trend towards impairment in the visual modality was observed. The researchers cautioned that the lack of evidence for a visual processing deficit might be due to a developmental resolution of a visual temporal processing deficit. Similarly, Heim et al. (2001) did not find evidence to support the hypothesis of a general temporal processing disorder. The results from their study revealed that while the children with reading disorder had impaired auditory processing, temporal sensitivity was enhanced rather than degraded in the visual modality, suggesting that the enhanced visual system may compensate for impaired auditory processing.

Breznitz and Misra (2003) investigated whether or not "asynchrony" in speed of processing between the visual and auditory modalities exists in reading impaired individuals. The "asynchrony phenomenon" holds that impaired synchronization between the visual and auditory modalities will inhibit automatic and fluent reading. Incoming visual information reaches the cortex at slower rates than incoming auditory information. The time for visual information to reach the cortex is approximately 70 ms post-stimulus onset whereas the time for auditory information to reach the cortex is approximately 30 ms post-stimulus onset (Breznitz & Misra, 2003). In order for successful reading to be achieved, "synchronization of information transfer must take place, and this synchronization can be achieved only if each modality is processing information at an appropriate pace" (Breznitz & Misra, 2003). Previous researchers have shown that individuals with reading impairment have prolonged temporal integration in both the auditory and visual modalities (Lehmkuhle et al., 1993; Lovegrove, 1993). The asynchrony phenomenon was compared between reading impaired and normal reading groups between and within the visual and auditory modalities, using both low-level nonlinguistic and high-level linguistic stimuli. Eighty (40 adults with reading disorder, 40 controls) male university students (age 19-25 years) participated in the study.

Behavioral baseline measures included IQ tests, decoding skills, reading comprehension, accuracy, and speed in context, word recognition skills, orthography, working memory, and rate of retrieval. Electrophysiological measures included low-level auditory and visual choice reaction time tasks in which the subjects were instructed to press a button when the target stimulus was presented. The auditory nonlinguistic stimuli consisted of target tones of 1000 Hz and nontarget tones of 2000 Hz. Auditory linguistic target stimulus was /d/ and the nontarget stimulus was /b/. Visual nonlinguistic stimuli were meaningless shapes (one horizontal line and one vertical line). Target stimulus was a shape made to look like a reversed "L" and the nontarget shape looked like a "T." Linguistic visual stimuli consisted of Hebrew letters where the target stimulus was /b/ ("bet") and the nontarget stimulus was /ch/ ("chaf"). A lexical decision task was also employed where a random series of 40 pairs of words and 40 pairs of pseudowords were presented on a computer screen. Participants were instructed to look at both items and determine if the word pairs were real words or pseudowords. Electroencephalogram (EEG) recordings were measured. Breznitz and Misra found that P200 latencies did not differ between modalities or between groups for lower level nonlinguistic and linguistic tasks. However, P300 latencies were slower for both groups when processing visual nonlinguistic and linguistic stimuli than for processing the auditory nonlinguistic and linguistic stimuli. Results also showed that speed of processing was prolonged in the group with reading disorder for the psuedoword discrimination task than for the control group. A connection was found to exist in speed of processing and accuracy: the longer the latency, the lower the accuracy. Thus, the study found an asynchrony phenomenon in adults; however, the researchers caution that it is not yet clear whether speed of processing deficits can be attributed to a more global impairment.

Laasonen, Service, and Virsu (2002) investigated crossmodal temporal processing in rapid sequential nonlinguistic stimuli in normal and reading impaired young adults. The researchers hypothesized that "accurate and fast crosstalk between visual and auditory, visual and tactile, and auditory and tactile modalities" is impaired in reading impaired individuals (p. 342). In other words, a global temporal processing deficit affecting the visual, auditory, and tactile modalities exist in the reading impaired population. Sixteen adults diagnosed with developmental reading disorder (20-36 years) and 16 age-matched controls participated in the study. The neuropsychological assessment included Wechsler Memory Scale Revised (WMS-R): associative learning, auditive discrimination, phonological synthesis, naming speed, reading speed, lexical decision, word segmentation speed, reading comprehension, letter rotation, nonword span, temporal acuity and temporal order judgment. Three crossmodal combinations were used for temporal acuity and temporal order judgment: audiotactile, visuotactile, and audiovisual. Headphones, a monitor, and tactile devise were connected to the participant. The participant was instructed to listen, watch or feel for the stimulus presentation. "Pulses" were presented in each combination either simultaneously or out of phase with each other. For the temporal order judgment, an adaptive yes/no threshold search was used to estimate stimulus onset asynchronies. The participant had to indicate which pulse came first in each combination. For the temporal acuity task, the "pulses" were presented in patterns of three and were presented either simultaneously or out of phase to one another. The participant had to determine if the pulses were the same or different.

The researchers found that individuals with reading disorder needed longer interstimulus intervals in order to correctly judge the order of events in every modality combination; however, only the audiotactile difference was statistically significant. They also found that the dyslexic readers needed longer interstimulus intervals in order to judge simultaneity/nonsimultaneity of stimulus pulses in every modality combination, although these differences were not statistically significant. The researchers concluded that both temporal order judgment and temporal acuity is impaired in dyslexic individuals as compared to normal readers across modalities (Laasonen et al., 2002).

Finally, Walker, Hall, Klein, and Phillips (2006) reported a cross-sectional study investigating performance on auditory, visual, and language tasks in 124 participants ranging in age from 7 to 45 years. Four auditory tasks, four visual tasks, and four language measures were administered and performance was analyzed to provide three lines of evidence:

> Behavioral evidence on the development of temporal processing skills that may be informative about reading performance, …evidence on the correlations between temporal processing performance and language/reading performance when age is partialled out, and … different kinds of perceptual temporal processes contributed unique variance to orthographic and phonological components of reading performance (p. 128).

The four auditory tasks administered were within- and between-channel gap paradigms, sequential overlapping temporal order judgment, and overlapping temporal order judgment. Likewise, the visual tasks administered were overlapping and sequential temporal order judgment tasks and coherent and transparent motion tasks. The language measures utilized in this study were the Token test, a phonological awareness subtest, the Olson test, and the Wide Ranging Achievement test. The researchers found that improvement on auditory and visual temporal processing tasks, with the exception of the coherent motion task, improved with age. It was also found that developmental improvement plateaus and performance becomes adult-like at around ages 9 to 12 years. They also found that language and reading development continued to improve and reach adult-like through 9-12 years, similar to that of temporal processing abilities. The researchers also found significant positive correlations between performance on temporal processing tasks and language/reading tasks. That is, the higher the score on temporal processing tasks, the better the language/reading performance. In regards to providing behavioral evidence that temporal processing abilities correlate with reading development, the researchers suggested that "perceptual development should co-occur with, or precede, language and reading development" (p. 135). Their study provided evidence of developmental improvement in both auditory and visual temporal processing skills and reading abilities at around the same age in children ages 9-12 years. Walker et al. also found that orthographic reading performance correlated more with the within-channel gap detection task, as it required the detection/identification of a single event. On the other hand, phonological reading performance correlated more with tasks requiring relative timing or temporal judgments of two separate events.

To understand how deficits in auditory temporal and visual temporal processing relate to reading disorder, it is important to understand aspects of the normal reading process. Auditory temporal processing deficits may underlie difficulties in phonological processing and subsequent reading disability whereas visual temporal processing deficits may influence reading fluency. Breakdowns in normal reading development, especially in auditory and visual perception, could be linked to more complex and global processing disorders.

Reading Disorders

Reading is a complex and interactive mode of human information processing, which involves decoding graphical stimuli and matching it to phonological, visual, and contextual information stored in the mental lexicon. Accurate decoding of auditory and visual stimuli relies on the processes of identification and discrimination. A high level of automaticity is involved in these processes in order to achieve fluency and comprehension. An individual cannot become a skilled reader "if he cannot automatize lower-order subskills or if he still requires much attentional direction to execute them accurately" (Lovett, 1984, p. 69). That is, disproportionate amounts of time required for processing may impede higher-level processes like comprehension (Catts & Kamhi, 1999; Shaywitz & Shaywitz, 2005).

Perceptual analysis of the spoken and written word, in which particular features are identified, allows access to the mental lexicon. The mental lexicon stores phonological and visual information as well as meaning and grammatical rules. Accessing the mental lexicon through reading occurs two ways: through phonological representation and through visual representation. Lexical access through the phonological route involves matching phonetic units to corresponding visual units, also known as grapheme to phoneme translation. Accessing the lexicon by analyzing the visual word form without phonological decoding, or through orthographic processing, occurs via the visual/lexical route (Brown, 1997). Individuals with reading disorder exhibit difficulty “mastering the sublexical orthographic and phonological structure of language” (Brown, 1997, p. 208).

Behavioral and neurological studies involving normal and impaired readers aid in the formulation of cognitive and neuroanatomical models of RD (Price, Winterburn, Giraud, Moore, Noppeney, 2003). A number of these studies have subtyped reading disorder into three groups, thus highlighting unique underlying deficits of reading disorder (Borsting et al., 1996; Lachmann et al., 2005). Dysphonetics are readers with deficits in phonological processing alone while dyseidetics are readers with visual processing speed deficits. Dysphonetics exhibit difficulty breaking down words into individual phonetic units. Therefore, a reader with a phonological processing deficit is unable to read unfamiliar words using the phonological approach. Dyseidetics are unable to recognize whole words and match them to information stored in the mental lexicon. In other words, these readers use phonological decoding as a primary means of reading, which slows reading rate. The third group, dysphoneidetics, exhibits deficits in both phonological processing and naming speed. With the identification of various underlying deficits in reading, two cognitive models have been developed in an attempt to understand the processes affected during reading development that lead to reading disorder: the Phonological Core Deficit (Brown, 1997; Hutzler, Ziegler, Conrad, Wimmer, & Zorzi. 2004; Lachmann et al., 2005; Shaywitz & Shaywitz, 2005; Torgeson, Wagner, & Raschotte, 1994) and the Double Deficit Hypothesis (Schatschneider, Carlson, Francis, Foorman, & Fletcher, 2002; Wolf, Bally, & Morris 1986; Wolf & Bowers, 1999). Supporters of the Phonological Core Deficit focus on phonological awareness and phonological capabilities while supporters of the Double Deficit Hypothesis separate naming speed from phonological processing and treat the two deficits as distinct and individual sources of reading disability.

Phonological Core Deficit

Based on the phonological theory of reading acquisition, words are segmented into individual phonological units, which are represented by letters in written text (Shaywitz & Shaywitz, 2005). Individuals with developmental reading disorder are unable to use the phonological structure of spoken words to make appropriate grapheme to phoneme conversions (Moisescu-Yiflach & Pratt, 2005). Research focusing on the relationship between phonological processing and reading achievement generally agree that "use of sublexical phonological units is an important stage in the normal reading development of skilled reading" (Brown, 1997, p. 208). Torgeson, Wagner, and Raschotte (1994) identified three phonological processing abilities that are positively related to reading achievement: phonological awareness, phonological memory, and the rate of access for phonological information. In learning to read, the child identifies, isolates, or blends phonemic units in words and stores that information in their long-term memory. The efficiency by which the child decodes and the rate at which he or she can access information stored in the mental lexicon influences reading ability.

Nonword reading provides a means of assessing a reader's phonological decoding ability. Because nonwords have no lexical representations, they can only be read using grapheme to phoneme translation. The reader must make a connection between unfamiliar letter sequences and words that are already stored in the mental lexicon. Difficulty with nonword reading is assumed to reflect deficient phonological representations or the inability to correctly decode letter sequences and construct new orthographic entries (Brown, 1997; Hutzler et al., 2004; Simos, Breier, Fletcher, Foorman, Bergman, Fishbeck, & Papanicolaou, 2000). Thus, readers with phonological decoding deficits are unable to accurately decode and read unfamiliar words and rely on their stronger visual/lexical processing capabilities. Research comparing nonword reading performance between normal and dyslexic readers indicates that readers with phonological processing deficits exhibit poor nonword reading skills (Brown, 1997). However, nonword reading tasks are not the only means of identifying phonological processing deficits. Assessing a reader's ability to manipulate, synthesize, and analyze phonemic units provides a means to assess phonemic awareness skills.

In a longitudinal study, Torgeson, et al. (1994) compared the development of phonological processing skills both before and after reading instruction as well as the growth rate of these skills in a two-year period and investigated relationships between phonological processing and reading. Two hundred forty-four children participated in the study and were randomly selected from various kindergarten classrooms in several elementary schools. Each of the schools from which the participants were selected had adopted a whole language approach to reading. Tests assessing five phonological abilities, serial naming (rapid naming of sequences), isolated naming (rapid naming when stimuli were presented one at a time), synthesis, analysis, and phonological memory were administered to the children in the first semester of each year of the study. For data analysis, the tasks measuring each variable were combined into a unit-weighted composite based on scores standardized with respect to kindergarten means and standard deviations. Their analyses indicated that serial naming developed the earliest of the five abilities with short-term memory developing the slowest. However, these skills remain stable during reading instruction. The researchers also found that phonological awareness was the phonological variable most strongly related to reading skill. As to whether a causal relationship exists between phonological processing abilities and subsequent reading achievement, the researchers suggested that there did, indeed, exist such a relationship when all five abilities were considered simultaneously. However, no significant causal relationship was found when examining how each of the five abilities uniquely affected reading skill individually.

In regards to reading development, cognitive psychology views the earliest stage of reading as the ability to segment words into small numbers of visual forms with the later stages involving the ability to develop appropriate spelling to sound translations (Brown, 1997). However, debate exists as to attributing reading disorder to only a phonological core deficit. Thus, research has also focused on the second of the two cognitive models, the Double Deficit Hypothesis. Proponents of this controversial model suggest that naming speed and phonological processing are two separate sources of reading disability. That is, supporters of this model assume that a visual processing component also exists in reading development.

Double Deficit Hypothesis

Current research has shifted from the perspective that automatic and fluent reading is a result of phonological processing alone and that naming speed deficits may also contribute to reading disorder (Karni, Morocz, Bitan, Shaul, Kushir, & Breznitz, 2005; Schatschneider et al., 2002; Wolf et al., 1986; Wolf & Bowers, 1999). The Double Deficit Hypothesis attempts to answer the question whether a phonological core deficit represents the processes underlying naming speed. Geshwind (1965) first hypothesized the connection between naming speed and reading achievement. Researchers operating under the Double Deficit Hypothesis have since identified four main lines of evidence supporting the naming speed hypothesis (Schatschneider et al., 2002). The first line of evidence claims that naming speed tasks predict reading performance beyond what phonological awareness skills predict. Wolf and Bowers reviewed the results of previous studies and found weak correlations between phonemic awareness and naming speed tasks. They also discovered that naming speed tasks independently contributed to "variance in word identification (accuracy and latency), orthographic skill, fluent text reading and comprehension" (Wolf and Bowers, 1999, p. 420). The second line of evidence provides support that children with both phonological and naming speed deficits had significantly lower reading abilities than children with deficits in only one area. The third line of evidence claims that phonological awareness is more closely related to pure decoding abilities and that naming speed is more closely related to fluency. That is, readers with phonological processing deficits present with no difficulty in naming speed but do have difficulty with phonological decoding, word attack, and comprehension skills while readers with naming speed deficits display greater difficulty with fluency and rapid naming, but do not exhibit significant difficulty with phonological processing skills (Wolf and Bowers, 1999). Finally, the fourth line of evidence provides support for the existence of the three subtypes of reading disorder.

In the past two decades, researchers investigating RD have focused on the relationship between naming speed and reading (Schatschneider et al., 2002; Wolf et al., 1986; Wolf & Bowers, 1999). The relationship between naming speed and reading is dependent upon "development and correspondence between lower and higher-level processes in specific tasks" (Wolf et al., 1986). The researchers found that word retrieval speed tasks provide a useful means for predicting reading rate and retrieval processing abilities in normal and impaired readers. Naming speed tasks require rapid transition from one unit to another. In other words, rapid word recognition speed strongly relates to automaticity (Lovett, 1984). Due to the implications naming speed deficits have on reading ability, more current research now focuses on whether visual processing deficits exist in dyslexic individuals (Breznitz & Myeler, 2003; Chase & Jenner, 1993; Farmer & Klein, 1993; Lehmkuhle et al., 1993). Boden and Brodeur (1999) have suggested that short temporal gaps are created by saccades during the reading process. Thus, reading requires retaining visual information from fixation to fixation.

It has been suggested that a primary deficit in auditory temporal processing exists in dyslexic readers (Bretherton & Holmes, 2003; Breznitz & Myeler, 2003; Tallal, 1980). Although the question of whether a visual temporal processing disorder affects reading ability remains controversial, psychophysical studies indicate that individuals with reading disorder perform less well on visual temporal processing tasks, specifically, flicker sensitivity and temporal order judgment (Breznitz & Meyler, 2003). Breznitz and Meyler (2003) suggested that the visual system processes information faster than the auditory system and that reading disability may depend on speed of processing deficits, which could affect the “visual/orthographic and auditory/phonological routes” (Plaza & Cohen, 2005, p. 190). In order to determine if processing strategies used by both normal and impaired readers, researchers have used a variety of neuroimaging techniques to examine neural activation patterns in both normal and dyslexic readers, including positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and magnetoencephalography (MEG). These studies have shown that activation patterns, primarily in the left hemispheric structures responsible for hearing, speech, and language may differ between normal and dyslexic readers.

Neurological Connections to Reading Disorders

Neuroimaging Studies and Reading Disorders

Various neuroimaging techniques have been utilized to identify and assess specific areas in the brain that are responsible for a variety of speech, language, and reading processes. These neuroimaging techniques include PET Scans, fMRI, and MEG. Each technique provides a different means for examining brain activity during reading and reading related tasks and has greatly contributed to the study of reading acquisition. Until recently, neuroimaging techniques were used primarily on adults to study the brain after acquired reading disorder. It was assumed that results from these studies could help researchers understand neural activation patterns during the normal reading process and apply theories regarding breakdowns in particular areas of the brain responsible for speech and language that might lead to developmental reading disorder (Price et al., 2003).

Shaywitz, et al. (2002) compared neural activity in dyslexic and normal reading children during phonological analysis tasks using fMRI techniques to determine if neuronal patterns exhibited by adults were a result of a lifetime of poor reading or if they occurred during a period of literacy acquisition. One hundred forty-four children were selected to participate in the study. Seventy children were identified as having reading disorder and 74 children were identified as normal readers. The children lay supine in the imaging system and were instructed to look at a screen placed inside the gantry. Tasks designed to activate processes in reading were shown on the screen. These tasks included identifying letters, sounding out letters, sounding out pseudowords, and sounding out and comprehending real words. The researchers found that children with reading disorder had more difficulty when engaged in tasks requiring phonological analysis but not during those tasks requiring visual perception. Imaging results also showed that these children exhibited significantly less brain activation during phonological analysis tasks in the left hemispheric regions, including inferior frontal, superior temporal, and parieto-temporal areas, as well as in right hemispheric regions, including the inferior frontal gyrus, parieto-temporal region, and in the occipito-temporal region. Since these different activation patterns existed in children, the researchers concluded that the deficits in the left hemispheric reading areas were present at birth and are not a consequence of a lifetime of poor reading.

Joseph, Noble, and Eden (2001) reviewed previous literature on neuroimaging and reading, focusing specifically on studies that used PET scans and fMRI techniques during word decoding tasks. Several areas of the brain have been associated with the reading process, including Wernicke’s and Broca’s areas, the temporoparietal cortex, the supramarginal gyrus, the angular gyrus, and portions of the frontal lobe, particularly the inferior frontal gyrus. Five components of reading have been identified and research related to each component was reviewed, suggesting some degree of connectivity between reading components. The reading components included visual word from processing, lexical orthography, lexical phonology, sublexical phonology, and semantic processing. Earlier researchers (Petersen, Fox, Snyder, & Raichle, 1990) suggested that visual word form processing, which involved the analysis of visual stimuli, occurred primarily in the left medial extrastriate cortex while more recent researchers (Price, Gorno-Tempini, Graham, Biggio, Mechelli, Patterson, & Noppeney, 2003) implied that the lingual and fusiform gyri may also be involved in visual word form analysis, thus suggesting functional connectivity with other areas during reading. In regards to lexical orthography, researchers have attempted to separate lexical orthography from lexical phonology in order to develop a better understanding of neural activation patterns for orthographic fluency. While data from these studies have implicated the left temporal, left inferior frontal, and left inferior parietal cortices, including Broca's area, activation patterns could not be attributed to orthographic processing alone because tasks used to illicit these activation patterns may have also included some degree of phonological decoding and processing. Thus, researchers examining activation patterns for lexical phonology, using tasks such as rhyme judgments and lexical decision tasks, have provided evidence of activation in the posterior superior temporal gyrus, the left insula, and the inferior frontal cortex. While there appears to be overlap in regions of the brain associated with lexical orthography and lexical phonology, research has also shown that overlap exists between lexical phonology and sublexical phonology but with a few differences (Joseph et al., 2001). As previously mentioned, lexical phonology was found to involve activation of the left insula; however, this was not the case for sublexical phonology. It was also found that while lexical phonology primarily involved activation in the superior regions of the temporal lobe, sublexical phonology involved activation in the middle temporal gyri and included the occipitotemporal junction. Finally, both lateral and medial regions of the frontal lobe tend to be more extensively involved in lexical rather than sublexical phonological processing (Joseph et al., 2001). The last component of reading reviewed included semantic processing. A review of the research indicated that tasks, such as category judgment and semantic generation, activated both various regions in the temporal and frontal cortices. In general, a review of neuroimaging studies focusing of word decoding skills across subcomponents of reading has provided evidence of left-hemispheric participation during the reading process (Joseph et al., 2001).

Review of anatomical and radiological research reveals that individuals with reading disorder exhibit different neural activation patterns in the left hemispheric planum temporale, which includes part of Wernicke's area. Generally, the left planum temporale is larger than the right planum in normal right-handed individuals and is important for language lateralization (Tervaniemi & Hugdahl, 2003). Therefore, one would expect to see asymmetrical activation between the left and right planums, with more activation occurring in the left planum. It assumed that the planum temporale is responsible for the analysis of speech information and is likely involved in early auditory processing (Tervaniemi & Hugdahl, 2003). Previous researchers investigating developmental reading disorder have found reduced activation in the left hemispheric regions and enhanced activation in the right hemisphere during performance on phonological tasks (Shaywitz et al., 2002; Simos et al., 2000).

There is a general consensus across studies that different neural patterns exist between normal and poor readers in the left and right hemispheres. Temple (2002) reviewed an fMRI study conducted by Temple, Poldrack, Salidis, Deutsch, Tallal, Merzenich, and Gabrieli (2001), which investigated whether or not the neural patterns exhibited by individuals with RD reflected a lifetime of compensation or a brain dysfunction fundamental to RD. Twenty-four dyslexic and 15 normal reading children were recruited for the study. During imaging, the children were instructed to perform a letter rhyme task. The researchers found that patterns of activation in the hemispheres for the children with RD were similar to those of dyslexic adults. That is, the children with RD showed left frontal activity but no significant activity in the left temporoparietal area.

The researchers thus suggested that the activation patterns exhibited by dyslexic individuals may indeed reflect a brain dysfunction specific to reading disorder.

Electrophysiological/Behavioral Studies and Reading Disorders

Neuroimaging studies have provided evidence suggesting that various regions of the brain are more specialized during particular reading tasks but do show overlap. In general, it is hard to isolate proximal brain regions for certain tasks due to the overlap in functional anatomy. Recent studies have begun to incorporate electrophysiological and behavioral measures to help identify the order in which areas are activated during reading and if atypical processing occurs in dyslexic individuals (Breznitz & Meyler, 2003; Georgiewa, Rzanny, Gaser, Gerhard, Vieweg, Freesmeyer, Mentzel, Kaiser, & Blanz, 2002; Heim, Eulitiz, Kaufmann, Fuchter, Pantev, Dinneson, Matulat, Scheer, Borstel, & Elbert, 2000; Lachmann et al., 2005; Simos et al., 2000; Tervaniemi & Hugdahl, 2003).

Heim, et al. (2000) investigated functional characteristics of the left hemispheric auditory cortex in dyslexic and normal children using both MEG and an electrophysiological measure (MMN). It was hypothesized that children with RD would show different organization of the left auditory cortex and would display absent MMN indicating psychoacoustic dysfunction. The hypotheses were based on evidence provided by Kraus et al. (1996) that suggested that deficits in phonemic discrimination have “origins in the auditory pathways and are pre-attentive in nature” (p. 1750). Eleven children identified as having reading disorder and 9 normal children between the ages of 8-13 years were selected to participate. An oddball paradigm using linguistic stimuli (consonant-vowel strands) was utilized to elicit neural activation. Recordings were obtained using the mismatched fields (MMF) and neuroimaging patterns were recorded from the left supratemporal cortex. MEG images showed different neural activation patterns between normal readers and children with reading disorder. That is, the children with reading impairment exhibited activation in more anterior regions of the left temporal lobe than normal readers. This finding supported the hypothesis that readers with reading disorder exhibit different organization in the left hemisphere than normal readers. When analyzing the MMF results, the researchers found that, in both the children with reading disorder and the children with normal reading ability, the M80 (positive deflection) was activated primarily in the auditory cortex. On the other hand, the M210 (negative deflection), representing a subsequent processing stage, was primarily activated in more anterior regions of the M80 as compared to the normal readers, in which M210 was activated in more posterior regions. The researchers concluded that difference did exist in organization of the left hemisphere but were not able to determine if the differences were functional or structural in nature.

Georgiewa, et al. (2002) also attempted to identify cerebral representation of phonological processing using both event related potentials (ERP) and fMRI techniques. Seventeen participants (mean age 13 years) were identified as having either normal reading ability or reading disorder and they were instructed to silently read similar linguistic stimuli during ERP and fMRI recordings. The researchers found that the fMRI revealed the greatest amount of neural activation primarily in the left inferior gyrus for normal readers. However, the dyslexic readers displayed three areas of activation: “in a cluster including the left inferior frontal gyrus, the left insula and the anterior part of the left temporal superior gyrus; in a posterior part of the left thalamus; and in part of the nucleus caudatus left" (Georgiewa et al., 2002, p. 6-7). The children with RD also showed hyperactivation in Broca's area, the anterior insula, and in the lingual gyrus. As for the event related potentials, the children with RD exhibited longer latencies than the normal reading children indicating greater difficulty with phonological processing in the group with reading impairment. The researchers suggested that hyperactivation in Broca's area in readers with reading disorder may reflect increasing effort and concentration in phonological decoding and could be attributed to difficulty in reading the stimuli.

Researchers suggest that longer latencies recorded during event related potential testing indicate slower speed of processing in individuals with reading disorder. It has been hypothesized that children with RD may have deficits at the perceptual level due to auditory processing speed impairments during reading (Breznitz & Meyler, 2003). Breznitz and Meyler (2003) investigated speed of processing in the visual, auditory, and cross-modal modalities in readers with normal reading ability and those with reading impairment. Eighty (40 normal readers and 40 readers with reading disorder) university students, age 22-25 years, were selected to participate in the study. EEG activity and event related potentials were obtained for each subject in the visual, auditory, and cross-modal conditions. The researchers found that the participants with RD were impaired as compared to normal readers when responding to low-probability stimuli. That is, individuals with reading impairment when processing low-probability targets for visual only, auditory only, and between modalities exhibited slower speed of processing. When analyzing single modality data, the researchers found that normal readers processed nonlinguistic stimuli in the left hemisphere whereas the individuals with RD processed the nonlinguistic stimuli in the right hemisphere. Breznitz and Meyer (2003) suggested that these individuals are predisposed to process in the right hemisphere due to deficits in the left hemisphere.

Bellis, Billiet, and Ross (2008) cited previous literature supporting the strong role of the left hemisphere in processing both auditory and visual stimuli due to the occurrence of right-ear advantage (REA) when disparate signals are presented to each ear simultaneously and a right-visual-field advantage (RVFA) when visuals tasks involved half-field presentation. It has been suggested that comparing auditory and visual analogs may be useful in determining if the mechanisms involved in temporal processing are similar or independent of one another. However, there is little research investigating the clinical utility of visual analogs in an auditory processing test battery for the differential diagnosis of CAPD. In two separate experiments, Bellis et al. (2008) explored maturational effects of visual processing and examined the validity of a dichotic listening task commonly used in clinical to assess central auditory processing disorders (CAPD) and a corresponding visual analog in normal adults and children and in children diagnosed with CAPD, with a specific deficit in interhemispheric transfer.

For the first experiment, Bellis et al. (2008) examined maturational effects of visual processing. Ten adults and ten children were recruited to participate. All participants had normal hearing, normal to corrected-normal vision, and had normal auditory processing abilities. The auditory task chosen for the study was the Dichotic

Digits Test (Musiek, 1983) because of its sensitivity to disruptions of the cerebellum and interhemispheric pathways. The visual analog consisted of the same digit pairs as the auditory paradigm, with the exception of the number “10” being substituted for the number “1.” This was due to the fact that “10” could be misconstrued as two separate numbers (i.e. “1” and “0”) or that the number “0” could be misinterpreted as a capital letter “O.” The visual analog was created using SuperLab Pro Experimental Laboratory Software version 2.0 (Cedrus Corporation, 1999). All visual stimuli were presented on a computer monitor with digits being presented in each visual half-field simultaneously for the duration of 200 ms. The second pair of digits were presented for 200 ms after a 100 ms ISI. Participants were required to freely recall all four digits presented for both modalities. A percent correct scoring method was used to determine performance on both the auditory and visual tasks. Results indicated greater asymmetries in REA and left-visual-field advantage (LFVA) in children as compared to adults. While ceiling effects were seen in the auditory task in adults, ceiling effects were not observed in the visual task. Given that visual half-field asymmetries were more pronounced in children than adults, it was suggested that both hemispheres equally process visual stimuli and represent them in visual form by adulthood.

To determine clinical utility of visual analogs in the differential diagnosis of CAPD, Bellis et al. (2008) also compared performance on the auditory and visual dichotic digits task between the same ten children from the first experiment to seven children diagnosed with CAPD, presumed to have a primary deficit in interhemispheric transfer. Test materials and procedures were the same as those used in the first experiment. Results revealed that children with CAPD exhibited significantly larger REA and a reversed pattern of asymmetry for the visual analog. In other words, children with CAPD demonstrated a RVFA as compared to an LFVA found in normal children. It was then concluded that deficits in interhemispheric transfer may significantly degrade visual information as it travels from the right hemisphere to the left for verbal report, thus resulting in a large RVFA in children diagnosed with CAPD. The results of the study suggested there is some degree of validity to using visual analogs in a CAPD test battery; however further exploration is necessary to determine if the use of visual analogs significantly adds to the differential diagnosis of CAPD from more global pansensory disorder.

Two theories have also been postulated regarding interhemispheric transfer functions in children with RD. The first theory predicts that the time associated with the exchange of information between the hemispheres may be too short for reading-disordered children. The second theory suggests, "an interhemispheric signal degrading may interfere with efficient, right-to-left hemisphere processing of visual information in reading-disordered children" (Walker, Spires, & Rastatter, 2001, p. 275). That is, children with RD required longer stimulus-duration thresholds to achieve the same accuracy rate as normal readers. Researchers have also provided evidence distinguishing right versus left hemisphere superiority for processing visual information. Previous researchers have reported anomalies in the "cerebral organization for linguistic information in reading-disordered adults may be influential in RD" (Walker et al., 2001, p. 274). For example, Walker et al. sited a research study by Olsen (1973) that found that normal readers had a right visual-field advantage whereas individuals with reading impairment did not have that superiority. In another study, Herman, Sonnabend, & Zeevi (1986) found that the lack of laterality or functional asymmetry for readers identified as dyslexic is consistent with the idea reading impairment may be a result of incomplete hemispheric dominance. In a normative study completed by Rastatter, Dell, McGuire, and Loren (1987), it was found that right visual-field stimulation yielded faster reaction times for abstract words while the opposite was true for the left visual-field (concrete words yielded faster reaction times).

Walker, et al. (2001) investigated interhemispheric interactions for visual language processing in normal and reading-impaired adults by analyzing vocal reaction times in a lexical decision task to tachistoscopically concrete and abstract word stimuli presented on a computer monitor. The authors suggested that word recognition would not occur in the reading-disabled population without interhemispheric transfer, which would allow for the interaction of both phonological and orthographic decoding. In other words, if a breakdown exists in visual analysis for sight-word reading, the individuals with RD would rely heavily on phonological decoding for the lexical decision task, which is represented through right or left hemisphere activation. This would, in turn, lead to prolonged reaction times and a greater number of errors. Walker et al. found that the right hemisphere did not perform lexical decisions predominantly over the left hemisphere for the individuals with RD. They, therefore, suggested that an underdeveloped lexical processing system was present in the participants with reading impairment, which may be assessed through lexical decision paradigms. Therefore, Walker et al. support the notion that adults with RD use different processing strategies for lexical decisions.

Neuroimaging and event related potential studies provide evidence for a neurological basis for phonological processing and speed of processing deficits as exhibited by readers with reading disorder (Breznitz & Myeler, 2003; Georgiewa et al., 2002; Heim et al., 2000; Joseph et al., 2001; Lachmann et al., 2005; Shaywitz et al., 2002; Simos et al., 2000; Tervaniemi & Hughdahl, 2003). Abnormal neural activation patterns during phonological decoding and processing tasks indicate that the temporal and frontal lobes of the left hemisphere, including the left planum temporale, are primarily affected in individuals with reading impairment and that these patterns are exhibited in childhood. Overactivation in Broca's area and activation in the right hemisphere may serve as a compensatory strategy but it has not been established that this activation pattern will enable a reader with reading disorder to become more automatic. Heim et al. (2001) hypothesized whether poor auditory processing abilities may be compensated for by an enhanced visual sensory modality. Their hypothesis was based on the research conducted by Talcott et al. (2000), which found that auditory and visual temporal processing abilities were independently engaged during phonological processing. However, based on results from numerous neuroanatomical and behavioral studies on visual temporal processing, it is still unclear as to whether individuals with reading disorder have a deficit in visual temporal processing. Further research is necessary to determine whether a pansensory temporal processing deficit exits in individuals with reading disorder.

Summary and Rationale

At present, several researchers have been able to replicate findings that auditory temporal processing deficits are associated with reading disability (Farmer & Klein, 1993; Ingelghem et al., 2001; Tallal, 1980; Wright et al., 1997). That is, the inability to detect changes in acoustic stimuli (i.e. frequency and duration modulation) may result in poor reading ability. However, over the past ten years, research has focused on the existence of a general temporal processing deficit and its relationship to phonological and visual/lexical processing (Chase & Jenner, 1993; Farmer & Klein, 1993; Lehmkuhle et al., 1993; Lovegrove, 1993). Temporal processing deficits in the auditory and visual systems may lead to breakdowns in basic decoding or in the ability to rapidly transition from word to word in written text thereby affecting automatic and fluent reading. Several models of reading disorder that associate the disorder with the central nervous system include: "(1) low-level visual processing difficulties due to selective impairment in magnocellular layers of the lateral geniculate nucleus, (2) a general auditory processing deficit, specifically in temporal coding or rapid auditory changes, and (3) speech sound processing problems arising from poor phonological awareness" (Heim et al., 2000, p. 1749). Methodologies used to assess visual temporal processing have included flicker fusion tasks, visual temporal order tasks, and color fusion tasks. Conflicting results from research assessing visual temporal processing abilities have resulted in an ongoing debate regarding the existence of a pansensory temporal processing deficit. It remains unclear as to what extent auditory and visual processing deficits play in reading disability and if their relationship to reading impairment is directly causative or indirectly correlated.

The conflicting evidence for the existence of a pansensory temporal processing deficit may be due in part to the hierarchy of tasks utilized during the experiments, how RD were defined and if individuals identified as dyslexic were grouped based on their particular deficit(s), and whether the auditory and visual tasks were analogous to each other. That is, uncertainty remains concerning whether or not the auditory and visual tasks assessed similar hierarchical processing abilities. A majority of the researchers in the studies reviewed above did not further subcategorize individuals with reading disorder as either having phonological deficits or visual/lexical deficits, but rather categorized these individuals under one broad definition. This may account for discrepancies observed when attempting to determine if auditory and visual temporal processing deficits were exhibited by reading disabled individuals. Not all individuals with reading disorder are alike. Some individuals may only exhibit deficits in either phonological processing or visual/lexical processing while others may exhibit deficits in both. In other words, deficits in phonological processing or visual/lexical processing manifest themselves in a variety of patterns, including the inability to read unfamiliar words, the inability to achieve automatic and fluent reading, or a combination of both. Numerous visual stimuli have been utilized to determine the existence of visual processing deficits, including light flashes, different shapes and sizes of symbols, and grades of color. The use of varying visual stimuli demonstrates the need to identify analogous stimuli for the auditory and visual modalities. However, it must be recognized that it is difficult to design a task that may identify the aspects of temporal processing that contribute to poor reading (Cestnick, 2001).

One way to further research the existence of a global temporal processing disorder is to investigate auditory and visual processing hierarchies through a variety of analogous tasks, such as detection, discrimination, and temporal order judgment and to attempt to find a relationship between performances on these tasks to the two groups of RD: phonological disorders and visual/lexical disorders. Therefore, this study will seek to determine if a relationship exists between auditory and visual temporal processing skills and RD, primarily in decoding and sight-word reading skills.

Plan of Study and Experimental Questions

In this study the relationship between auditory and visual temporal processing abilities in reading disorders in school-aged children was investigated. The investigation sought to determine if an association exists between reading disability and impairment in the visual and auditory sensory receptors or if it is interactive with these systems. Participants included children between the ages of 10 to 13 years who were identified as either having normal reading ability or reading disorders based on a series of pre-experimental tasks. The following experimental questions were divided into two sections.

Auditory

1. Is there a difference in performance between children with normal reading ability and those children with reading disorders (dysphonetic and dysphoneidetic) in an auditory detection task as measured by temporal thresholds (ms) in within- and between-channel gap detection paradigms?

2. Is there a difference between children with normal reading ability and those children with reading disorders (dysphonetic and dysphoneidetic) in an auditory temporal processing task involving duration discrimination abilities?
3. Is there a difference between children with normal reading ability and those children with reading disorders (dysphonetic and dysphoneidetic) in an auditory temporal patterning task involving temporal order accuracy?

Visual

1. Is there a difference in performance between children with normal reading ability and those children with reading disorders (dysphonetic and dysphoneidetic) in a visual detection task as measured by temporal thresholds in critical flicker fusion?
2. Is there a difference between children with normal reading ability and those children with reading disorders (dysphonetic and dysphoneidetic) in a visual temporal processing task involving duration discrimination abilities?
3. Is there a difference between children with normal reading ability and those children with of reading disorders (dysphonetic and dysphoneidetic) in a visual temporal patterning task involving temporal order accuracy?

CHAPTER II

METHODS

Participants

Participants included 27 school-aged children between 10 and 13 years of age. Participants were separated into two experimental groups, control and RD, based on performance on a series of standardized reading and language tests during the pre-experimental session of the study. All participants were recruited from the research participant pool at the East Carolina University Speech, Language, and Hearing Clinic or from ads placed in local tutoring centers and newspapers (Appendix A). All participants had English as their native language and had negative histories of neurological disorders, head trauma or surgery, active otologic disorder, dizziness, or emotional/behavioral disorders. Children diagnosed with attention deficit disorder/attention deficit hyperactivity disorder were permitted to participate in the study but were required to take their medication prior to participating in all sessions of the study. All children were from Greenville, North Carolina or surrounding counties. Table 1 provides mean age for each group.

Prior to testing, all participants were screened for normal hearing sensitivity as defined by pure tone thresholds screened at 20 dB HL at octave frequencies 500 to 4000 Hz. Middle ear function was also screened via tympanometry and normal middle ear function was defined as peak compensated static admittance < 0.4 mmho and a tympanometric width of > 200 daPa (Nozza, Bluestone, Kardatzke, & Bachmann, 1994). In addition, all participants were screened for normal or corrected normal visual acuity as

Table 1:

Means and Standard Deviations (SDs) of Age for the Control and Reading Disorder Groups.

Group	N	Mean Age (Yrs)	SD
Control	12	11.8	.94
RD	15	11.9	1.20
Total	27		

measured by a Keystone Telebinocular system. From the 27 participants who completed the study, three participants wore eyeglasses and had corrected normal vision. Normal visual acuity was defined as 20/40 or better and was assessed using the Visual Skills Assessment test card kit.

Each participant and their parent/guardian gave informed consent and minor assent using approved forms [including Health Insurance Portability and Accountability (HIPPA) consent] that were orally reviewed by the examiner and then signed. These forms are presented in Appendix B.

Pre-experimental testing was conducted to aid in identifying the control and the RD groups. Pre-experimental tests included the *Word/Nonword Test*, 1994 (Coltheart and Leahy, 1996), the Word Identification and Word Attack subtests of the Woodcock Reading Mastery Test – Revised (*WRMT-R*, form H), the Peabody Picture Vocabulary Test – IV (*PPVT-IVT*, form B), and the Raven's Coloured Progressive Matrices. Normal readers were defined as having average scores based on age norms on the *Word/Nonword Test* and standard scores of $\geq$ 85 on both subtests of the *WRMT-R*. The RD groups (dysphonetic and dysphoneidetic) were defined as having below average performance based on age norms taken from Edwards and Hogben (1999) on one or more of the reading lists (i.e. regular word, exception word, nonword) on the *Word/Nonword Test* and a standard score of $\leq$ 84 on at least one subtest of the *WRMT-R*. Specifically, the two groups of RD (dysphonetic and dysphoneidetic) were further determined as follows. Children were assigned to the dysphonetic (phonological decoding deficit) group if a below average standard score on the Word Attack subtest of the *WRMT-R* ($\leq$ 84) or a score falling below age-based norms for the nonword list on the *Word/Nonword Test* was obtained. Children were assigned to the dysphoneidetic (mixed deficits) group if a standard score of ≤ 84 was obtained on both subtests of the *WRMT-R* and a below average score was obtained on both the irregular word or nonword lists for the *Word/Nonword Test*. All participants, regardless of group assignment, obtained average standard (≥ 85) scores on the *PPVT-IVT* and at least an average intellectual rating on the Raven's Coloured Progressive Matrices. Participants who had undergone a comprehensive diagnostic language and reading evaluation at the East Carolina University Speech-Language-Hearing Clinic were exempted from pre-experimental testing and were grouped according to their official diagnosis.

Materials and Stimuli

Auditory Gap Detection Task

Both a within-channel gap paradigm and a between-channel gap paradigm were utilized for the gap detection task. For the within-channel paradigm, the leading marker was a short 10 ms, narrowband noise burst centered at 1000 Hz. The trailing marker was a 300 ms narrowband noise burst centered around 1000 Hz. In the between-channel gap paradigm, which was used for this study due to the fact that this paradigm more closely resembles voice onset time in spoken language, the leading marker was a short 10 ms, wideband noise burst, bandpassed from 10 Hz to 20,000 Hz with a rise/fall time of 1 ms. The trailing marker was a 300 ms, half octave narrowband noise with a rise/fall time of 10 ms, and filter roll-off of 48 dB/octave. The center frequency of the trailing marker was 4000 Hz. The intertrial interval for both paradigms was determined based on participants' reaction time to the preceding trial and followed 300 ms after a response on the response pad.

Each stimulus trial had three sequences (two control and one target) with an inter-sequence interval of 500 ms. The control sequences had a leading and trailing marker separated by an inaudible gap of 1.0 ms. The target sequence had the leading and trailing markers separated by a gap varied by an adaptive tracking procedure; specifically, a two-down, one-up procedure to obtain 70.7% threshold on a psychometric function (Levitt, 1971).

Auditory Duration Discrimination Task

Similar to a study conducted by Walker (2005), test stimuli of 75 ms 1000 Hz tones were generated using the same apparatus and software program used for creating the gap detection tasks described above. Each trial sequence contained three 1000 Hz tones with two standard tones 75 ms in duration and one target tone of 50 ms in duration. Interstimulus intervals were set at 400 ms and intertrial intervals were set at 500 ms. The target stimulus length varied by an adaptive tracking procedure (two-down, one-up procedure) and a mean threshold was calculated.

Auditory Duration Pattern Judgment Task

The test stimuli for the duration pattern test consisted of the Auditec Duration Pattern Test traditionally used in clinical settings. This test consisted of 30 sequences, with each sequence consisting of three 1000 Hz tone patterns, with silent inter-tone intervals of 300 ms. The tones were either short (250 ms) or long (500 ms) with 10 ms rise/fall times and shaped with a cosine-squared function. The inter-pattern interval was

6 seconds. There were six possible pattern combinations of the three tones: short, short, long; short, long, short; short, long, long; long, short, short; long, short, long; long, long, short.

Visual Critical Flicker Fusion Task

In order to assess gap detection abilities of the visual system, a flicker fusion task was employed. A Lafayette Instrument 12021 Flicker Fusion system was used to measure the flicker fusion thresholds of each participant. This test was designed to detect the critical flicker fusion threshold (CFF). The CFF threshold was measured when a beam of light was interrupted intermittently causing the light to either flash or flicker. If the flicker rate exceeded a certain point, the light appeared to remain steady. This was termed fusion threshold. On the other hand, the point at which the steady light appeared to change and flicker was termed the flicker threshold. Critical flicker fusion was calculated as the average of the flicker and fusion thresholds.

Visual Duration Discrimination Task

It has been found that speed of processing for visual stimuli is slower than for auditory stimuli. In fact, visual information reaches the visual cortex approximately 70 ms post stimulus onset (Breznitz and Misra, 2003). Therefore, visual stimuli were longer in duration than the auditory stimuli given the nature of slower visual processing. Stimulus sequences consisted of a nonlinguistic symbol (*) presented discreetly one right after another on a computer screen with a duration of either 300 ms (short) or 600 ms. (long). A black (*) stimulus was presented on a white screen. The size of the (*) was set to size 72 font for easy visibility. All presentations were presented in the center of the screen and were viewed binocularly.

Visual Duration Pattern Judgment Task

One duration pattern test was created for temporal order judgment. The test stimuli for the duration pattern test consisted of 30 sequences with each sequence containing three flashes of a black (*) on a white computer screen. The (*) was in size 72 font for easy visibility. Durations of the (*) were either 300 ms (short) or 600 ms (long) with interstimulus intervals of 1000 ms. Intertrial intervals were 6000 ms. All presentations were presented in the center of the screen and were viewed binocularly.

Instrumentation

Auditory Gap Detection Task

The stimuli and apparatus for the auditory gap detection tasks were similar to those used by Elangovan (2005). All noise stimuli was generated by a Dell Optiplex GX1 computer (Pentium II, 400 MHz, 512 MB RAM, operating on a Windows 95 operating system) and a digital to analog converter (D/A) (Tucker Davis Technologies, TDT, model DD1) with a 32-bit resolution and a sampling period of 20 μs. A signal processing card (AP2 array processor, TDT systems II) communicated with the D/A system via optical interface. The stimuli were generated using the SigGen 32 (version 3.1) software of the TDT (TDT system II) and were low pass filtered (TDT, model FT6-2) to prevent aliasing, were attenuated (TDT, model PA4), and then power amplified (TDT, model HB6) before being presented binaurally to the participants through EAR-3A insert earphones. Participants were given a response box controlled by a 25 pin connection to one of the real-time processors. All stimuli were calibrated to reach an overall level of 70 dB pSPL.

Auditory Duration Discrimination Task

Test stimuli for the duration discrimination task were generated using the same TDT apparatus and software program (SigGen) used for creating the gap detection tasks above. All generated stimuli were filtered (TDT Model FT6-2) to prevent aliasing, were attenuated (TDT Model PA-4), digitally filtered (TDT Model PF1), and power amplified (TDT Model HB6) before being presented binaurally through EAR-3A insert earphones at a level of 70 dB pSPL.

Auditory Duration Pattern Judgment Task

The Auditec Duration Pattern Test was presented via a compact disc player and routed through a GSI 61 audiometer. All presentations were presented through both channels on the audiometer. All stimuli were presented binaurally through EAR-3A insert earphones at 60 dB HL.

Visual Critical Flicker Fusion Task

The Lafayette Instrument 12021 Flicker Fusion system uses digital circuitry to provide electrical frequency generation ranging from 1.0 Hz to 100.0 Hz in 0.1 Hz steps. The viewing chamber contained two lights, one for the left eye and one for the right eye. The inside of the viewing chamber was a dull black to minimize reflection and the stimulus color was white, which was presented at 100% luminance. The typical maximum luminance level was 58 Cd/m^2. All stimuli were presented and viewed binocularly.

Visual Duration Discrimination Task

All visual stimuli were generated using a Dell XPS laptop computer and SuperLab (Cedrus Corporation, version 4.1.3) software. Trials consisted of 3 stimulus sequences, two standards and one target. Participants indicated the target stimulus by pressing the appropriate key on a computer keyboard.

Visual Duration Pattern Judgment Task

The same apparatus and software program used to generate the stimuli for the duration discrimination task was also used to create the stimuli for the duration pattern test [Dell XPS laptop computer using SuperLab software (Cedrus Corporation, version 4.1.3)]. Participants indicated the correct pattern by pressing the appropriate key on a computer keyboard.

Calibration and Fast Fourier Transforms

All auditory stimuli used for the gap detection and discrimination tasks were calibrated to 70 dB SPL using a Bruël and Kjær precision sound level meter (Model 2231) with an octave band filter (Model 1625) and a Bruel and Kjaer pressure microphone (Model 4144). The signals were routed from the TDT system to insert earphones, which were connected to the sound level meter via a 2 cm^3 coupler. In the case of the Duration Pattern test, signals were routed from a compact disc player, audiometer, and insert earphones to the sound level meter.

Fast Fourier Transforms (FFTs) were obtained using SpectraPro (SOFTEST Version 3.32.17) software package. Prior to FFT analysis, signals were recorded using Cool Edit 96 software, which were then saved in a .wav format. The .wav files were imported into SpectraPro where the FFTs were carried out. The sampling rate for all stimuli was 44,100 Hz. For the gap stimuli, FFT size was 4096, which generated an effective resolution of 10.77 Hz. Sampling was obtained from 22 to 10030 with a Hanning window. The FFT size for the tonal stimuli was 1024 Hz with a decimation ratio of 3. Results of the FFTs for all stimuli were saved in an Excel workbook and exported to Cricket Graph III (Version 1.5.3) for display. Figure 1 and Figure 2 displays the FFTs for the gap and tonal stimuli, respectively.

General Procedures

A double walled sound attenuated audiometric booth, meeting standards for permissible ambient noise (American National Standards Institute, 1999), served as the test environments for all auditory testing. The visual experiments were conducted in a research lab room, which contained a table with the laptop used to present the visual stimuli. The order of presentation for all experimental tasks was randomized between all participants. All testing, including pre-experimental and experimental testing, lasted approximately 3 hours and was conducted over a two-day period. Participants were given a 10 minute break between experimental tasks to reduce the occurrence of fatigue and inattention during testing.

Auditory Gap Detection Task

Similar to the study conducted Elangovan (2005), gap detection thresholds were estimated using a three-interval, forced choice method for both paradigms. The three-interval, forced-choice method was the preferred procedure of choice due to the reasoning that listeners are able to understand the stimulus parameters under investigation

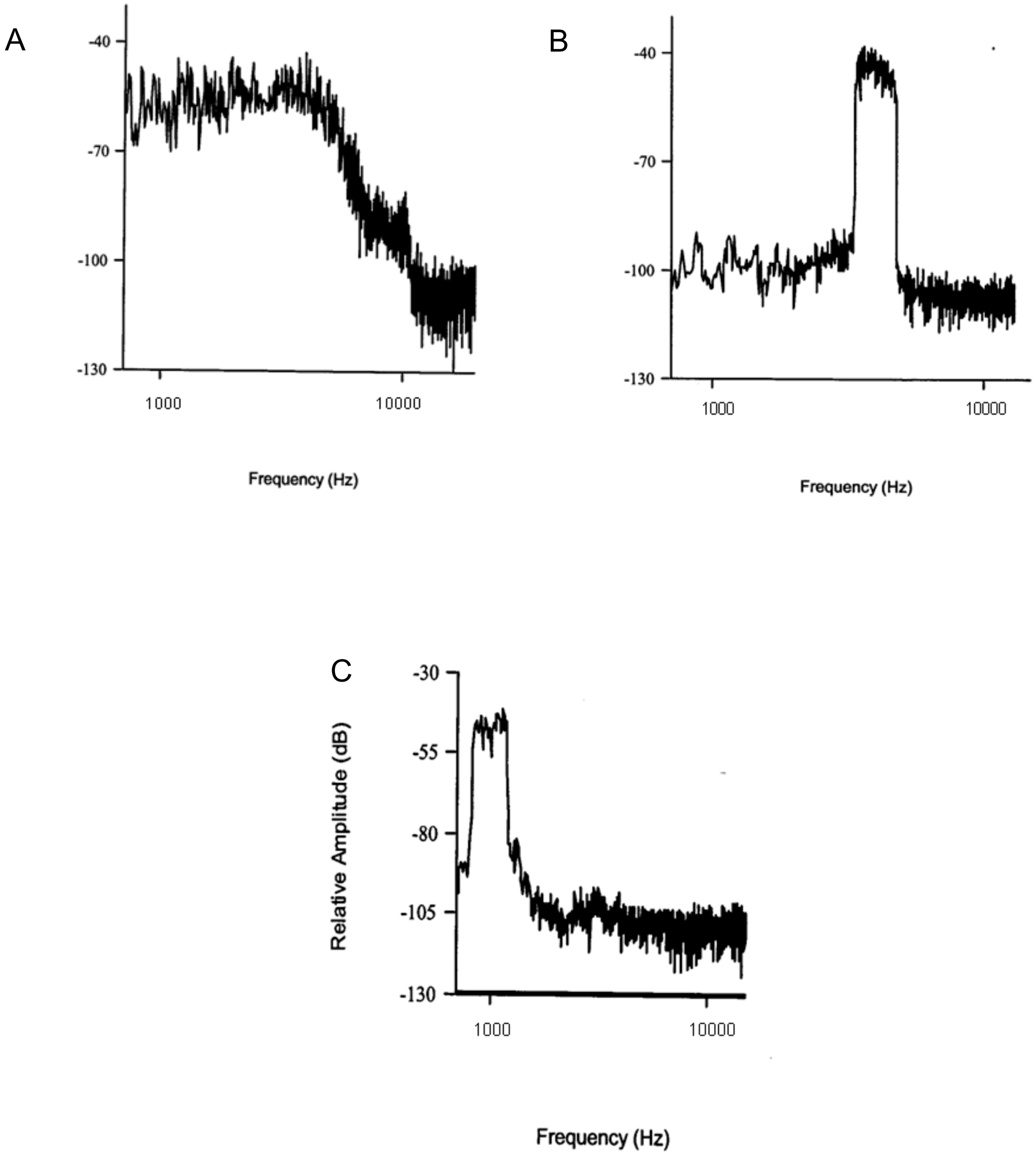

Figure 1: FFT analysis for the between channel (A) leading marker and (B) trailing marker and (C) of the within channel marker for the Auditory Gap Detection Task.

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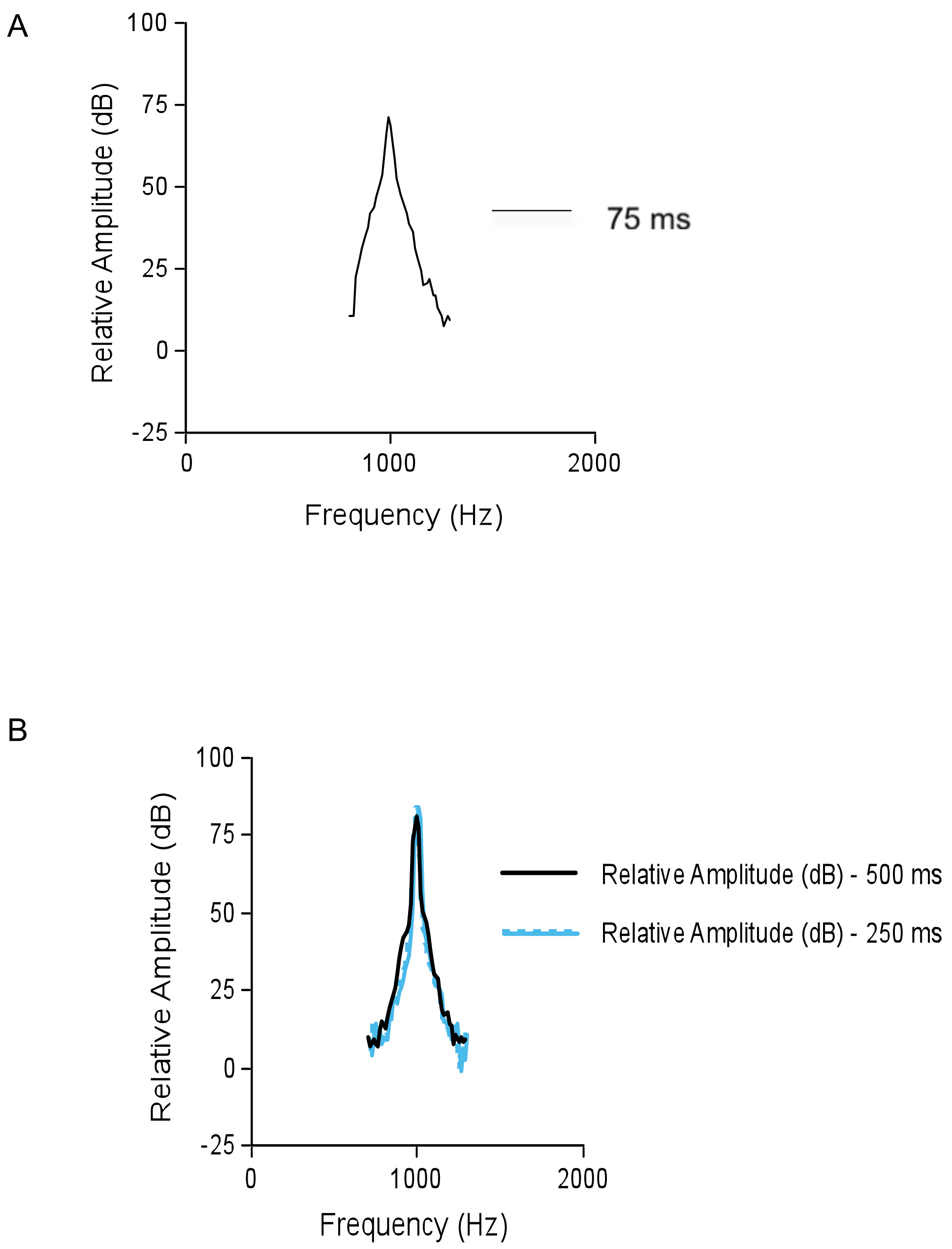

Figure 2: FFT analysis for the (A) 1000 Hz tone used in the Auditory Duration Discrimination Task and (B) tokens from the Auditory Duration Pattern Test.

without detailed explanation or reinstruction once the task is underway or when one task is substituted for another (Tyler, Summerfield, Wood, & Fernandes, 1982). The participants were instructed to indicate which stimulus sequence contained the longer gap. The response method consisted of the participant pressing a button on a response pad. The PsychoSig (Version 3.11, TDT System II) software controlled stimulus presentation and the order of stimulus presentation for each stimulus trial was randomized. The inter-trial interval was determined by the participant's reaction time to the preceding trial and followed 300 ms after the response on the response pad. Initially, the gap duration was long to aid in familiarity of the task. Gap duration was increased after incorrect responses and decreased for every two successive correct responses. The two-down, one-up procedure was used to measure the 70.7% point on the psychometric function (Levit, 1971). Prior to testing, a 10-item practice test was administered using a 20 ms gap to ensure that the participants understood the task requirements and were able to achieve at least 90% correct. For the experimental test, the initial step size for the gap detection was 20 ms and was then decreased to 5 ms after three reversals. Test trials continued until 30 total trials or 8 reversals were obtained and gap detection threshold was stable and desirable (i.e. lower than the initial gap duration). The mean gap duration threshold was calculated as the arithmetic mean of the duration of the gap obtained from the last 4 reversals for both paradigms (Hall & Grose, 1994).

Auditory Duration Discrimination Task

Discrimination thresholds were estimated using three-interval, forced choice procedure. Prior to testing, a 10-item practice test was administered with a standard tone of 75 ms and a target tone of 50 ms. A correct score of at least 90% was obtained from each participant to ensure task familiarity and ability to complete the task without difficulty. For the experimental test condition, the initial duration of the target was long so as to aid in familiarity of the task. A two-down, one-up stepwise tracking procedure was implemented to measure the 70.7% point on the psychometric function (Levit, 1971). The participants were instructed to indicate (push button on response pad) which stimulus was different in the sequence of three tones. The inter-trial interval was determined by the participant's reaction time to the preceding trial and followed 300 ms after the response on the response pad. Based on Elfenbein, Small and Davis (1993), the initial step size of the target was 40 ms but was then reduced to 10 ms after the second reversal. Test trials continued until 30 total trials or 8 reversals were obtained and discrimination thresholds were stable and desirable (i.e. lower than the initial target duration). The mean discrimination threshold was calculated as the arithmetic mean of the thresholds obtained from the last 4 reversals for both paradigms.

Auditory Duration Pattern Judgment Task

The Auditory Duration Pattern test was presented in a sound attenuated booth. Prior to testing a 10-item practice test was administered and a score of at least 90% was obtained to ensure that participants understood task directions and performed the task without difficulty. A stimulus pattern of three tones was presented with two tones of the same duration and one tone of a different duration. Participants were instructed to point to the correct pattern represented on paper (Appendix C). The examiner marked correct answers on the score sheet and calculated percent correct score.

Visual Critical Flicker Fusion Task

Flicker fusion thresholds were estimated using one of the three automatic protocols: the adaptive tracking procedure. The participants were instructed to indicate, by push of a button, when the light seemed to flicker or remain steady. Software controlled stimulus presentation and depending on the participant's response, the next frequency displayed was either at a higher or lower frequency. To determine CFF, the software limited frequency steps from +/- 10 Hz after the first reversal to +/- 2.5, 1.2, 0.6, 0.3, and 0.1 from the second to the sixth reversal, respectively. The test was stopped after the sixth reversal. The CFF was considered the stopping frequency after the sixth reversal had been reached. Similar to the auditory gap detection task, participants underwent three trials and the mean flicker fusion threshold was obtained. Prior to testing, thorough instructions were given to the participants to ensure that task requirements were understood.

Visual Duration Discrimination Task

Participants were seated 18 inches from the computer screen and were instructed to indicate (push button on response pad) which stimulus was different in the sequence. The "long" and "short" categorizations were explained to the participants prior to testing. If the "different '*'" stimulus occurred first, then the participant was instructed to press number "1" on the keyboard. If the "different '*'" stimulus appeared second in the sequence of three flashes, then the participant was instructed to press number "2" and so on. Interstimulus intervals were 1000 ms and inter-trial intervals were 6000 ms. The initial duration of the target was long so as to aid in familiarity of the task. The initial step size of the target was 50 ms but will be reduced to 25 ms after the third reversal. Prior to testing a 10-item practice test was administered and a score of at least 90% was obtained to ensure task familiarity and ability to perform the task without difficulty. When participants reached 90% accuracy, testing began. Due to the inability of the software to stop automatically after 8 reversals, thirty test trials were administered. The mean discrimination threshold was obtained from the last 4 reversals. All presentations were presented in the center of the screen and were viewed binocularly.

Visual Duration Pattern Judgment Task

Participants were seated 18 inches from a computer screen. The duration pattern sequences were presented in a randomized order. A stimulus pattern of three (*) flashes were presented with two duration of equal length and one duration of a different length. As with the auditory duration pattern test, there were six possible patterns: long, long, short; short, long, long; long, short, short; short, short, long; long, short, long; and short, long, short. Participants were instructed to press the appropriate button on a computer keyboard corresponding to the correct pattern observed. Placed in front of the participants was a laminated paper indicating the six possible patterns and their corresponding key on the keyboard. For example, if the participant observed “short-short-long” on the screen, he or she was instructed to press number “2” on the keyboard. A percent correct score was calculated once the test was completed. Prior to testing a 10-item practice test was administered and a score of at least 90% was obtained to ensure task familiarity and ability to perform the task without difficulty. When participants reached 90% accuracy, testing began.

Statistical Methods

SPSS (Version 15.0) was used as the statistical analysis tool for all data collected from the study. Descriptive analysis of the data was done to examine the mean and standard deviations of scores obtained on all experimental tasks between groups (control, dysphonetic, and dysphoneidetic). Percent correct scores on the temporal order task were also converted to proportional values and submitted to an arcsine transformation. For all data, if a significant main effect of group was observed, then appropriate post-hoc comparisons were conducted. Specifically, a two orthoginal single-*df* comparison was carried out to determine the source of the main effect and to answer the question, "is there a difference in performance one task as a function of group (control, dysphonetic, and dysphoneidetic)?"

To answer the question of whether there was an effect of group and paradigm on gap threshold, a 2-factor mixed analysis of covariance (ANCOVA) was utilized. The independent variables included group (control, dysphonetic, dysphoneidetic) and gap paradigm (within- and between-channel). The dependent variable was threshold (ms).

For the auditory duration discrimination task, a one-way ANCOVA was utilized. The independent variable for this analysis was group (control, dysphonetic, dysphoneidetic) and the dependent variable was threshold (ms).

For the auditory duration pattern judgment task, a one-way ANCOVA was utilized. The independent variable for this analysis was group (control, dysphonetic, dysphoneidetic) and the dependent variable was percent accuracy. The percent accuracy scores were transformed to rationalized arcsine units for inferential analysis.

A one-way ANCOVA was also utilized for the visual critical flicker fusion task. The independent variable for this analysis was group (control, dysphonetic, dysphoneidetic) and the dependent variable was threshold (Hz).

A one-way ANCOVA was utilized for the visual duration discrimination task. The independent variable for this analysis was group (control, dysphonetic, dysphoneidetic) and the dependent variable was threshold (ms).

For the visual duration pattern judgment task, a one-way ANCOVA was utilized. The independent variable for this analysis was control (control, dysphonetic, dysphoneidetic) and the dependent variable was percent accuracy. The percent accuracy scores underwent an arcsine transformation to convert the percents to proportional values for analysis.

Since it was found that the control group and the dysphonetic and dysphoneidetic groups combined had significantly lower mean language standard scores (SS = 102.60) on the *PPVT-IVT* as compared to mean language standard scores of the control group (SS=115.08), *PPVT–IV* scores were used as a covariate to determine if verbal ability affected significance found during inferential analysis of the experimental data.

Finally, to determine if performance on a standardized reading test, such as the *WRMT-R* or the *Word/Nonword Test*, was related to performance on the experimental tasks, a series of parametric correlation (Pearson Product-Moment correlational coefficient) tests were performed for each experimental task that yielded significant differences in performance.

CHAPTER III

RESULTS

Reading is an intricate process that involves several actions of the reader, such as the complex processes of accessing one's lexicon through both the phonological and visual/lexical routes. Phonological processing serves as the precursor to phonological decoding and requires accurate analysis of the acoustic event. Phonological decoding is defined as the word recognition process that transforms print into words. Thus, accessing the lexicon using the phonological route requires explicit awareness of the phonological structure of words and accurate auditory temporal processing. Auditory temporal processing involves receiving and analyzing temporal cues within the acoustic message, such as voice onset time, formant structure, and frequency and duration modulations. When readers access the mental lexicon through the visual/lexical route no phonological decoding is needed, but rather orthographic or visual/lexical processing. Thus, the visual/lexical strategy relies on the reader's ability to appropriately recognize whole words or specific letter patterns and match them to information already stored in the mental lexicon. Readers with deficits in orthographic processing and decoding have difficulties accessing the mental lexicon through the visual/lexical route and continue to rely on segmenting written words into individual units, which results in an overreliance on phonological decoding skills. Due to the fact that efficient reading depends on the ability of the reader to successfully decode and identify words in written text by both decoding strategies, two separate sources of reading failure account for differential types of reading disorders (Torgeson et al., 1994; Wolf & Bowers, 1999).

To date, research remains inconclusive as to the role general temporal processing deficits play in phonological and visual/lexical decoding during reading. Thus, it remains unclear as to what extent auditory and visual processing deficits play in reading disorders and if their relationship to reading impairment is directly causative or associative. The purpose of this study was to examine the relationship between auditory and visual temporal processing skills and RD, primarily in decoding and sight-word reading skills.

Experimental tasks were designed to assess detection, discrimination, and temporal order judgment abilities in the auditory and visual modalities. In the auditory domain, both within- and between-channel gap paradigms were utilized to assess the ability of the auditory system to detect a silent gap between individual auditory events when gap duration was manipulated and became progressively imperceptible. Likewise, in the visual domain, a critical flicker fusion task was utilized to assess the ability of the visual system to detect separate visual events when individual events became progressively imperceptible. Discrimination tasks for both sensory domains were designed to assess the ability of each system to discriminate differences between a target stimulus and a constant when the duration of the target stimulus was manipulated to become progressively imperceptible. Finally, temporal order judgment tasks were designed to assess the ability of the auditory and visual systems to identify the sequence of events. Presentation modes for the visual discrimination and temporal order tasks were similar to those of the auditory discrimination and temporal tasks such that stimuli were presented discreetly (one after another) within a trial with fixed interstimulus intervals between events.

Participants

Twenty-seven children (20 males, 7 females; mean age = 12.1 years) were recruited to participate in the study. Twelve children (8 males, 4 females; mean age = 11.8 years) served as the control group and 15 (7 males, 2 females; mean age = 11.9 years) children were identified as RD based on their scores on two of the pre-experimental reading and language tests, specifically, the *Woodcock Reading Mastery Test – Revised (WRMT-R)* and the *Word/Nonword Test* (Coltheart & Leahy, 1996). Readers assigned to the control group had standard scores of ≥ 85 on both subtests of the *WRMT-R* and raw scores within a normal range based on age norms for the *Word/Nonword Test* as calculated by Edwards and Hogben (1999). Children were grouped into the RD group if standard scores on one or both of the subtests of the *WRMT-R* fell below 84 and raw scores on one or more subtests of the *Word/Nonword Test* fell below normal range based on age norms. To differentiate RD subtypes, children were assigned to the dysphonetic (DP) group if standard scores were ≤ 84 on the Word Attack subtest of the *WRMT-R* and raw scores on the nonword list of the *Word/Nonword Test* were outside the age-based norms (Edwards & Hogben, 1999). Additionally, children assigned to the dysphoneidetic group (or mixed group [M]) had standard scores of ≤ 84 on the Word Attack and Word Identification subtests of the *WRMT-R* and raw scores on the irregular word and nonword lists of the *Word/Nonword Test* outside the age-based norms (Edwards & Hogben, 1999). Means and standard deviations for the standard scores on the *WRMT-R* and *Peabody Picture Vocabulary Test – IV (PPVT – IV)* along with mean raw scores and standard deviations on the *Word/Nonword Test* as a function of group are shown in Tables 2 and 3 and in Figures 3 and 4, respectively. Individual standard scores and performances on the *WRMT-R, PPVT – IV*, and the *Word/Nonword Test* as a function of group are in Appendix D.

Age

An independent samples *t*-test was utilized to examine differences in average age as a function of group. There was no significant difference in the average age between the control group and the RD group (i.e., dysphonetic and dysphoneidetic groups combined) [*t* (25) = -0.20, *p* = 0.85, Mean difference = -0.08, *SE* = 0.42, 95% confidence interval of the difference = -0.95 to 0.78].

Verbal Ability

An independent samples *t*-test was utilized to examine verbal ability, as measured by the *PPVT-IVT,* as a function of group. There was a significant difference in average standard scores on the *PPVT-IVT* between the control group and the RD group (i.e., dysphonetic and dysphoneidetic groups combined) [*t* (25) = 2.36, *p* = 0.03, Mean difference = 12.48, *SE* = 5.29, 95% confidence interval of the difference = 1.58 to 23.39]. The RD group had significantly lower mean language standard scores (SS = 102.60) on the *PPVT-IVT* as compared to the mean language standard scores of the control group (SS = 115.08). Therefore, *PPVT-IV* scores were used as a covariate for all inferential analyses.

Data Screening

Prior to descriptive and inferential analysis, threshold data for the auditory and visual gap detection and duration discrimination tasks, as well as the accuracy scores for

Table 2.

Mean and Standard Deviations of Standard Scores on the Word Identification and Word Attack Subtests of the WRMT-R and Standard Scores on the PPVT-IV as a Function of Group (i.e., Control, Dysphonetic, and Dysphoneidetic).

		Group		
		Control (*N* =12)	DP (*N*=6)	M (*N* = 9)
WRMT-R				
Word Identification				
	Mean	106.8	92.0	81.9
	Range	92-132	85-99	72-89
	SD	11.9	5.1	5.8
Word Attack				
	Mean	112.0	93.3	87.3
	Range	101-127	84-107	73-107
	SD	8.9	9.2	10.2
PPVT				
	Mean	115.1	105.0	101.0
	Range	96-146	96-111	86-123
	SD	17.4	5.5	11.9

Table 3.

Mean Raw Score and Standard Deviations for Regular Word, Irregular Word, and Nonword Lists of the Word/Nonword Test as a Function of Group (i.e., Control, Dysphonetic [DP] and Dysphoneidetic [M]).

		Group		
		Control (*N* =12)	DP (*N*=6)	M (*N* = 9)
Regular Word				
	Mean	28.4	25.3	21.3
	Range	25-30	23-28	14-28
	SD	1.7	2.1	5.0
Irregular Word				
	Mean	24.9	21.3	15.6
	Range	20-30	19-25	8-21
	SD	3.6	2.4	4.3
Nonword				
	Mean	26.3	15.0	12.1
	Range	21-30	11-19	3-20
	SD	2.8	3.4	6.9

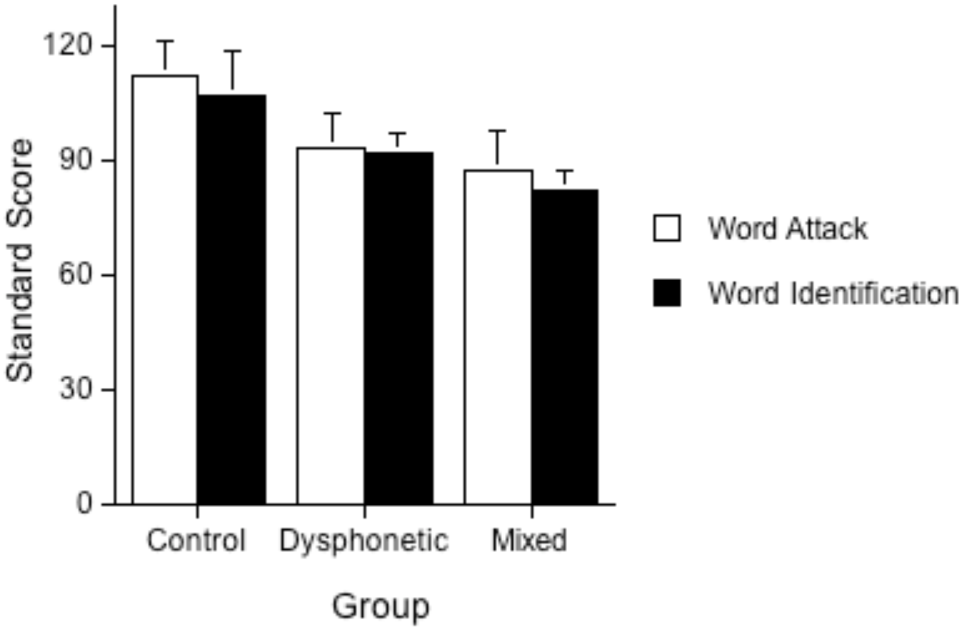

Figure 3. Mean standard scores on the Word Attack and Word Identification subtests of the *WRMT-R* as a function of group. Error bars represent plus one *SD* of the mean.

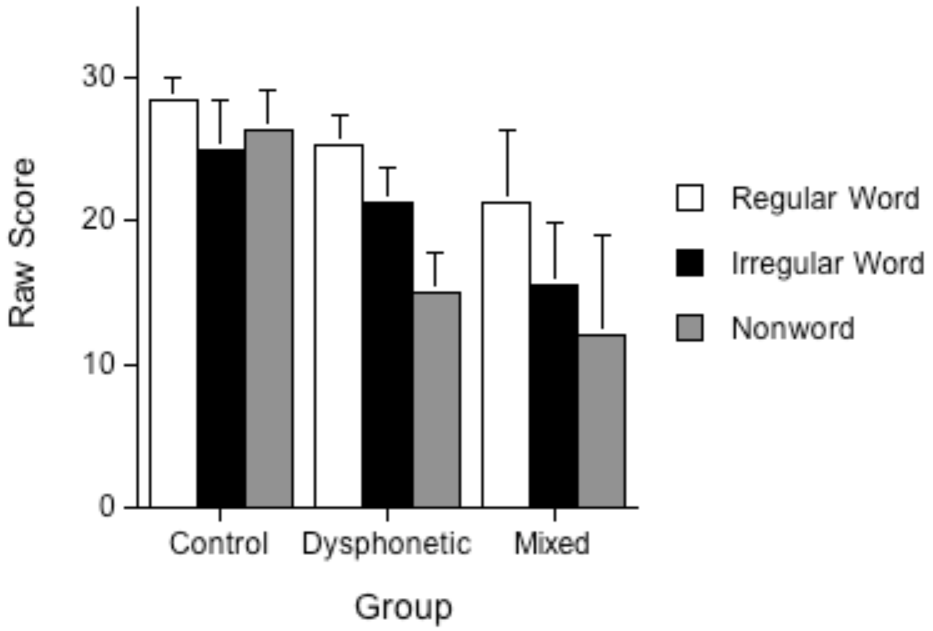

Figure 4. Mean standard scores on the Regular Word, Irregular Word, and Nonword lists on the *Word/Nonword Test* as a function of group. Error bars represent plus one *SD* of the mean.

the auditory and visual duration pattern tasks were examined within and across trials with SPSS Explore (SPSS 16.0 for Mac, SPSS, Inc) for accuracy of data entry and to identify missing values and outlying data points. Outliers were eliminated and threshold data was analyzed for averaged data (i.e., two or three trials) and for best threshold. Two participants, participant 5 in the control group and participant 22 in the dysphoneidetic group, could not complete the between-channel gap detection task. Similarly, participant 8 in the control group could not complete the visual duration discrimination task and a linear mixed model analysis of variance (ANOVA) was used to account for the missing threshold data.

Auditory Experimental Tasks

Auditory Gap Detection

In Experimental Task One, participants were required to complete a three-trial gap detection task in both between-channel and within-channel paradigms. For both paradigms, each stimulus trial had three sequences (i.e., two control and one target) with an inter-sequence interval of 500 ms. The control sequences had a leading and trailing marker separated by an inaudible gap of 1.0 ms. The target sequence had the leading and trailing markers separated by a gap varied by an adaptive tracking procedure. Participants indicated which sequence contained the gap by pressing the appropriate button on a response pad. For threshold analysis, independent variables included group and gap paradigm (i.e., between-channel and within-channel). The dependent variable was threshold (ms). Mean and best thresholds and standard deviations as a function of group (i.e., control, dysphonetic, and dysphoneidetic) and gap paradigm are provided in

Table 4 and 5, respectively, and illustrated in Figure 5. Individual mean and best thresholds (ms) as a function of group are reported in Appendix E. One participant in the control group and one participant in the dysphoneidetic group were unable to achieve 90% accuracy on the familiarization task and therefore did not complete the between-channel gap detection experimental task.

Auditory Gap Detection Analyses. The first experimental question addressed whether statistically significant differences in threshold performance (ms) existed in a gap detection task as a function of group (i.e., control, dysphonetic, and dysphoneidetic). Two separate three-factor linear mixed model ANOVAs (SPSS 16.0 For Mac, SPSS Inc.) were conducted to examine differences in mean and best gap threshold as a function of group and gap paradigm (i.e., within- vs. between-channel). Standard scores on the *PPVT-IV* were entered as a covariate. The repeated measures were modeled with a first-order autoregressive moving average (ARMA [1, 1]) covariance structure. This analysis can accommodate missing data in a repeated measures design (Little & Rubin, 2002). Recall from above that two participants (i.e., one participant in each of the control and dysphoneidetic groups) could not complete the between-channel gap task. The summaries of the ANOVAs are in Tables 6 and 7. As seen in both tables, significant main effects of group and paradigm were found. As expected mean and best within-channel gap paradigm thresholds were found to be significantly lower than between-channel gap paradigm thresholds. With both the mean and best gap detection data sets, two orthogonal single-df contrasts were undertaken to find the source of the main effect of

Table 4.

Mean Gap Threshold (ms) and Standard Deviations for the Within- and Between-Channel Gap Paradigm Tasks as a Function of Group (i.e., Control, Dysphonetic [DP] and Dysphoneidetic [M]).

	Group		
	Control	DP	M
Within-Channel Gap Paradigm			
N	12	6	9
Mean	6.78	9.04	13.11
Range	3.75-10.42	2.92-18.83	5.50-40.75
SD	2.15	5.34	12.72
Between-Channel Gap Paradigm			
N	11*	6	8*
Mean	24.33	52.42	68.69
Range	5.00-85.00	22.17-89.00	23.50-144.00
SD	18.18	5.34	43.98

Note: * One participant could not complete task.

Table 5.

Best Gap Threshold (ms) and Standard Deviations for the Within- and Between-Channel Gap Paradigm Tasks as a Function of Group (i.e., Control, Dysphonetic [DP] and Dysphoneidetic [M]).

	Group		
	Control	DP	M
Within-Channel Gap Paradigm			
N	12	6	9
Best	4.79	5.83	9.42
Range	2.50-8.75	2.50-10.00	3.75-27.50
SD	1.91	2.70	9.64
Between-Channel Gap Paradigm			
N	11*	6	8*
Best	19.00	37.08	62.56
Range	5.00-54.00	14.00-69.00	21.50-144.00
SD	15.49	20.47	44.37

Note: * One participant could not complete task.

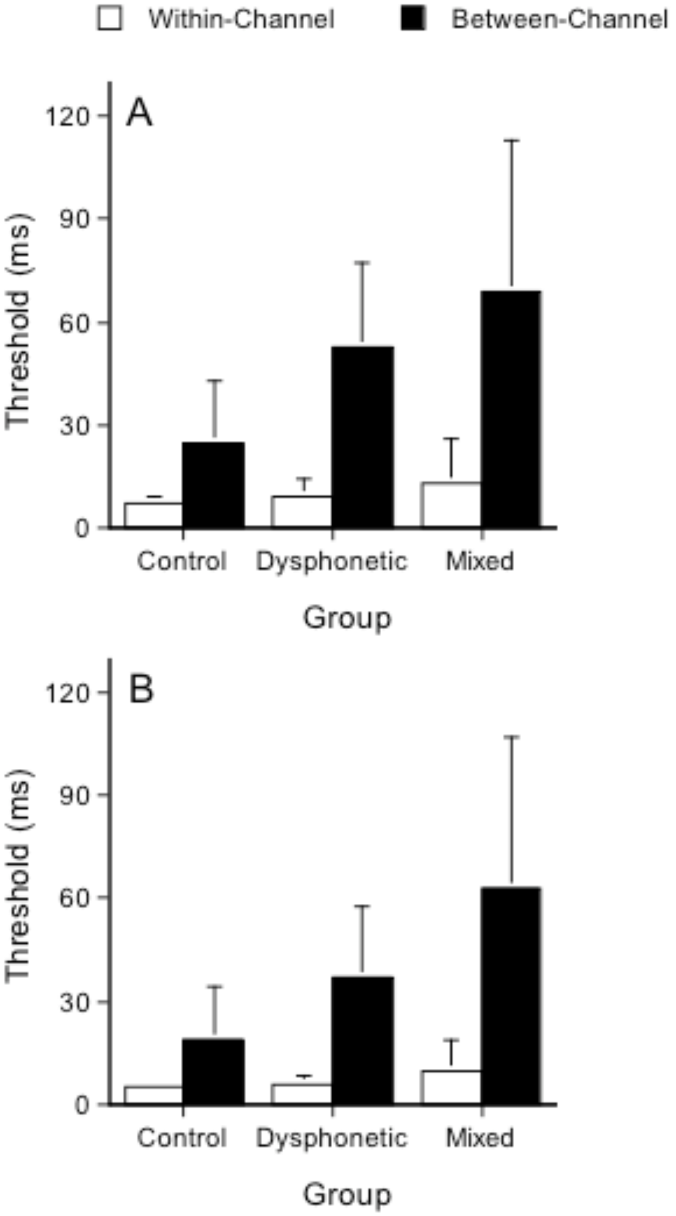

Figure 5. Mean (A) and best thresholds (B) on the Within-Channel and Between-Channel Gap Detection Task as a function of group. Error bars represent plus one SD of the mean.

Table 6.

Summary Table for the Three-Factor, Linear Mixed Model ANCOVA Investigating Differences in Mean Gap Threshold (ms) as a Function of Within- Subjects Variable Gap Paradigm (i.e., Within- and Between-Channel) and Between-Subjects Variable Group (i.e., Control, Dysphonetic, and Dysphoneidetic).

Source	*df*	*F*	*p*
Group	2	4.51	0.02*
Gap	1	6.41	0.02*
PPVT	1	7.43	0.01*
Group X Gap	2	2.01	0.16
Group X PPVT	2	3.46	0.05
Gap X PPVT	1	4.55	0.04*
Group X Gap X PPVT	2	1.63	0.22

Note: * Significant at $p < 0.05$

Table 7.

Summary Table for the Three-Factor, Linear Mixed Model ANCOVA Investigating Differences in Best Gap Threshold (ms) as a Function of Within- Subjects Variable Gap Paradigm (i.e., Within- and Between-Channel) and Between-Subjects Variable Group (i.e., Control, Dysphonetic, and Dysphoneidetic).

Source	*df*	*F*	*p*
Group	2	4.95	0.02*
Gap	1	7.40	0.01*
PPVT	1	7.26	0.01*
Group X Gap	2	3.29	0.06
Group X PPVT	2	3.87	0.04*
Gap X PPVT	1	5.55	0.03*
Group X Gap X PPVT	2	2.72	0.09

Note: * Significant at $p < 0.05$

group. In both average and best threshold analysis, the control group performed significantly better than the RD groups ($p < 0.05$). Further, there was no significant difference between the two RD groups ($p > 0.05$).

Auditory Duration Discrimination

In Experimental Task Two, participants were required to complete and three-trial duration discrimination task in which they were instructed to determine which trial contained the "different" stimulus. Each trial sequence contained three 1000 Hz tones with two standard tones 75 ms in duration and one target tone of 50 ms in duration. Depending on participant response, target duration varied by an adaptive tracking procedure. Participants indicated which sequence contained the target by pressing the appropriate button on a response pad. For threshold analysis, the independent variable was group. The dependent variable was threshold (ms). Mean and best threshold and standard deviations as a function of group (i.e., control, dysphonetic, and dysphoneidetic) are provided in Table 8 and in Figure 6. Individual mean and best duration discrimination thresholds (ms) and standard deviations as a function of group are reported in Appendix E.

Auditory Duration Discrimination Analyses. The second experimental question addressed if statistically significant differences in threshold existed in a duration discrimination task as a function of group. Two separate univariate analyses of covariance (ANCOVA) were conducted on mean and best threshold (ms) as a function of group (i.e., control, dysphonetic, and dysphoneidetic) when controlling for verbal ability

Table 8.

Mean and Best Thresholds (ms) and Standard Deviations on the Auditory Duration Discrimination Task as a Function of Group (i.e., Control, Dysphonetic [DP] and Dysphoneidetic [M]).

		Group		
		Control (*N* = 12)	DP *(N* = 6)	M (*N* = 9)
Average Threshold (ms)	Mean	14.20	16.67	21.51
	Range	8.33-24.58	10.83-30.00	7.08-36.25
	SD	5.36	7.21	9.17
Best Threshold (ms)	Mean	11.04	12.08	17.64
	Range	3.75-22.50	8.75-20.00	6.25-32.50
	SD	5.30	4.08	8.01

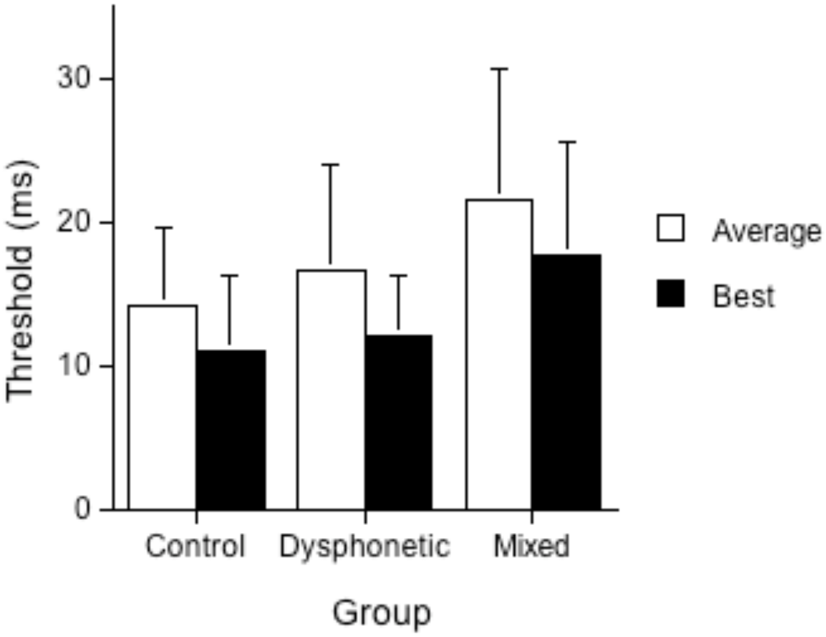

Figure 6. Mean and best thresholds on the Auditory Duration Discrimination Task as a function of group. Error bars represent plus one SD of the mean.

(i.e., standard scores on the *PPVT-IV* as a covariate). The results of the ANCOVAs are displayed in Table 9. As shown in Table 9, results of the ANCOVAs revealed no significant main effect of group.

Auditory Duration Pattern Judgment

In Experimental Task Three, participants were required to complete a 30-sequence auditory duration pattern test. Each sequence consisted of three 1000 Hz tones that were either short (250 ms) or long (500 ms) making up one of six possible tonal patterns. Participants indicated which pattern was heard by pointing to the appropriate pattern represented on a piece of paper. For duration pattern accuracy analysis, the independent variable was group (i.e., control, dysphonetic, and dysphoneidetic) and the dependent variable was accuracy (i.e., percent correct). Mean percent correct scores and standard deviations as a function of group are provided in Table 10 and in Figure 7. Individual accuracy scores and standard deviations as a function of group are listed in ppendix E.

*Accuracy Data***.** The third experimental question addressed if statistically significant differences in accuracy existed on an auditory duration pattern test as a function of group (i.e., control, dysphonetic, and dysphoneidetic). Prior to inferential analysis, raw data (i.e., proportion) were submitted to an arcsine transformation. A univariate ANCOVA was conducted on accuracy as a function of group when controlling for verbal ability (i.e., standard scores on PPVT -IV as a covariate). The results of that ANCOVA are displayed in Table 11. As shown in Table 11, there was no significant main effect of group.

Table 9.

Summary Table for the One-Way ANCOVAs Investigating Differences in Mean and Best Thresholds (ms) on the Auditory Duration Discrimination (ADD) as a Function of Group (i.e., Control, Dysphonetic, and Dysphoneidetic).

Task	Condition	Source	*df*	*F*	*p*	η^2	θ
ADD	Mean	Group	2	2.50	0.10	0.18	0.45
		PPVT	1	0.17	0.68	0.007	0.40
	Best	Group	2	3.38	0.05	0.23	0.58
		PPVT	1	0.60	0.45	0.03	0.12

Table 10.

Mean Accuracy (Percent) and Standard Deviations on the Auditory Duration Pattern Test as a Function of Group (i.e., Control, Dysphonetic [DP] and Dysphoneidetic [M]).

	Group		
Auditory Duration Pattern Test	Control (*N* = 12)	DP (*N* = 6)	M (*N* = 9)
Mean	81.0	70.5	60.4
Range	43-100	53-80	37-80
SD	17.2	10.0	16.7

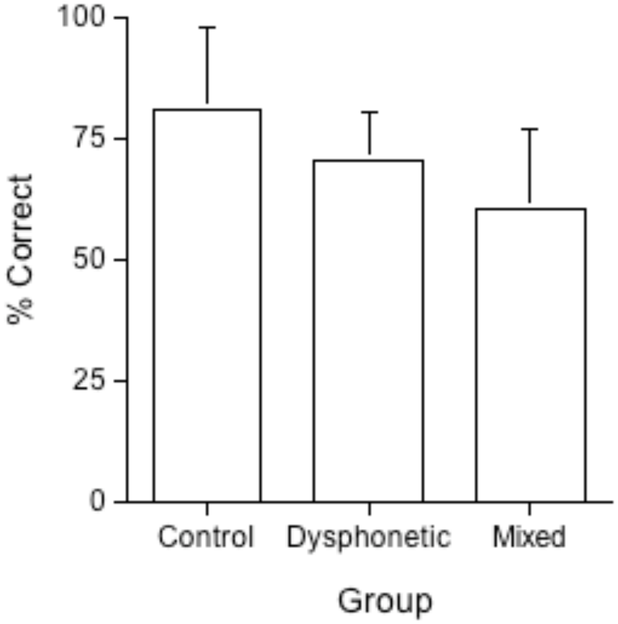

Figure 7. Mean percent correct on the Auditory Duration Pattern Judgment Task as a function of group. Error bars represent plus one SD of the mean.

Table 11.

Summary Table for the One-Way ANCOVAs Investigating Differences in Accuracy (proportion) on the Auditory Duration Pattern Judgment (ADPT) Task as a Function of Group (i.e., Control, Dysphonetic, and Dysphoneidetic).

Task	Condition	Source	*df*	*F*	*p*	η^2	θ
ADPT		Group	2	1.88	0.18	0.14	0.35
		PPVT	1	7.25	0.01	0.24	0.73

Visual Experimental Tasks

Visual Critical Flicker Fusion

In experimental task one, participants were required to complete a three-trial critical flicker fusion task in which they were instructed to indicate, by press of a button, the presence or absence of flicker in two beams of light presented inside a viewing chamber. The beams of light were interrupted intermittently causing the lights to either flash or flicker. If the flicker rate exceeded a certain frequency point, the lights appeared to remain steady. Based on participant response, frequency of flicker was varied by an adaptive tracking procedure. For critical flicker fusion threshold (Hz) analysis, the independent variable was group (i.e., control, dysphonetic, and dysphoneidetic) and the dependent variable was flicker fusion threshold (Hz). Mean and best thresholds and standard deviations as a function of group and are provided in Table 12 and in Figure 8. Individual mean and best thresholds (Hz) as a function of group are reported in Appendix E.

Visual Critical Flicker Fusion Analyses. The first experimental question addressed if statistically significant differences in threshold existed on a visual critical flicker fusion test as a function of group (i.e., control, dysphonetic, and dysphoneidetic). Two separate univariate ANCOVAs were conducted on the mean and best threshold (ms) as a function of group controlling for verbal ability when standard scores on the *PPVT-IV* were used as a covariate. The results of those ANCOVAs are summarized in Table 13. As shown in Table 13, results of the ANCOVAs revealed no significant main effect of group.

Table 12.

Mean and Best Thresholds (Hz) and Standard Deviations on the Visual Critical Flicker Fusion Task as a Function of Group (Control, Dysphonetic [DP] and Dysphoneidetic [M]).

		Group		
		Control (*N* = 12)	DP (*N* = 6)	M (*N* = 9)
Average Threshold (Hz)	Mean	41.5	38.0	40.1
	Range	34.9-45.1	32.9-41.9	31.2-59.2
	SD	3.2	3.2	8.9
Best Threshold (Hz)	Mean	44. 5	40.4	42.7
	Range	37.8-42.2	38.0-42.2	34.6-67.4
	SD	5.3	1.5	10.5

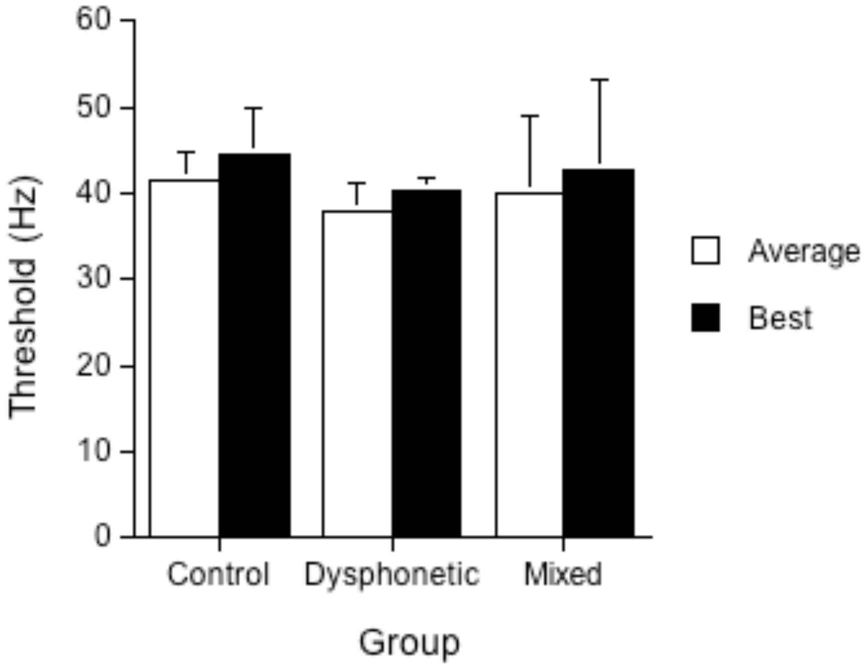

Figure 8. Mean and best thresholds on the Visual Critical Flicker Fusion Task as a function of group. Error bars represent plus one SD from the mean.

Table 13.

Summary Table for The One-Way ANCOVAs Investigating Differences in Mean and Best Threshold (Hz) on the Visual Critical Flicker Fusion Task (CFF) as a function of Group (i.e., Control, Dysphonetic, and Dysphoneidetic).

Task	Condition	Source	*df*	*F*	*p*	η^2	θ
CFF	Mean	Group	2	0.44	0.65	0.04	0.11
		PPVT	1	2.70	0.11	0.11	0.35
	Best	Group	2	0.35	0.71	0.03	0.10
		PPVT	1	2.62	0.12	0.10	0.34

Visual Duration Discrimination

In Experimental Task Two, participants were required to complete a three-trial duration discrimination task in which they were instructed to determine which trial sequence contained the “different” stimulus. Each trial sequence contained three asterisks (*) presented on a computer screen with two standard asterisks presented for 300 ms in duration and one target asterisk presented for 600 ms in duration. Depending on participant response, target duration varied by an adaptive tracking procedure. Participants indicated which sequence contained the target by pressing the appropriate button on a computer keyboard. For threshold analysis, the independent variable was group (i.e., control, dysphonetic, and dysphoneidetic). The dependent variable was threshold (ms). Mean and best thresholds and standard deviations as a function of group are provided in Table 14 and in Figure 9. One participant in the control group was unable to achieve 90% accuracy on the familiarization task and, therefore, did not complete the experimental trials. Individual mean and best thresholds (ms) as a function of group are reported in Appendix E.

Visual Duration Discrimination Analyses. The second experimental question addressed if statistically significant differences in threshold existed in a duration discrimination task as a function of group (i.e., control, dysphonetic, and dysphoneidetic). A two-factor linear mixed ANOVA (SPSS 16.0 For Mac, SPSS, Inc) was conducted to examine differences in visual duration discrimination as a function of group. Standard scores on the *PPVT-IV* were entered as a covariate. This analysis can accommodate missing data in a repeated measures design (Little & Rubin, 2002). Recall from above

Table 14.

Mean and Best Thresholds (ms) and Standard Deviations on the Visual Duration Discrimination Task as a Function of Group (i.e., Control, Dysphonetic [DP] and Dysphoneidetic [M]).

		Group		
		Control (*N* = 12)	DP (*N* = 6)	M (*N* = 9)
Average Threshold (Hz)	Mean	65.83	62.15	39.35
	Range	25.00-137.50	43.75-110.42	12.50-87.50
	SD	34.12	25.60	23.14
Best Threshold (Hz)	Mean	99.24	101.04	66.66
	Range	31.25-237.50	68.75-181.25	18.75-225.00
	SD	55.24	43.20	63.35

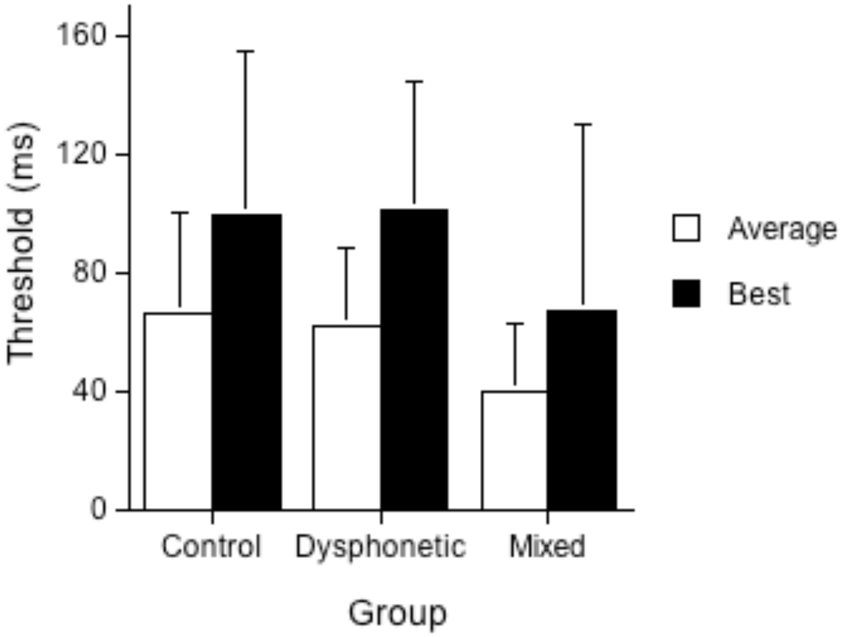

Figure 9. Mean and best thresholds on the Visual Duration Discrimination Task as a function of group. Error bars represent plus one SD of the mean.

that one participant in the control group could not complete the visual duration discrimination task. The summaries of the ANOVAs are in Tables 15 and 16. As seen in the tables, all main effects and interactions were not significant.

Visual Duration Pattern Judgment

In Experimental Task Three, participants were required to complete a 30-sequence visual duration pattern test. Each sequence consisted of three asterisks (*) presented on a computer monitor for either 300 ms or 600 ms, making up one of six possible visual patterns. Participants indicated which pattern was viewed by pressing the appropriate key on a computer keyboard. The six patterns were represented on a piece of paper for ease of pattern identification. For duration pattern accuracy analysis, the independent variable group (i.e., control, dysphonetic, and dysphoneidetic) and the dependent variable was accuracy (i.e., percent correct). Mean accuracy scores and standard deviations as a function of group is provided in Table 17 and Figure 10. Individual accuracy scores as a function of group are reported in Appendix E. Prior to inferential analysis, raw data (percent correct scores) were submitted to an arcsine transformation.

Visual Duration Pattern Judgment Analyses. The third experimental question relative to visual processing addressed if statistically significant differences in accuracy (i.e., proportion) existed on a visual duration pattern test as a function of group (i.e., control, dysphonetic, and dysphoneidetic). Prior to inferential analyses, the proportion correct scores were transformed to arcsine units. A univariate ANCOVA was conducted on accuracy as a function of group controlling for verbal ability when standard scores on

Table 15.

Summary Table for the Two-Factor, Linear Mixed Model ANCOVA Investigating Differences in Mean Visual Duration Discrimination Threshold (ms) as a Function of Group (i.e., Control, Dysphonetic, and Dysphoneidetic).

Source	*df*	*F*	*p*
Group	2	2.04	0.08
PPVT	1	2.90	0.46
Group X PPVT	2	2.98	0.07

Table 16.

Summary Table for the Two-Factor, Linear Mixed Model ANCOVA Investigating Differences in Best Visual Duration Discrimination Threshold (ms) as a Function of Group (i.e., Control, Dysphonetic, and Dysphoneidetic).

Source	*df*	*F*	*p*
Group	2	1.61	0.23
PPVT	1	0.69	0.42
Group X PPVT	2	1.65	0.22

Table 17.

Mean Accuracy (Percent) and Standard Deviations on the Visual Duration Pattern Task as a Function of Group (i.e., Control, Dysphonetic [DP], and Dysphoneidetic [M]).

	Group		
Visual Duration Pattern Test	Control (*N* = 12)	DP (*N* = 6)	M (*N* = 9)
Mean	54.7	55.8	52.2
Range	30-80	17-87	27-80
SD	17.3	26.9	17.0

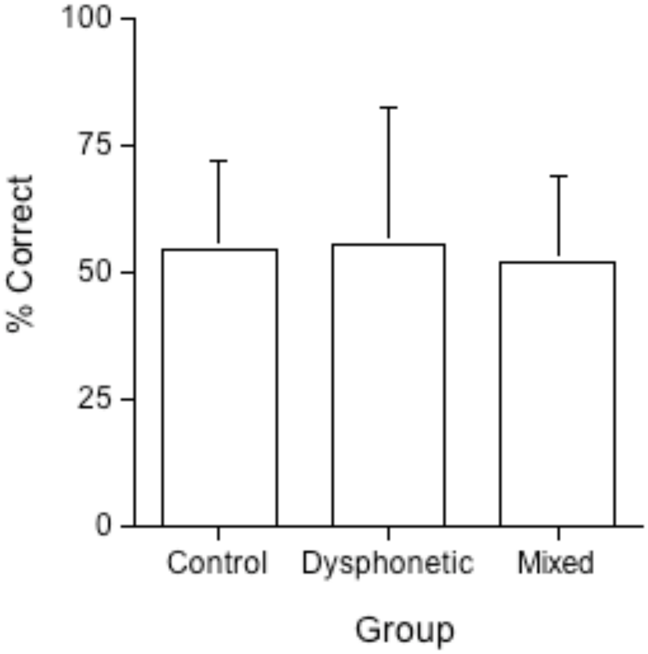

Figure 10. Mean percent correct on the Visual Duration Pattern Judgment Task as a function of group. Error bars represent plus one SD of the mean.

the *PPVT-IV* were used as a covariate. The results of that ANCOVA are displayed in Table 18. Results of the ANCOVA revealed no significant main effect of group.

Correlational and Linear Regression Data Analyses

A series of parametric correlation (Pearson Product-Moment correlational coefficient) tests were conducted to examine the association between the pre-experimental Word Identification and Word Attack subtests of the *WRMT-R* and the Regular Word, Irregular Word, and Nonword lists of the *Word/Nonword Test.* The analyses were undertaken to determine if both reading measures similarly assessed phonological decoding and sight-word reading abilities. Correlations were also conducted to investigate the association between performance on the pre-experimental tasks and performance on all experimental tasks. In addition, linear regression analyses were conducted to determine the predictive nature of the experimental tasks to reading scores on the Word Identification and Word Attack subtests of the *WRMT-R*. Finally, Pearson Product-Moment correlational coefficient analyses were conducted to investigate the association between performances on the auditory experimental tasks to performance on the visual experimental tasks.

Pre-experimental Tasks

Significant positive correlations were found between standard scores on the Word Identification of the *WRMT-R* and raw scores on the Regular Word, the Irregular Word, and the Nonword lists of the *Word/Nonword Test*. Additional positive correlations were found between the standard scores on the Word Attack subtest of the *WRMT-R* and raw scores on the Regular Word, the Irregular Word, and the Nonword lists of the *Word/Nonword Test*. The results of those correlations are summarized in Table 19.

Table 18.

Summary Table for Three Separate One-Way ANCOVAs Investigating Differences in Proportion of Accuracy on the Visual Duration Pattern Task (VDPT) as a function of Group (i.e., Control, Dysphonetic, and Dysphoneidetic).

Task	Condition	Source	*df*	*F*	*p*	η^2	θ
VDPT		Group	2	0.41	0.67	0.03	0.11
		PPVT	1	5.35	0.03	0.19	0.60

Table 19.

Pearson Product-Moment Correlations Between Performance on Word Identification (WI) and Word Attack (WA) Subtests of the WRMT-R and the Regular Word (RW), Irregular Word (IW), and Nonword (NW) Lists of the Word/Nonword Test.

	Word/Nonword Test Subtests		
WRMT-R Subtests	RW	IW	NW
WI	0.76**	0.81**	0.80**
WA	0.80**	0.81**	0.87**

Note: ** $p < 0.01$

Further, simple linear regression analyses revealed that the relation between performance on the Word Identification subtest, as a function of performance on the regular word, irregular word, and nonword reading lists of the *Word/Nonword Test*, were statistically significant ($p < 0.05$). A summary of independent ANOVAs that tested significance of the linear relationship between the Word Identification subtest of the *WRMT-R* and all word lists of the *Word/Nonword Test* are presented in Table 20. Bivariate scatterplots and linear regression lines for performance on the Word Identification subtest, as a function of performance on the *Word/Nonword Test* is shown in Figure 11.

Additional simple linear regression analyses also revealed that the relation between performance on the Word Attack subtest, as a function of performance on the regular word, irregular word, and nonword reading lists of the *Word/Nonword Test*, were statistically significant ($p < 0.05$). A summary of independent ANOVAs that tested significance of the linear relationship between the Word Attack subtest of the *WRMT-R* and all word lists of the *Word/Nonword Test* are presented in Table 21. Bivariate scatterplots and linear regression lines for performance on the Word Attack subtest, as a function of performance on the *Word/Nonword Test* is shown in Figure 12.

Finally, significant positive correlations were found between performance on the *PPVT-IV* and performance on the Word Attack ($r = 0.60, p < 0.01$) and Word Identification ($r = 0.74, p < 0.01$) subtests of the WRMT-R. Simple linear regression analyses revealed that the relation between performance on the Word Attack and Word Identification subtests of the *WRMT-R*, as a function of performance on the *PPVT-IV*, were statistically significant ($p < 0.05$). A summary of independent ANOVAs that tested

Table 20.

Summary of Independent ANOVAs Investigating the Linear Relationship Between Performance on the Word Attack Subtest of the WRMT-R as a Function of Performance on the Word/Nonword Test.

Task	Source	*df*	*F*	*p*
Regular Word	Regression	1	45.04	0.00
	Residual	25		
Irregular Word	Regression	1	47.42	0.00
	Residual	25		
Nonword	Regression	1	78.23	0.00
	Residual	25		

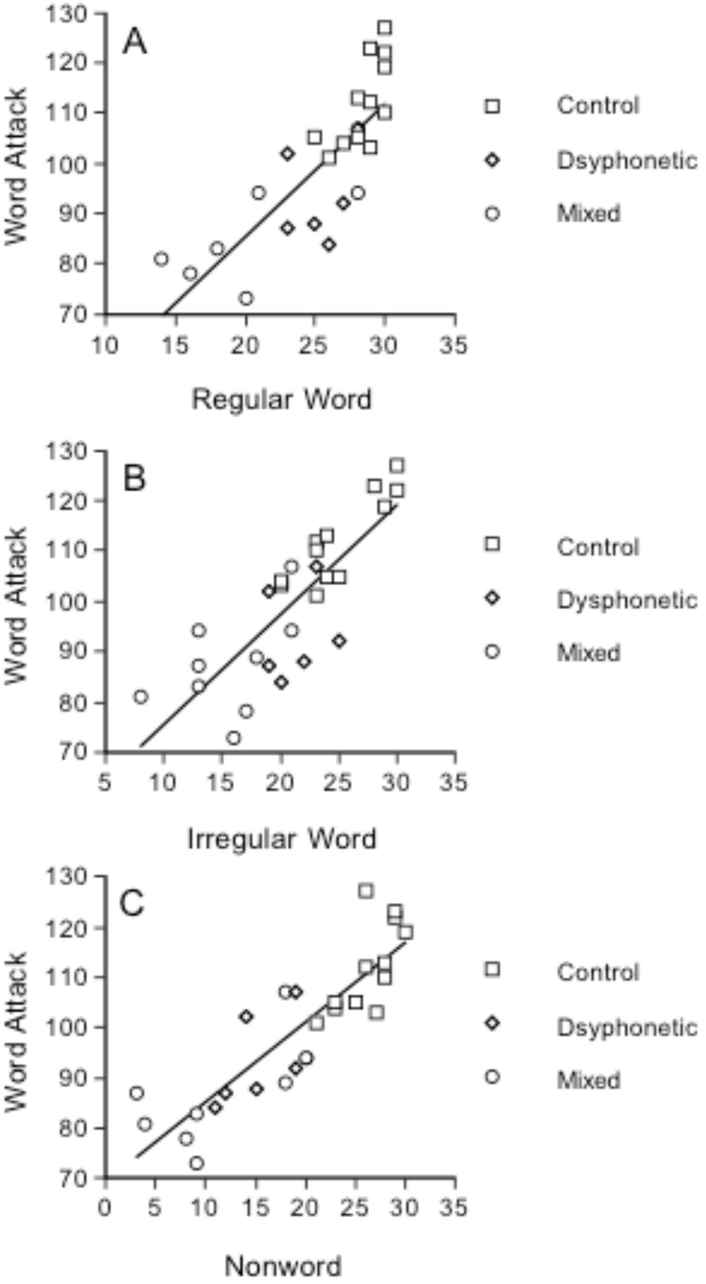

Figure 11. Bivariate scatterplots and linear regression lines for performance on the Word Attack Subtest of the *WRMT-R* as a function of performance on the (A) Regular Word, (B) Irregular Word, and (C) Nonword lists of the *Word/Nonword Test*.

Table 21.

Summary of Independent ANOVAs Investigating the Linear Relationship Between Performance on the Word Identification Subtest of the WRMT-R as a Function of Performance on the Word/Nonword Test.

Task	Source	*df*	*F*	*p*
Regular Word	Regression	1	34.87	0.00
	Residual	25		
Irregular Word	Regression	1	49.04	0.00
	Residual	25		
Nonword	Regression	1	45.04	0.00
	Residual	25		

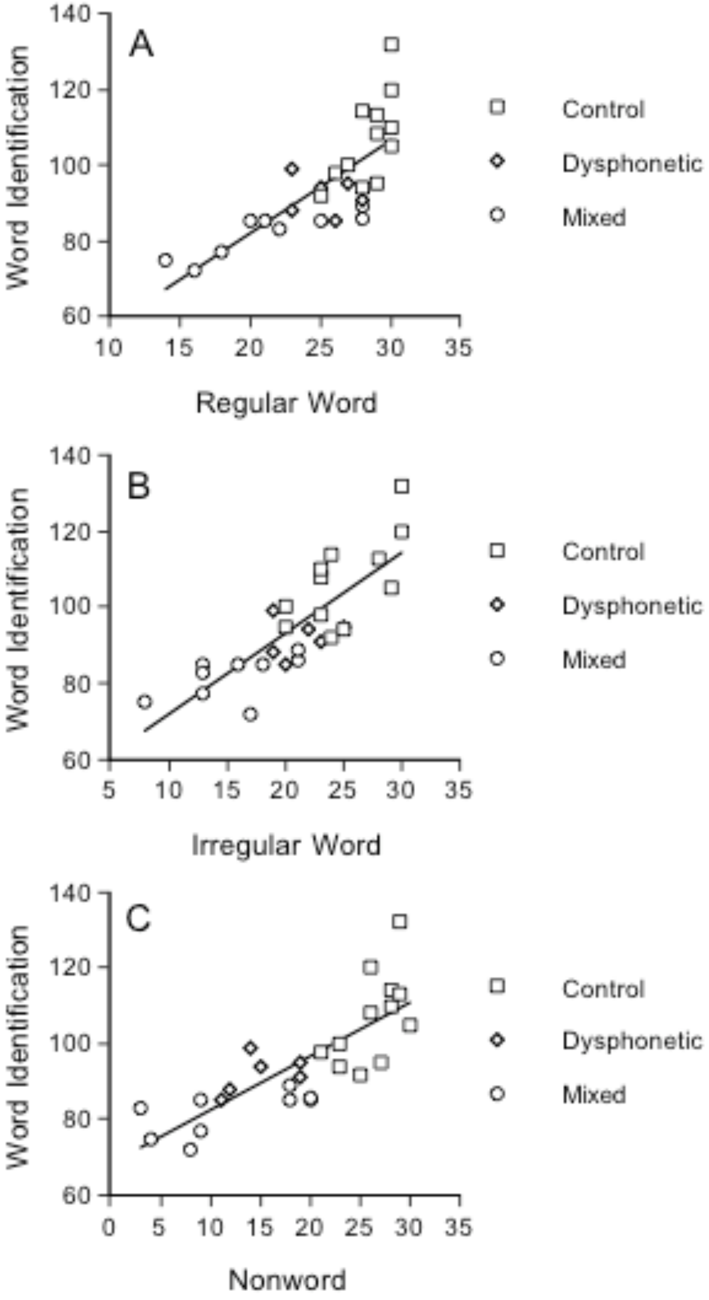

Figure 12. Bivariate scatterplots and linear regression lines for performance on the Word Identification Subtest of the *WRMT-R* as a function of performance on the (A) Regular Word, (B) Irregular Word, and (C) Nonword lists of the *Word/Nonword Test*.

significance of the linear relationship between the Word Attack and Word Identification subtests of the *WRMT-R*, as a function of performance on the *PPVT-IV* is presented in Table 22. Bivariate scatterplots and linear regression lines for performance on the Word Attack and Word Identification subtests, as a function of performance on the *PPVT-IV* are shown in Figure 13.

Pre-experimental Tasks and Experimental Tasks

To better understand the relationship between auditory and visual temporal processing and performance on reading measures assessing phonological decoding and sight-word reading skills, an additional series of Pearson Product-Moment correlational coefficient analyses were conducted to investigate the performance on each experimental task to performance on the Word Identification and Word Attack subtests of the *WRMT-R*. It has been suggested that poor phonological decoding skills is directly related to deficits in auditory temporal processing. Furthermore, it has been suggested that deficits in visual temporal processing may be related to deficits in sight-word reading abilities. The Word Attack subtest is a nonword reading measure assessing phonological decoding skills. It was expected that performance on all auditory experimental tasks would be strongly correlated with performance on the Word Attack subtest. The Word Identification subtest is assumed to assess sight-word reading abilities; however, this subtest does not contain purely non-phonetic words. Therefore, individuals may use both phonological and sight-word reading strategies to decode words on the Word Identification subtest. It was expected that performance on both the auditory and visual experimental tasks would be correlated to performance on the Word Identification subtest.

Table 22.

Summary of Independent ANOVAs Investigating the Linear Relationship Between Performance on the PPVT-IV as a Function of Performance on the WRMT-R.

Task	Source	*df*	*F*	*p*
Word Attack	Regression	1	14.03	0.00
	Residual	25		
Word Identification	Regression	1	29.59	0.00
	Residual	25		

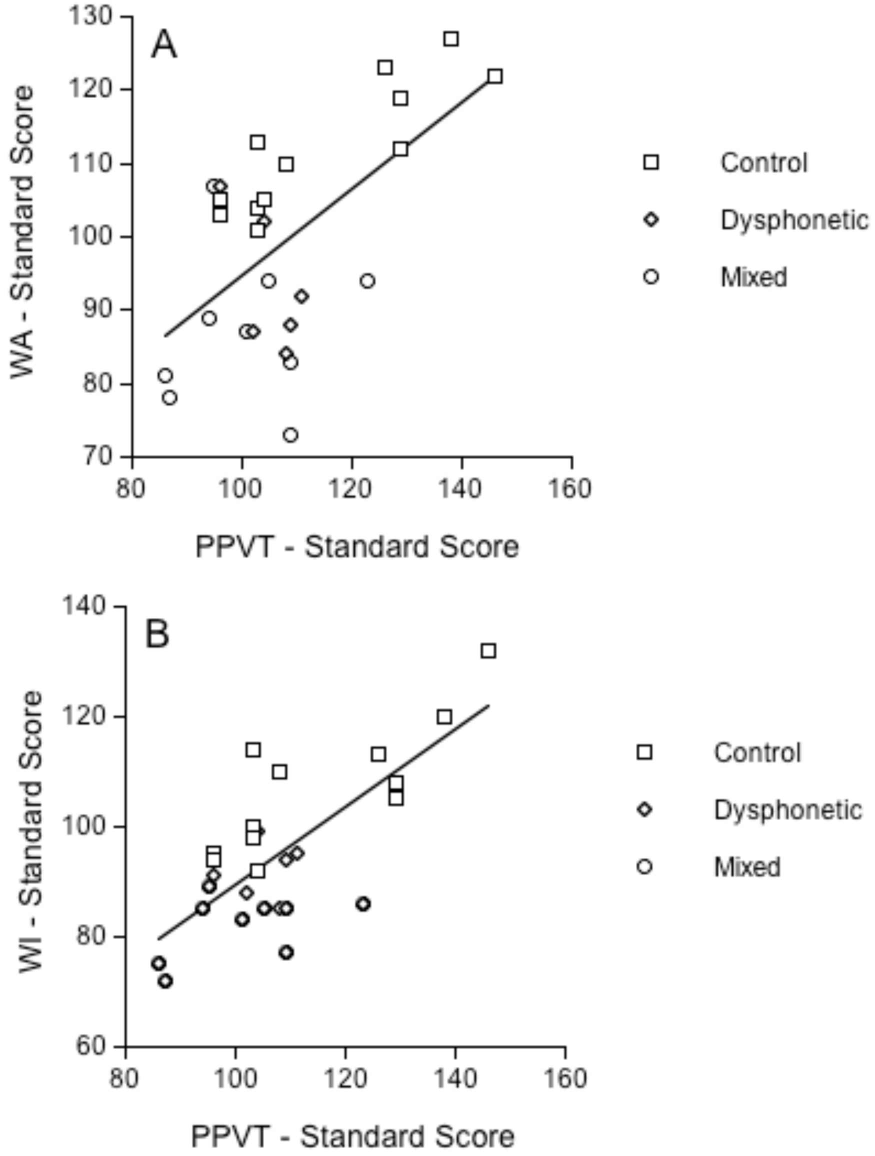

Figure 13. Bivariate scatterplots and linear regression lines for performance on the (A) Word Attack [WA] and (B) Word Identification [WI] subtests of the *WRMT-R* as a function of performance on the *PPVT-IV*.

Auditory Tasks and Word Attack. Average and best threshold (ms) for the auditory gap detection and auditory duration discrimination tasks, as well as accuracy (i.e., proportion) on the auditory duration pattern task, were compared to performance on the Word Attack subtest of the *WRMT-R*. This analysis revealed several significant correlations between performances on all auditory tasks assessing detection (i.e., within- and between-channel gap paradigm), duration discrimination, and duration temporal order judgment and performance on the Word Attack subtest as summarized in Table 23. Specifically, significant negative correlations were found between average and best thresholds (ms) on the between-channel and within-channel gap detection paradigms and the average and best thresholds (ms) on the auditory duration discrimination task and standard scores on the Word Attack subtest of the *WRMT-R*. However, a significant positive correlation was found between accuracy on the auditory duration pattern judgment task and the Word Attack subtest of the *WRMT-R*. Simple linear regression analyses revealed that the relation between performance on the Word Attack subtest, as a function of performance on the auditory temporal processing tasks, were statistically significant ($p < 0.05$). A summary of independent ANOVAs that tested the significance of the linear relationships between the Word Attack subtest of the *WRMT-R* and all auditory tasks (i.e., average and best thresholds and accuracy proportion) are presented in Table 24. Bivariate scatterplots and linear regression lines for performance on the Word Attack subtest of the *WRMT-R* as a function of performance on all experimental auditory tasks are shown in Figures 14-17.

Table 23.

Pearson Product-Moment Correlations Between Performance the Word Attack (WA) Subtest of the WRMT-R and the Mean (avg) and Best (best) Threshold on the Auditory Gap Detection Task (Within-[WC] and Between-Channel [BC]), Auditory Duration Discrimination Task (ADD), and Proportion of Accuracy on the Auditory Duration Pattern Judgment Task (ADPT.)

	WCavg	WCbest	BCavg	BCbest	ADDavg	ADDbest	ADPT
WA	-0.44*	-0.46*	-0.50*	-0.49*	-0.45*	-0.45*	0.67**

Note: *$p < 0.05$; **$p < 0.01$

Table 24.

Summary of Independent ANOVAs Investigating the Linear Relationship Between Performance on the Word Attack (WA) Subtest of the WRMT-R as a Function of Performance on the Experimental Auditory Tasks.

Task	Source	*df*	*F*	*p*
WCavg	Regression	1	6.10	0.02
	Residual	25		
WCbest	Regression	1	6.86	0.02
	Residual	25		
BCavg	Regression	1	7.60	0.01
	Residual	23		
BCbest	Regression	1	7.08	0.01
	Residual	23		
ADDavg	Regression	1	6.50	0.02
	Residual	25		
ADDbest	Regression	1	6.17	0.02
	Residual	25		
ADPT	Regression	1	19.98	0.00
	Residual	25		

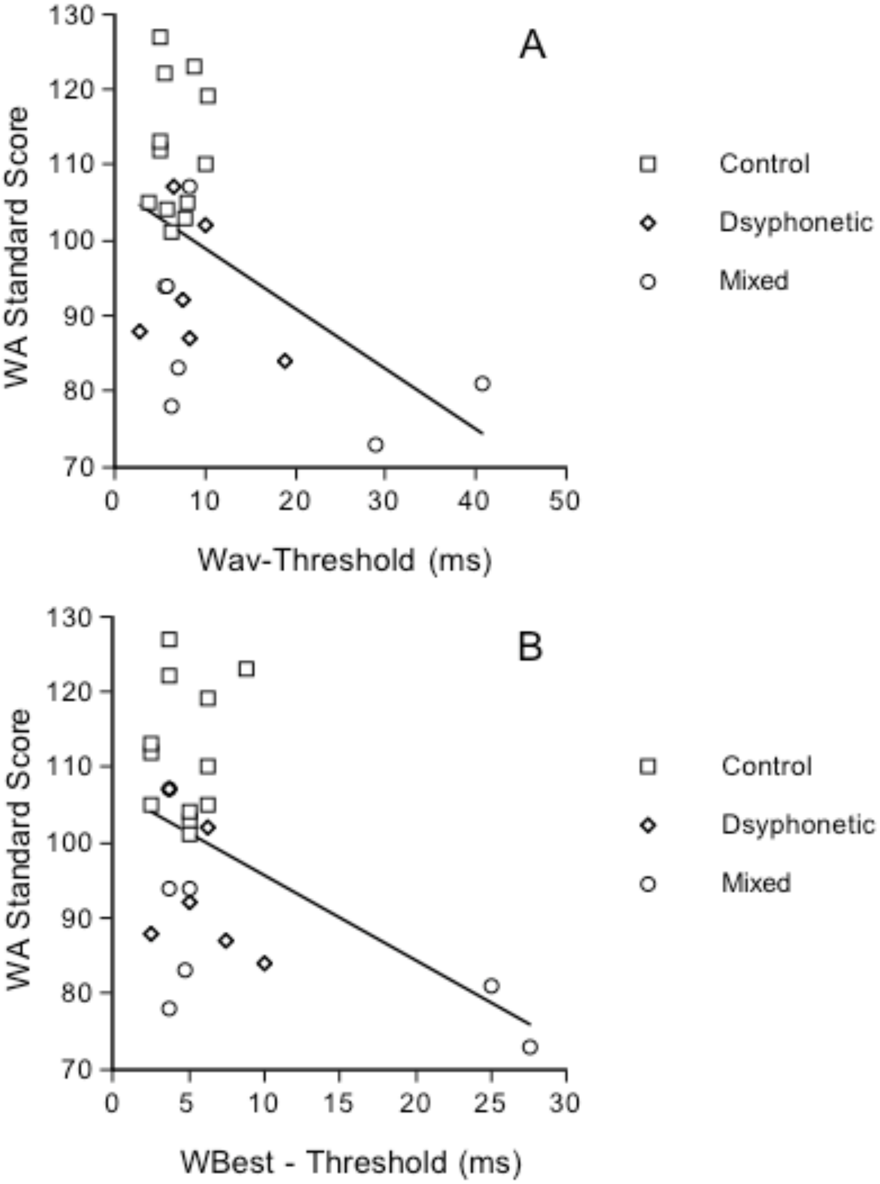

Figure 14. Bivariate scatterplots and linear regression lines for performance on the Word Attack subtest of the *WRMT-R* as a function of (A) mean and (B) best performance on the Within-Channel Gap Detection Task.

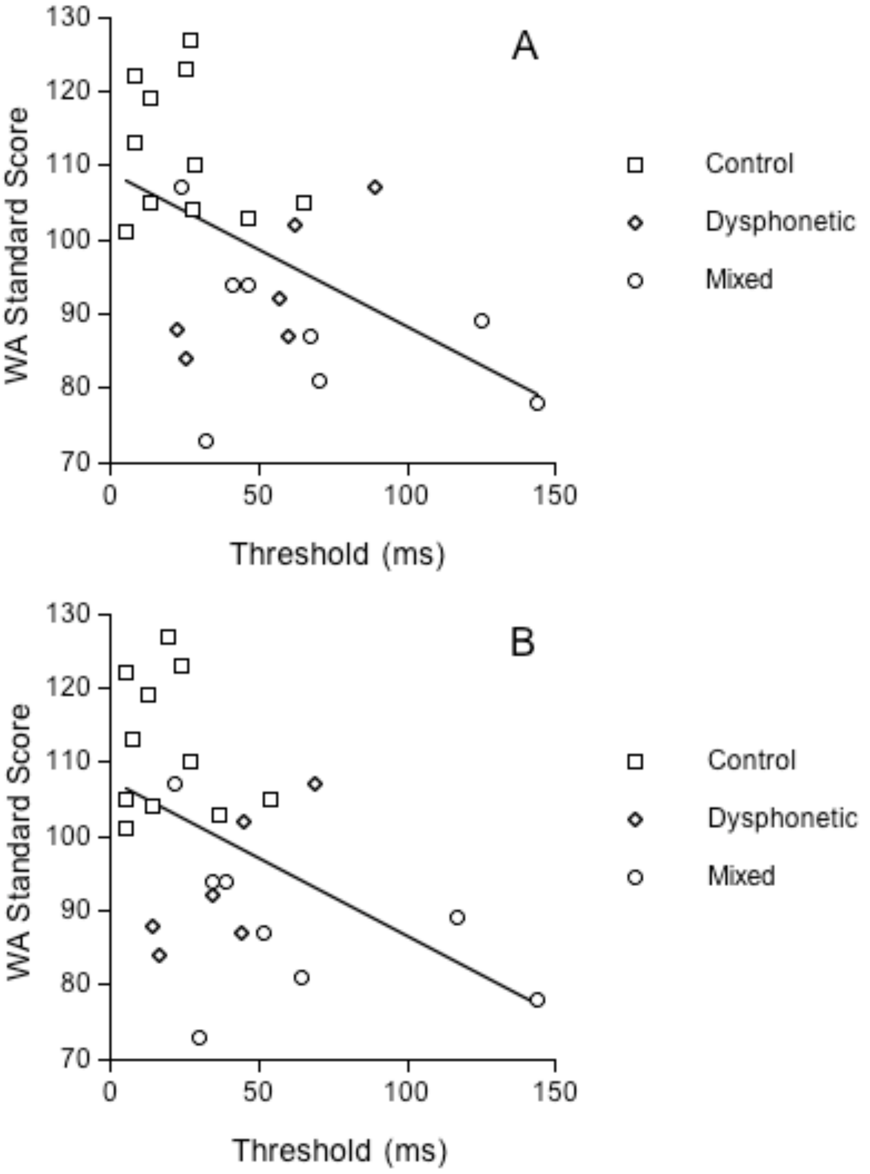

Figure 15. Bivariate scatterplots and linear regression lines for performance on the Word Attack subtest of the *WRMT-R* as a function of (A) mean and (B) best performance on the Between-Channel Gap Detection Task.

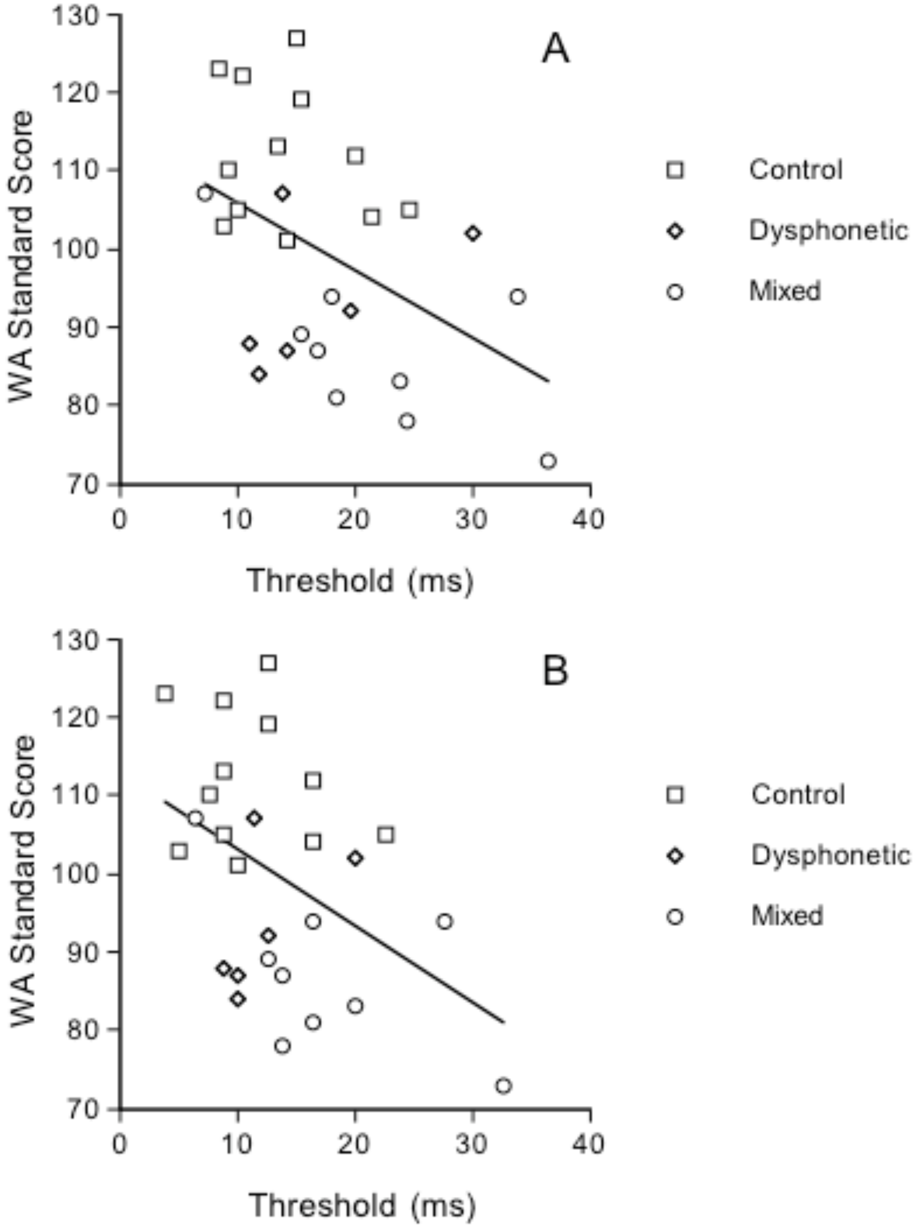

Figure 16. Bivariate scatterplots and linear regression lines for performance on the Word Attack subtest of the *WRMT-R* as a function of (A) mean and (B) best performance on the Auditory Duration Discrimination Task.

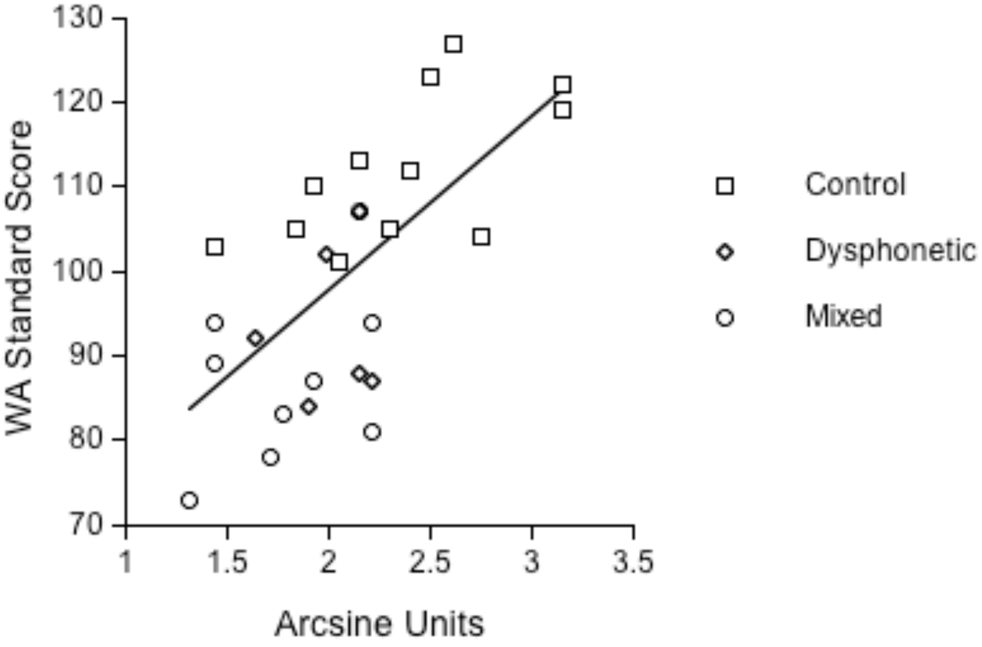

Figure 17. Bivariate scatterplot and linear regression line for performance on the Word Attack subtest of the *WRMT-R* as a function of performance on the Auditory Duration Pattern Judgment Task.

Auditory Tasks and Word Identification. Average and best threshold (ms) for the auditory gap detection and auditory duration discrimination tasks, as well as accuracy (i.e., proportion) on the auditory duration pattern task, were also compared to performance on the Word Identification subtest of the *WRMT-R*. This analysis revealed several significant correlations between performance on auditory tasks assessing between-channel gap detection, duration discrimination, and duration temporal order judgment and performance on the Word Identification subtests as summarized in Table 25 and illustrated in Figures 18-20. Specifically, significant negative correlations were found between average and best thresholds (ms) on the between-channel gap detection paradigm and the average and best thresholds (ms) on the auditory duration discrimination task and standard scores on the Word Identification subtest of the *WRMT-R*. A significant positive correlation was found between accuracy on the auditory duration pattern judgment task and the Word Identification subtest of the *WRMT-R*. Further, simple linear regression analyses revealed that the relation between performance on the Word Identification subtest, as a function of performance on the auditory temporal processing tasks, were statistically significant ($p < 0.05$). A summary of independent ANOVAs that tested the significance of the linear relationships between the Word Identification subtest of the *WRMT-R* and all auditory tasks (average and best thresholds and accuracy proportion) is presented in Table 26.

Visual Tasks and Word Attack and Word Identification. To better understand the relationship between visual temporal processing and performance on reading measures

Table 25.

Pearson Product-Moment Correlations Between Performance the Word Identification (WI) Subtest of the WRMT-R and the Mean (avg) and Best (best) Threshold on the Auditory Gap Detection Task (Within-[WC] and Between-Channel [BC]), Auditory Duration Discrimination Task (ADD), and Proportion of Accuracy on the Auditory Duration Pattern Judgment Task (ADPT).

	WCavg	WCbest	BCavg	BCbest	ADDavg	ADDbest	ADPT
WI	-0.36	-0.32	-0.61**	-0.60**	-0.38*	-0.38*	0.63**

Note: *p < 0.05; **p < 0.01

Table 26.

Summary of Independent ANOVAs Investigating the Linear Relationship Between Performance on the Word Identification (WI) subtest of the WRMT-R as a Function of Performance on the Experimental Auditory Tasks.

Task	Source	*df*	*F*	*p*
BCavg	Regression	1	13.80	0.001
	Residual	23		
BCbest	Regression	1	12.95	0.002
	Residual	23		
ADDavg	Regression	1	4.30	0.04
	Residual	25		
ADDbest	Regression	1	4.26	0.04
	Residual	25		
ADPT	Regression	1	12.56	0.002
	Residual	25		

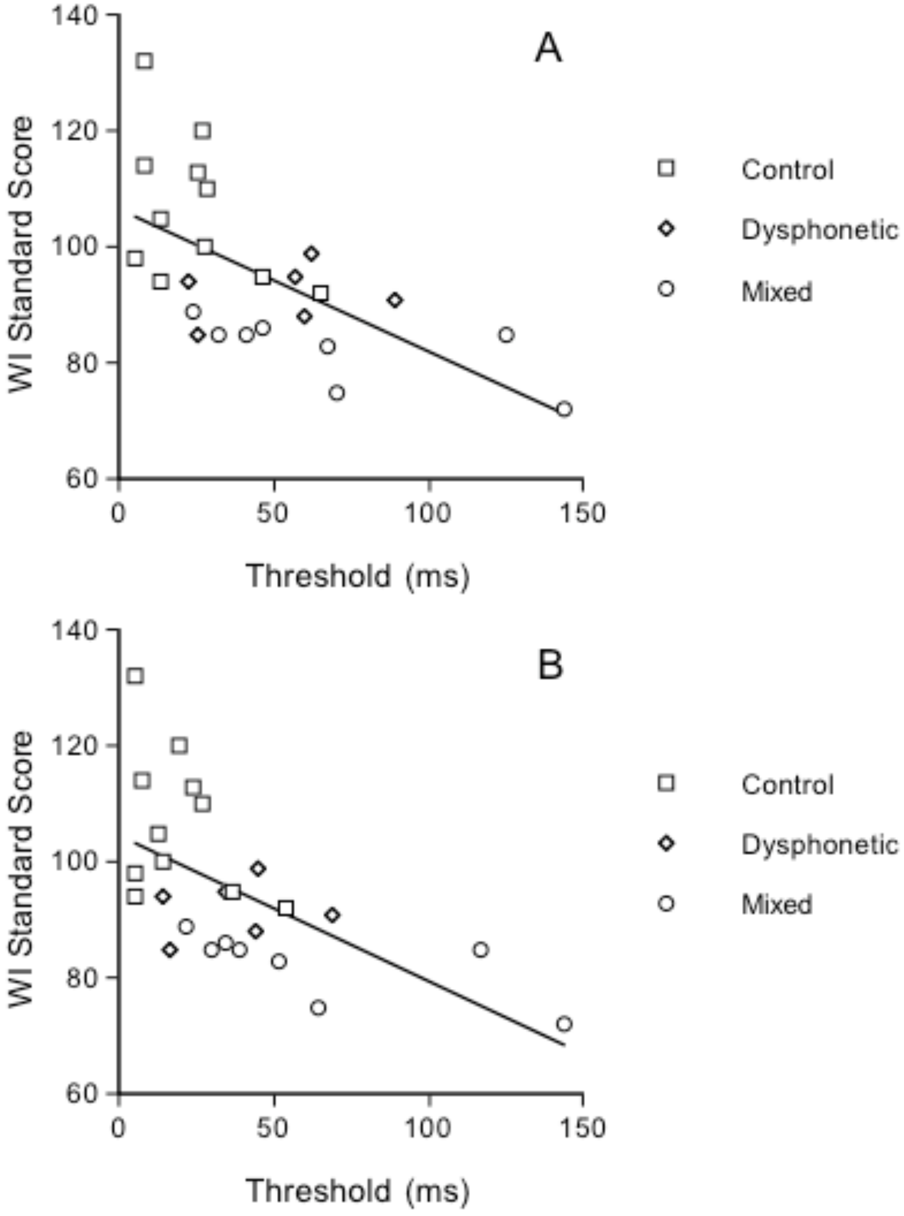

Figure 18. Bivariate scatterplots and linear regression lines for performance on the Word Identification subtest of the *WRMT-R* as a function of (A) mean and (B) best performance on the Between Channel Gap Detection Task.

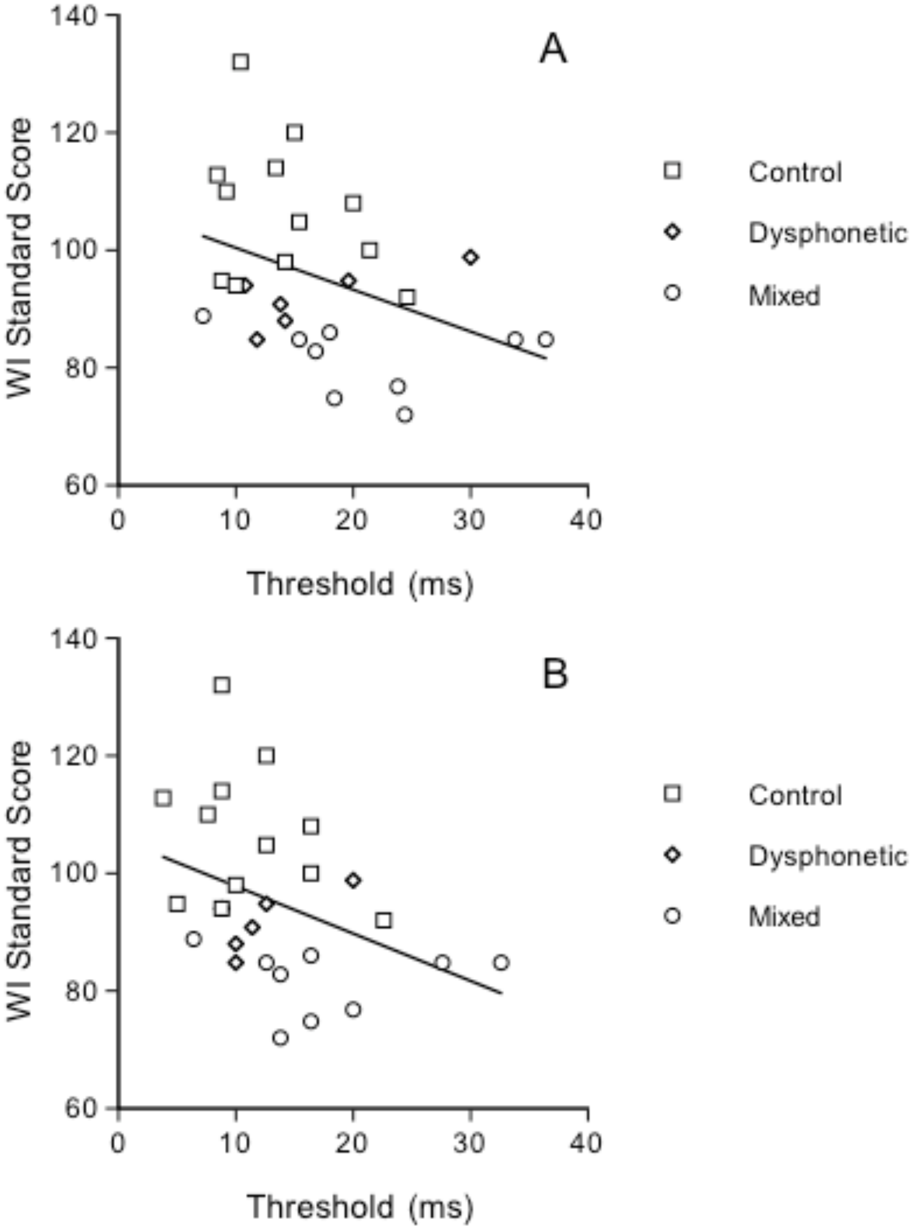

Figure 19. Bivariate scatterplots and linear regression lines for performance on the Word Identification subtest of the *WRMT-R* as a function of (A) mean and (B) best performance on the Auditory Duration Discrimination Task.

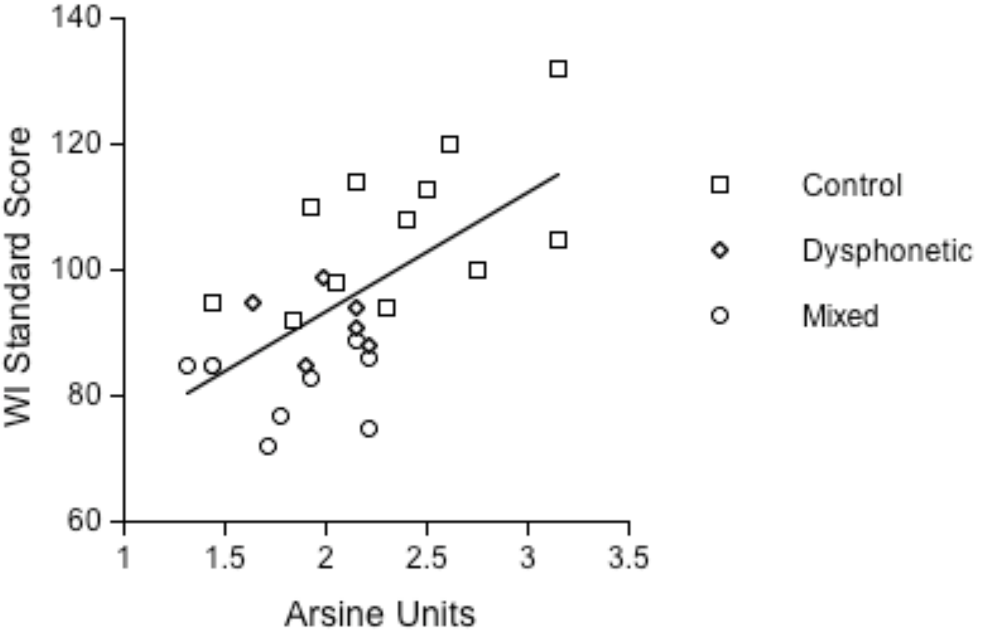

Figure 20. Bivariate scatterplot and linear regression line for performance on the Word Identification subtest of the *WRMT-R* as a function of performance on the Auditory Duration Pattern Judgment Task.

assessing phonological decoding and visual/lexical processing (or sight-word reading) skills, average and best threshold (ms) for the visual Critical Flicker Fusion (CFF), the visual duration discrimination tasks, as well as accuracy (i.e., proportion) on the visual duration pattern task, were compared to performance on the Word Attack and Word Identification subtests of the *WRMT-R* as summarized in Table 27. For the visual experimental tasks, no significant correlations were found between thresholds (Hz) on the visual CFF task and the visual duration pattern task and performance on the Word Attack and Word Identification subtests of the *WRMT-R*. However, significant positive correlations were found between average and best threshold (ms) on the visual duration discrimination task and Word Identification subtests of the *WRMT-R*. A summary of independent ANOVAs that tested the significance of the linear relationships between the Word Attack and Word Identification subtests of the *WRMT-R* and the visual duration discrimination task (i.e., average and best thresholds) are presented in Tables 28 and 29, respectively. Bivariate scatterplots and linear regression lines for performance on the Word Attack and Word Identification subtests as a function of performance on the experimental visual duration discrimination task are shown in Figures 21 and 22, respectively.

Experimental Tasks

Similar to the pre-experimental reading tasks, Pearson Product-Moment correlational coefficient analyses were also conducted to investigate mean and best performance on experimental tasks within and across modalities among all participants.

Table 27.

Pearson Product-Moment Correlations Between Performance the Word Attack (WA) Word Identification (WI) Subtest of the WRMT-R and the Mean (avg) and Best (best) Threshold on the Visual Critical Flicker Fusion Task (CFF), Visual Duration Discrimination Task (VDD), and Proportion of Accuracy on the Visual Duration Pattern Judgment Task (VDPT).

	CFFavg	CFFbest	VDDavg	VDDbest	VDPT
WA	0.25	0.22	0.55**	0.46**	0.29
WI	0.25	0.27	0.63**	0.46**	0.35

Note: $*p < 0.05$; $**p < 0.01$

Table 28.

Summary of Independent ANOVAs Investigating the Linear Relationship Between Performance on the Word Attack (WA) subtest of the WRMT-R as a Function of Performance on the Visual Duration Discrimination Task (VDD).

Task	Source	*df*	*F*	*p*
VDDavg.	Regression	1	10.54	0.003
	Residual	24		
VDDbest	Regression	1	6.39	0.02
	Residual	24		

Table 29.

Summary of Independent ANOVAs Investigating the Linear Relationship Between Performance on the Word Identification (WI) subtest of the WRMT-R as a Function of Performance on the Visual Duration Discrimination Task (VDD).

Task	Source	*df*	*F*	*p*
VDDavg.	Regression	1	16.16	0.001
	Residual	24		
VDDbest	Regression	1	7.69	0.01
	Residual	24		

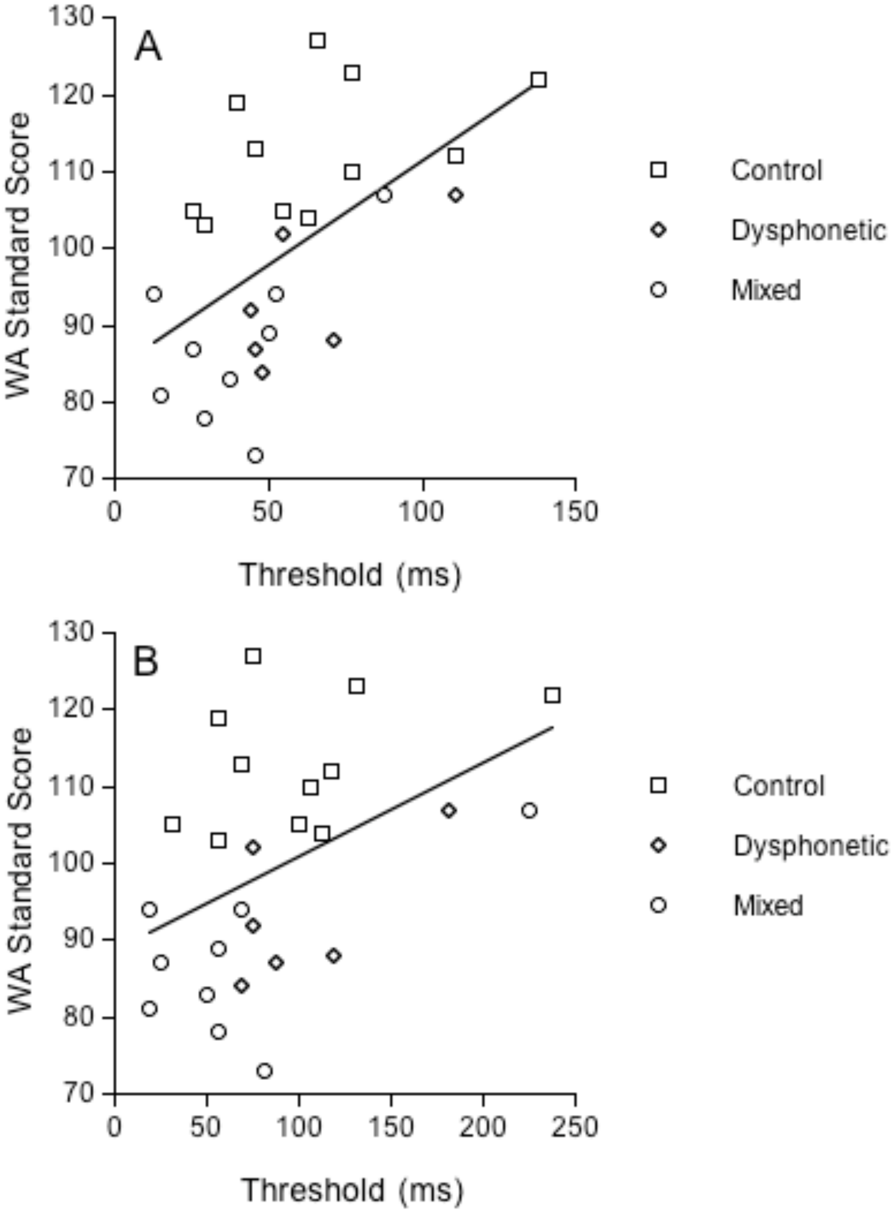

Figure 21. Bivariate scatterplots and linear regression lines for performance on the Word Attack subtest of the *WRMT-R* as a function of (A) mean and (B) best performance on the Visual Duration Discrimination Task.

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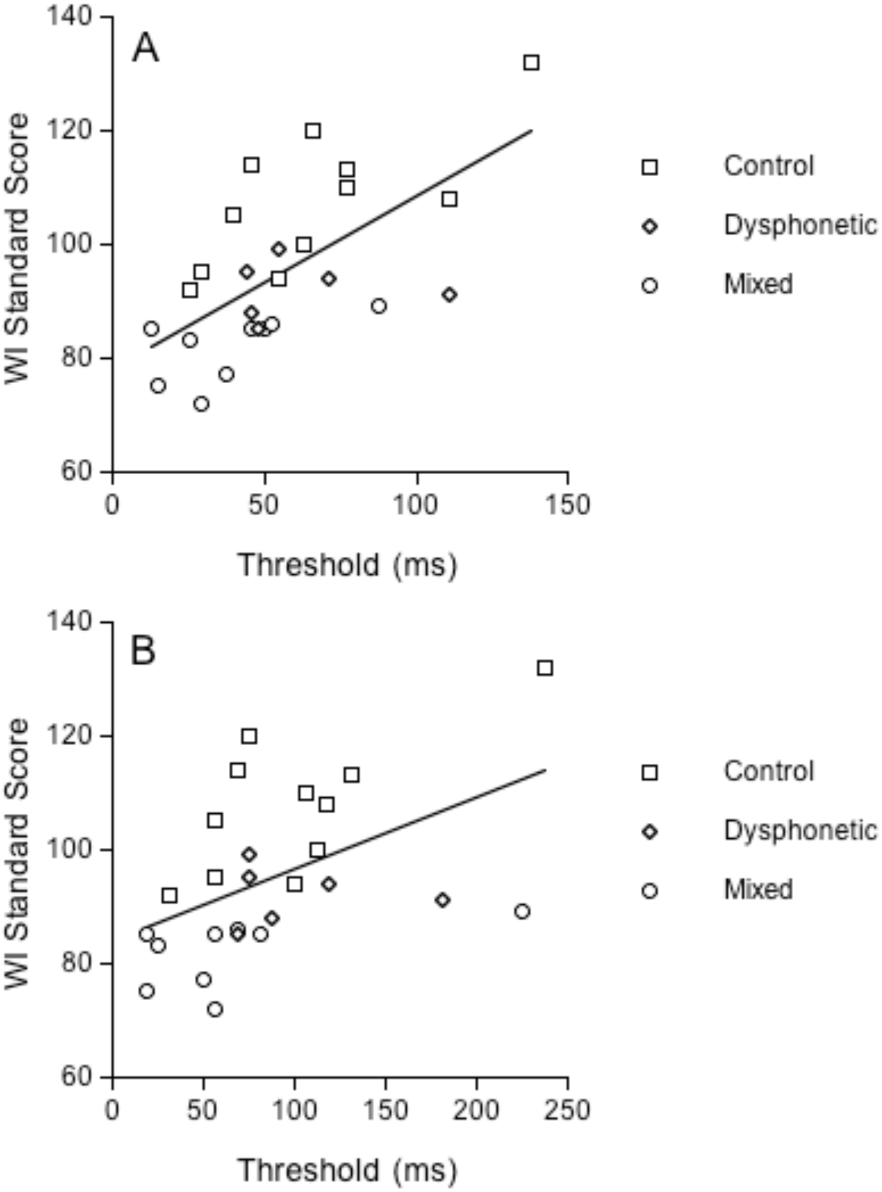

Figure 22. Bivariate scatterplots and linear regression lines for performance on the Word Identification subtest of the *WRMT-R* as a function of (A) mean and (B) best performance on the Visual Duration Discrimination Task.

The results of those correlations are summarized in Tables 30 and 31. A significant negative correlation between the average threshold and the best threshold on the between-channel gap detection task and the auditory duration pattern test was revealed. A significant negative correlation was also found between the average threshold and the best threshold on the auditory duration discrimination task and the auditory duration pattern test.

Likewise, when all performances on experimental tasks within the visual modality were compared among all participants, a significant positive correlation between the average threshold on the visual duration discrimination task and the visual duration pattern test was revealed. No other significant correlations were found within the visual experimental tasks. Finally, when performance experimental tasks were compared across modalities, significant correlations were revealed and are also summarized in Tables 30 and 31. A significant negative correlation was found between the average threshold on the auditory duration discrimination task and the average threshold and the best threshold on the visual duration discrimination task. A significant negative correlation was also revealed between the best threshold on the auditory duration discrimination task and the best threshold on the visual duration discrimination task. A significant positive correlation was found between proportion of accuracy on the auditory duration pattern judgment task and the average threshold and the best threshold on the visual duration discrimination task.

Table 30.

Pearson Product-Moment Correlations Between Mean Performances on Auditory Experimental Tasks (i.e., WCGap and BCGap, ADD, ADPT), and Visual Experimental Tasks (i.e., CFF, VDD, VDPT).

Experimental Task	BCGap	ADD	ADPT	CFF	VDD	VDPT
WCGap	0.07	0.25	-0.17	-0.31	-0.32	-0.15
BCGap	---	0.30	-0.46*	-0.17	-0.30	-0.17
ADD	---	---	-0.41*	0.03	-0.42*	0.19
ADPT	---	---	---	0.21	0.53**	0.13
CFF	---	---	---	---	0.01	0.22
VDD	---	---	---	---	---	0.45*

Note: $*p < 0.05$; $**p < 0.01$

Table 31.

Pearson Product-Moment Correlations Between Best Performances on Auditory Experimental Tasks (i.e., WCGap and BCGap, ADD, ADPT), and Visual Experimental Tasks (i.e., CFF, VDD, VDPT).

Experimental Task	BCGap	ADD	ADPT	CFF	VDD	VDPT
WCGap	0.56	0.45*	-0.21	-0.15	-0.25	-0.06
BCGap	---	0.19	-0.47*	-0.19	-0.32	-0.20
ADD	---	---	-0.42*	0.03	-0.44*	0.17
ADPT	---	---	---	0.22	0.46*	0.14
CFF	---	---	---	---	0.11	0.17
VDD	---	---	---	---	---	0.38

Note: *$p < 0.05$; **$p < 0.01$

CHAPTER IV

DISCUSSION

It has been suggested that deficits in auditory and visual temporal processing may contribute to the lack of development of basic decoding skills or the ability to rapidly transition from word to word in written text; thereby, ultimately affecting automatic and fluent reading. Research focusing on the processes involved in normal reading development has concluded that intact phonological and visual/lexical processing are the primary phenomena required to achieve automatic and fluent reading (Brown, 1997; Catts & Khami, 1999). Previous studies examining the extent of which deficits within these two processes relate to reading disorders have resulted in the emergence of two hypotheses of reading disorders: the Phonological Core Deficit and the Double Deficit Hypothesis (Brown, 1997; Hutzler et al, 2004; Schatschneider et al., 2002; Shaywitz & Shaywitz, 2005; Torgeson et al., 1994; Wolf et al., 1986; Wolf & Bowers, 1999). The Phonological Core Deficit hypothesis states that the inability to use the phonological structure of spoken words to make appropriate grapheme-to-phoneme conversions underlie most reading disorders (Moisescu-Yiflach & Pratt, 2005; Wolf and Bowers, 1999). Alternatively, proponents of the Double Deficit Hypothesis posit that, while phonological processing deficits are strongly associated with reading disorders, weaknesses in lexical access, often noted in rapid automatized naming, is a separate source of reading failure and independently contributes to the type of a reading disorder. Both theories of reading emphasize the reliance upon the auditory and visual subsystems for appropriate development of decoding skills and naming speed ability but in different ways.

Within the past decade, research has focused on a third hypothesis of reading disorders: a general temporal processing deficit (Chase & Jenner, 1993; Farmer & Klein, 1993; Lehmkuhle et al., 1993; Lovegrove, 1993). Several links between sensory systems and reading abilities have been identified (Boets, Wouters, van Wieringen, De Smedt, Ghesquiere, 2008; Karni et al., 2005; Plaza & Cohen, 2005; Schatschneider et al., 2002; Share, Jorm, Maclean, & Matthews, 2002). The first link states that accessing the lexicon through the phonological route requires the auditory system to receive and analyze temporal cues within the acoustic message. Deficits in basic perception of rapid temporal modulations, likely to occur in running speech, have been shown to impair the analysis and segmentation of speech at the phonemic level, resulting in poor phonological awareness and phonological memory as well as impaired higher-level processing of sequence patterns (Tallal, 1980; Torgeson et al., 1994). The second link asserts that accessing the lexicon via the visual/lexical route requires the visual system to accurately recognize visual features in printed text during orthographic processing for rapid retrieval of lexical information while reading (Wolf & Bowers, 1999). Deficits in basic perception of visual features in text at either the syllable or whole-word level have been linked to poor performance on naming speed tasks, the demands of which are similar to those during continuous reading. These links provide evidence to support the three subtypes of reading disorder: dysphonetic (phonological decoding deficits only), dyseidetic (sight-word reading deficits only), and dysphoneidetic (combination of phonological decoding and sight-word reading deficits) (Boder, 1973).

There continues to be debate regarding the existence of a pansensory temporal processing deficit in reading disorders. Researchers have speculated that individuals classified in one of the three RD subtypes would exhibit different patterns of performance on auditory and visual tasks (Ben-Artzi et al., 2005; Cestnick & Coltheart, 1999; Farmer & Klein, 1993; Heim et al., 2001; Ingelghem et al., 2001; Rose et al., 1999; Williams et al., 2003). Contemporary research has supported the relationship of auditory temporal processing deficits to reading disorders in both children and adults (Boets, et al., 2008; Ingelghem et al., 2001; Shaywitz & Shaywitz, 2005; Tallal, 1980; Walker et al., 2002; Walker et al., 2006; Wright et al., 1997). That is, deficits in the ability to detect rapid and subtle changes in acoustic stimuli (i.e. frequency and duration modulation) result in poor speech perception and may affect reading acquisition; however, results from visual studies investigating the magnocellular theory of reading disorder remain inconclusive (Galaburda & Livingstone, 1993; Hood & Conlon, 2004; Lehmkuhle et al., 1993; Skottun, 2000). It remains unclear as to the extent that both auditory and visual processing deficits contribute to the nature of reading disorders and if the relationship to reading disorders is causative or comorbid conditions.

The purpose of the study was to further investigate the existence of a pansensory (auditory and visual) temporal processing deficit in school-aged children with reading disorders to determine if an association existed between specific subtypes of reading disorders and differences in auditory and visual sensory processing abilities. The current investigation examined auditory and visual temporal processing hierarchies through a series of analogous tasks assessing detection, discrimination, and temporal order judgment abilities in an attempt to determine if a pattern of performance was specific to either of the two subtypes of reading disorders (i.e., dysphonetic and dysphoneidetic) identified by the current investigation using criteria outlined by Boder (1973). In this investigation, it was hypothesized that children identified as dysphonetic readers would exhibit greater difficulty with tasks assessing auditory temporal processing abilities due to the primary deficit in phonological awareness. However, children with miexed or phonological and visual/lexical (sight-word) reading disorder (i.e., dysphoneidetic) would exhibit deficits on tasks assessing auditory and visual temporal processing due to the mixed nature of the reading disorder. Therefore, evidence of different patterns of auditory and visual temporal processing, as a function of the nature of the reading disorder, would further explain and define a possible pansensory temporal processing deficit in individuals with reading disorders.

For the purposes of this study, descriptive and inferential analyses were critically conducted on each of the auditory and visual temporal processing tasks between the control group and the dysphonetic and dysphoneidetic groups when RD was treated as heterogeneous disorder. The purpose was to determine if the above mentioned specific patterns of deficient performance observed on each of the experimental tasks (i.e., detection, discrimination, and temporal order judgment), in both modalities, were indicative of underlying deficits in one or both of the sensory systems, thereby giving credence to the pansensory deficit hypothesis of reading disorders.

Auditory Gap Detection Task: Threshold Analysis

The first experimental question addressed whether statistically significant differences in mean and best gap thresholds (ms) were found as a function of group (i.e., control, dysphonetic, dysphoneidetic) and gap paradigm (i.e., within-channel or between-channel). Analysis of thresholds revealed a significant main effect of gap paradigm between the groups. That is, the within-channel gap paradigm yielded lower average thresholds (i.e., control = 6.78 ms; dysphonetic = 9.04 ms; and dysphoneidetic = 13.11 ms) than the average thresholds on the between-channel gap paradigm (i.e., control = 24.33 ms; dysphonetic = 52.42 ms; dysphoneidetic = 68.69 ms). These findings supported previous research by Schulte-Körne et al. (1998), Phillips and Smith (2004) and Hautus, Setchell, Waldie, and Kirk (2003) that found within-channel auditory gap detection thresholds of approximately 10 ms in normal listeners. Additionally, in the present study, the mean threshold for the between-channel gap paradigm observed for the control group (24.33 ms) was consistent with previous research where between-channel gap detection tasks with a short-duration leading marker yielded thresholds between 25-40 ms in normal listeners (Phillips, Taylor, Hall, Carr, & Mossop, 1997; Phillips, 1999; Phillips & Smith, 2004). In the present study, a significant main effect was observed for both average and “best” thresholds obtained on the between-channel gap detection task as a function of group (i.e., control and RD). Overall, the dysphonetic and dysphoneidetic readers, as a whole, had significantly elevated thresholds as compared to the normal readers. Furthermore, when analyzing performance among groups of reading disorders (i.e., control, dysphonetic, and dysphoneidetic), the present data revealed significant main effects as a function of group and gap paradigm for both the mean and “best” threshold across trials for the between-channel gap detection task. It was observed that the dysphonetic readers (i.e., mean = 52.42 ms; best = 37.08 ms) and dysphoneidetic readers (i.e., mean = 68.69 ms; best = 62.56 ms) had significantly poorer thresholds as compared to normal readers (25.37 ms) for the between-channel gap detection task. The findings of significant main effects on threshold data in the between-channel gap paradigm as a function of group support the original hypothesis that individuals with reading disorders would perform poorer on auditory tasks requiring detection of temporally modulated acoustic signals.

It has been suggested that asymmetries in allotment of attention to the perceptual channels activated by the between-channel task may be responsible for the difference in gap detection thresholds between the within-channel and between-channel paradigms (Phillips, 1999). In other words, allocating perceptual or attentive resources to one channel may “impoverish the time stamping of the event in any other channel” (Phillips, 1999, p. 348). As previously mentioned, the between-channel paradigm assesses the relative timing of the offset of activity in one perceptual channel and the relative timing of the onset of activity in a different perceptual channel in the auditory system. Thus, the listener must attend to information processed in two separate channels in the auditory system when an acoustic signal is presented containing leading and trailing markers differing from one another in frequency, duration, or intensity, as is demonstrated in speech perception. The more rapid rates of temporal modulation in running speech are evidenced in formant transitions. “Whereas the first function of transitions is to carry phonetic information, another is to bind together phonetic segments so that at rapid transmission rates the temporal order of speech may be preserved" (Tallal, 1980, p. 196). The inability to detect rapid transitions in running speech is important when examining the relationships between auditory temporal processing, speech perception, and phonological awareness.

Elangovan and Stuart (2008) investigated the role of the auditory mechanisms involved in distinguishing among different phonetic features in speech. Within- and between-channel gap paradigms were utilized to determine the psychoacoustic relationship between gap paradigm and perception of categorical voice onset time in the stop consonants /b/ and /p/. They found that the between-channel gap detection thresholds were significantly correlated to categorical voice onset time perception. This was not the case with the within-channel thresholds. With regards to speech perception, the inability to perceive subtle differences between phonemes acoustically similar to one another, such as those that are voice onset time oppositions (i.e. /ba/-/pa/) may indicate a deficit in phonological awareness. Deficits at the phoneme level prevent "[normal manipulation of] phonological information thus impairing [the] ability to acquire phonological prerequisites to learning to read" (Habib, 2000, p. 2381). The inability to master phonological prerequisites during reading acquisition prevents the ability to develop appropriate spelling-to-sound correspondences. It has been argued that temporal cues convey important phonetic information in spoken language; therefore, deficits in auditory temporal processing may lead to deficits in speech perception and, subsequently, phonological processing (Talcott, Witton, McClean, Hansen, Rees, Green, & Stein, 1999).

As widely reported in the literature (Brown, 1997; Schatschneider et al., 2002; Shaywitz & Shaywitz, 2005; Torgeson et al., 1994), intact phonological skills are needed, but not independently sufficient, in the development of phonological decoding strategies.

The auditory experimental tasks utilized in the current study examined performance on auditory temporal processing skills (i.e., detection, discrimination, and temporal ordering) relative to phonological decoding in order to determine if breakdowns in low-level auditory processing abilities were reflected in reading disorder subtypes. The current investigation found overall poorer performance on nonword reading tasks during pre-experimental testing and a general elevation of between-channel gap detection thresholds for the dysphonetic (52.42 ms) and dysphoneidetic (68.69 ms) readers as compared to the nonword reading task performance and subsequent between-channel gap detection thresholds for the normal readers (24.33 ms). When further examining the bottom-up direction of the relationship between auditory and phonological processing, phonological awareness skills are directly influenced by sound knowledge acquired during speech perception. Deficits in this area can contribute to poor reading decoding, specifically in the phonological decoding strategy. Phonological decoding is a reading strategy that relies on the segmentation and analysis of words into individual phonetic units and matching them to their corresponding letter representations in text (Talcott, Witton, McLean, Hanson, Rees, Green, & Stein, 2000). The quality of phonological representations stored in the mental lexicon is highly dependent upon the ability of the auditory system to accurately perceive the temporal cues embedded in a speech signal. Disruptions in speech perception, due to deficits in auditory temporal processing, may result in misrepresentations of phonological information stored in long-term memory thus impairing decoding skills in individuals, which results in a dysphonetic reading/spelling pattern. The inability to process temporal cues related to phonetic features in speech, such as for voiced and voiceless consonants and formant transitions, may negatively impact accurate speech perception and thus impair higher-level phonological processing and phonological decoding skills. Thus, underlying auditory temporal processing deficits may explain the reason that a dysphonetic reading pattern exists in some individuals.

Auditory Duration Discrimination Task: Threshold Analysis

The second experimental questions addressed whether statistically significant differences in mean threshold (ms) were found as a function of group (i.e., control, dysphonetic, dysphoneidetic). Statistical analysis of threshold data revealed no significant main effect of threshold as a function of group. Thus, individuals with RD were found to be as efficient as the control group at discriminating differences in a sequence of auditory events when the duration of one event was manipulated. This finding did not support the hypothesis that individuals with differing subtypes of RD would perform significantly poorer on tasks assessing discrimination abilities when the acoustic signal was manipulated in the temporal domain.

The lack of significant difference in thresholds between the normal, dysphonetic, and dysphoneidetic readers for the auditory discrimination task may be explained by interstimulus interval (ISI) duration, which was held constant at 400 ms. It has been suggested that a faster rate of presentation may significantly interfere with higher-level processing, such as discrimination of the acoustic signal in individuals with reading disorders (Cestnick & Jerger, 2000; Tallal, 1980). Cestnick and Jerger (2000) investigated a series of auditory temporal processing tasks, of which a Fast Same-Different and Slow Same-Different task were utilized in groups of good readers, poor nonlexical readers (i.e., poor nonword readers), and poor lexical readers (i.e., poor irregular word readers) based on performance on the same *Word/Nonword Test* utilized in the current investigation. In the "fast" condition, ISIs were varied from 8 to 305 ms whereas for the "slow" condition, ISIs were kept constant at 428 ms. The researchers found group differences in performance between good and poor readers for the "fast condition" but not the "slow" condition. The poor readers had higher thresholds on the Fast Same-Different task than the good readers. Thus, the more rapidly in succession the stimuli were presented, the more taxing the task on the auditory system for the poor readers. Therefore, shortening the ISI duration between stimuli in the auditory duration discrimination task similar to Cestnick and Jerger's (2000) Fast Same-Different task should be taken into consideration for future investigations.

Auditory Duration Pattern Judgment: Accuracy Analysis

The third experimental question addressed whether statistically significant differences in mean percent accuracy on an auditory duration pattern task were observed as a function of group (i.e., control, dysphonetic, or dysphoneidetic). Accuracy analysis revealed no significant main effect of group (i.e., control = 81.00%, dysphonetic = 70.50%, and dysphoneidetic = 60.44%). The lack of significant difference in performance between the control group and the dysphonetic and dysphoneidetic groups does not support the hypothesis, posed by the current investigation, that individuals with reading disorders would perform poorer on tasks assessing temporal order judgment abilities when the acoustic stimuli were manipulated in the temporal domain.

For the current investigation, the mean percent accuracy for the control group was 81.00% (SD =17.20). The mean percent correct scores obtained by the control group in this investigation were consistent with normative data (Musiek, 1994) cited in Bellis (2003) who reported norms for the Duration Pattern Test set two standard deviations below the mean at 70%, 71%, and 73% for normal listeners at ages 10, 11, and 12 years, respectively. Thus, normal readers performed within the normal limits for the duration pattern temporal order judgment task (DPT).

When investigating performance on an auditory duration pattern task (DPT) in children with reading disorders (RD), Walker et al. (2006) found that children (mean age 10.75) performed significantly poorer on the DPT task as compared to age-matched, normal reading peers (mean age 10.67). She reported DPT mean percent correct scores of 57.3% (SD = 19.8) and 56.9% (SD = 19.3) for the right and left ears, respectively. In the current study, the mean percent correct score for the dysphonetic and dysphoneidetic groups was observed at 70.50% (SD = 10.01) and 60.44% (SD = 16.79), respectively. When comparing mean percent scores for the RD group in the current study to norms reported by Musiek (1994), the overall RD group performance did not fall two standard deviations below the mean, suggesting that an auditory temporal judgment task, in which duration of the stimuli is manipulated, was not found in children with reading disorders in the current investigation.

The lack of significant difference in accuracy on the duration pattern judgment task, utilized in the current investigation, may have been due to the nonlinguistic mode of response. Participants were provided a piece of paper depicting the duration sequences and were instructed to point to the sequence that corresponded to the pattern perceived. It has been suggested that temporal order judgment tasks require a child to "focus auditory attention, discriminate meaningless segments of sound, and retain these elements briefly in auditory short-term/working memory…" (Share, Jorm, Maclean, & Matthews, 2002, p. 174). By providing graphical depictions of all possible duration patterns, the participant was able narrow down possible pattern choices, thereby, diminishing the use of short-term memory. In the current study, if the manual response mode been hand gesturing, t perhaps significant differences in accuracy on the temporal order judgment task would have been observed as it would have required the participant to rely more heavily on attention, discrimination, and temporal sequencing abilities, which are utilized during speech perception. Significantly poorer ability in the retention of identified unfamiliar patterns of sound sequences, that could be stored in short term memory and retrieved during the temporal order judgment task, may reflect the presence of disproportional phonological processing skills, which "pertains to the analysis of larger phonological units such as rhymes or syllables" (De Jong et al., 2000, p. 276). Deficits in lower-level auditory temporal processing abilities may subsequently impair higher-level analysis and manipulation of phonemic information used in decoding novel words and in acquiring receptive vocabulary. This observation provides further support for the relationship between auditory temporal processing deficits and reading disorders.

Visual Critical Flicker Fusion Task: Threshold Analysis

The first visual experimental task addressed the question of whether statistically significant differences in threshold (Hz) on a flicker/fusion task were observed as a function of group (i.e., control, dysphonetic, and dysphoneidetic). Threshold analysis revealed no main effect of group. It was expected that the individuals identified as dysphoneidetic would demonstrate a marked difference in performance on a visual temporal processing task assessing detection of visual stimuli that had been manipulated in the temporal domain. The lack of evidence indicating poorer performance on a detection task in the visual domain failed to support the hypothesis posed by the current investigation. The grand mean and "best" threshold (Hz) for the control group was 41.45 Hz (SD = 3.19) and 44.45 Hz (SD = 5.34), respectively and were not statistically significant as compared to the grand mean and "best" thresholds (Hz) for the dysphonetic readers (mean = 37.97 Hz, SD = 3.16; best = 40.42 Hz, SD = 1.51) and dysphoneidetic readers (mean = 40.09 Hz, SD = 8.94; best = 42.66 Hz, SD = 10.46). The findings of critical flicker fusion (CFF) thresholds in the current study are consistent with in-phase thresholds reported by Cross (1963), who reported normative mean CFF threshold data of 41.6 Hz (SD = 4.2) and 43.4 Hz (SD = 3.8) for children ages 10 and 12 years, respectively.

The results of the current investigation did not provide evidence of a visual temporal processing deficit in individuals with reading disorders as previously found in a series of a variety of behavioral and electrophysiological studies, utilizing flicker sensitivity and double flash tasks that have found the presence of visual temporal processing deficits in individuals with reading disorders (RD) (Lehmkuhle et al., 1993; Ingelghem et al., 2001). While these investigations found elevated thresholds in individuals with reading disorders as compared to normal readers, the nature of the behavioral visual CFF task utilized in the present study differs from the double flash tasks utilized in those studies in stimuli presented, experimental apparatus, and stimulus presentation. Thus, inconsistencies in support of the magnocellular theory of reading disorder warrant further exploration of visual gap detection task that assesses the magnocellular pathway of the visual system.

Visual Duration Discrimination Task: Threshold Analysis

The second experimental task addressed the question of whether statistically significant differences in threshold (ms) on a visual discrimination task, in which duration of the visual stimuli was modified, were observed as a function of group (i.e., control, dysphonetic, and dysphoneidetic). Threshold analysis for both the mean and best thresholds revealed no significant main effect of group. The lack of evidence indicating poorer performance on a detection task in the visual domain failed to support the initial hypothesis where a significantly poorer performance on a visual temporal processing involving discrimination of visual stimuli was expected for children with a dysphoneidetic reading disorder as compared to the control and dysphonetic readers. The grand mean average and “best” thresholds were 65.83 ms (SD = 34.12) and 99.24 ms (SD = 55.24) for the normal readers, respectively, and were not statistically significant from the mean and “best” thresholds for the dysphonetic (mean = 62.15 ms, SD = 25.60; best =

101.04 ms, SD = 43.20) and dysphoneidetic (mean = 39.35 ms, SD = 23.14; best = 66.66 ms, SD = 63.35) readers.

It is believed that the visual duration discrimination task utilized in this study taxed the magnocellular pathway of the visual system due to the temporal nature of its design. As with auditory temporal processing, the ability of the visual system to detect subtle and rapid changes in stimuli aids in the ability to automatically identify and discriminate whole word or letter patterns in text during continuous reading, thereby enhancing automaticity and fluency. There are no known studies to date that have assessed visual duration discrimination utilizing the same methods as the current investigation. The visual duration discrimination task employed in this study yielded large amounts of variance for all groups. The results (i.e. high variance) of the present study suggest that further examination of the current stimulus design for the visual duration discrimination task utilized is warranted to determine the most effective manner in which the relationship between visual temporal processing and orthographic processing and decoding may be investigated.

Visual Duration Pattern Judgment Task: Accuracy Analysis

The third visual experimental question addressed whether statistically significant differences in mean accuracy on a visual duration pattern test were observed as a function of group (i.e., control, dysphonetic, and dysphoneidetic). Accuracy analysis revealed no significant main effect of group. In the original hypothesis, it was expected that the individuals identified as dysphoneidetic would demonstrate a marked difference in performance on a visual temporal processing task assessing temporal order judgment of visual stimuli that had been manipulated in the temporal domain. The lack of evidence indicating poorer performance on a detection task in the visual domain failed to support the origninal hypothesis. The grand mean percent correct scores were 54.67% (SD = 17.25), 55.83% (SD = 26.91), and 52.22% (SD = 16.99) for the control group and the dysphonetic and dysphoneidetic groups, respectively, which demonstrates essentially the same performance for all groups regardless of reading ability.

There been no known studies to date that have assessed visual temporal order judgment abilities utilizing the same methods as the current investigation, which was designed to mimic the presentation mode of the auditory Duration Pattern Test. That is, nonlinguistic stimuli (*) were presented discretely with ISI held constant and were varied in length of presentation on the computer screen, similarly to the six duration patterns for the auditory duration pattern task. As with the auditory temporal order judgment task, the visual temporal patterning task required the child to focus attention, discriminate segments of nonlinguistic symbols, and retain this information briefly in working memory. The findings of the current investigation indicated the possibility that the visual temporal judgment task may have been too demanding on working memory or that there may have been a general level of task difficulty for all the groups, regardless of reading ability. Future investigation of the parameters in the present visual temporal order judgment task is warranted.

Verbal Ability

Since there was a significant difference of receptive vocabulary between the control and RD groups, the contributing effects of verbal ability on performance on auditory and visual temporal processing tasks were controlled. All data were statistically analyzed with and without verbal ability (i.e., *PPVT-IV*, Quotient) as a covariate to analyze whether verbal ability significantly affected performance on auditory and visual experimental tasks. While the effects of verbal ability did not change the findings of significance previously revealed in the statistical analyses, a trend towards stronger significance was observed when verbal ability was not controlled. This was the case for all experimental tasks, with the exception of the visual duration temporal order judgment task. However, significant differences in performance found in each of the tasks before and after verbal ability was used as a covariate suggested that while there may be differences in auditory temporal processing abilities between normal readers and individuals with varying subtypes of reading disorders, verbal ability (or lexical knowledge) may also play a role in the development of reading.

Lexical ability has been linked to both language and cognitive ability. In fact, a reciprocal relationship has been identified between oral language abilities and reading. This was evidenced by the significant positive correlations between performance on the *PPVT-IV* and the Word Attack ($r = 0.60$, $p < 0.01$) and the *PPVT-IV* and the Word Identification ($r = 0.74$, $p < 0.01$) subtests of the *WRMT-R*. It has been suggested that expanded oral vocabularies enable the ability to analyze representations of sounds in unfamiliar words by using knowledge of sound structure already stored in the lexicon (Goswami, 2001). However, lexical knowledge also directly contributes to reading by bridging the gap between phonological processing and comprehension by allowing the reader to map spoken sounds to words in print (De Jong, et al., 2000; Rvachew, 2007). In other words, enhanced lexical ability aids in the synthesis and analysis of sound at the phoneme level that require greater auditory temporal acuity; likewise, higher performance on auditory tasks assessing the ability to identify and discriminate subtle distinctions of an acoustic event allows for greater access to information stored and retrieved from the mental lexicon during phonological decoding.

Correlations

Correlations between pre-experimental reading tests were undertaken to determine if word stimuli from the *WRMT-R* and *Word/Nonword Test* assessed the same decoding strategies (i.e. phonological decoding and visual/lexical decoding) since these measures were used to identify and subtype the reading groups. Several significant positive correlations were observed including significant relationships between standard scores on both subtests (Word Identification and Word Attack) of the *WRMT-R* and raw scores on all word lists (Regular Word, Irregular Word, and Nonword) of the *Word/Nonword Test*. These findings were expected and suggest that the two different reading measures assess similar decoding strategies, specifically phonological decoding and sight-word reading. When examining specific relationships between the Word Identification and Word Attack subtests of the *WRMT-R* and the Regular Word, Irregular Word, Nonword lists of the *Word/Nonword Test*, the Word Identification subtest of the *WRMT-R* was most strongly correlated with the Irregular Word list of the *Word/Nonword Test* ($r = 0.81$, $p < 0.01$). Likewise, the Word Attack subtest of the *WRMT-R* was most strongly correlated with the Nonword list of the *Word/Nonword Test* ($r = 0.87$, $p < 0.01$). Again, these findings were expected as the Word Identification and Irregular Word list each primarily assess sight-word reading abilities and the Word Attack and Nonword lists each purely assess phonological decoding abilities, as these tests consist of nonsense words.

To better understand the relationship between auditory and visual temporal processing and performance on reading measures assessing phonological decoding and sight-word reading skills, additional Pearson Product-Moment correlational coefficient analyses were conducted to investigate the performance on each experimental task to performance on the Word Identification and Word Attack subtests of the *WRMT-R*. Since the *WRMT-R* was strongly correlated with the *Word/Nonword Test*, it was used for the reading measure in correlational analyses. Given that the Word Attack subtest is a nonword reading measure assessing phonological decoding skills, it was expected that performance on all auditory experimental tasks would be strongly correlated with performance on the Word Attack subtest. Conversely, the Word Identification subtest is assumed to assess sight-word reading abilities and it was expected that performance on the visual experimental tasks would be strongly correlated with performance on the Word Identification subtest.

Several significant correlations were observed when examining correlations between the Word Attack and Word Identification subtests of the *WRMT-R* and auditory experimental tasks. Specifically, when examining the association between performance on the Word Attack subtest, as a function of performance on the auditory experimental tasks, significant negative correlations were found between the mean and best performance on the within-channel (i.e., Mean: $r = -0.44$, $p < 0.05$; Best: $r = -0.46$, $p <$

0.05) and between-channel auditory gap detection (i.e., Mean: $r = -0.50$, $p < 0.05$; Best: $r = -0.49$, $p < 0.05$) and the mean and best performance on the auditory duration discrimination tasks (i.e., Mean: $r = -0.45$, $p < 0.05$; Best: $r = -0.45$, $p < 0.05$) and the Word Attack subtest of the *WRMT-R*. Additionally, a significant positive correlation between the auditory duration pattern judgment task and the Word Attack subtest of the *WRMT-R* ($r = 0.67$, $p < 0.01$). These correlations suggest that tasks assessing auditory temporal processing are also taxed during reading tasks that primarily require phonological decoding, as with nonword reading. Further, simple linear regression analyses revealed a significant ($p < 0.05$) predictive nature of performance on auditory tasks to performance on the Word Attack subtest of the *WRMT-R*. That is, the lower the threshold on a gap detection task or auditory duration discrimination task, as well as higher accuracy on an auditory temporal order judgment task, the better the performance on the Word Attack subtest of the *WRMT-R*.

Likewise, when comparing performance on visual experimental tasks to the Word Attack subtest of the *WRMT-R*, a significant positive correlation was revealed for the mean threshold ($r = 0.55$, $p < 0.01$) and best threshold ($r = 0.46$, $p < 0.05$) on the visual duration discrimination task, which was the only visual processing task that showed significant association to nonword decoding. Of importance to note was that the auditory and visual duration discrimination tasks were significantly correlated with one another ($r = -0.44$, $p < 0.05$) and that both these tasks were significantly correlated to performance on the Word Attack subtest of the *WRMT-R*. Although all auditory experimental tasks were correlated with the Word Attack subtest, the significant relationship observed between performance on the visual duration discrimination task and nonword reading skills suggest that sensory processing across modalities (i.e., auditory and visual) may aid in the development of sound to symbol translations, or phoneme/grapheme associations, which are needed to decode when reading printed text, particularly in unfamiliar text or nonwords. The correlational analyses between experimental tasks and the Word Attack subtest provide evidence supporting the need for efficient visual discrimination abilities, which are crucial for orthographic or grapheme discrimination and in the development of grapheme/phoneme associations. These underlying skills would, therefore, underlie the deocoding of nonwords, which provides evidence for a pansensory (auditory and visual) relationship to reading.

Additionally, when comparing performance on the auditory experimental tasks to the Word Identification subtest of the *WRMT-R*, significant negative correlations were observed between the mean and best gap threshold for the between-channel gap detection task (Mean: $r = -0.61$, $p < 0.01$; Best: $r = -0.60$, $p < 0.01$) and the mean and best auditory duration discrimination tasks (Mean: $r = -0.38$, $p < 0.05$; Best: $r = -0.38$, $p < 0.05$) and performance on the Word Identification subtest. A significant positive correlation was observed between performance on the auditory duration pattern judgment task and the Word Identification subtest of the *WRMT-R* ($r = -0.63$, $p < 0.01$). This finding is congruent with a study conducted by Walker et al. (2002), where a significant association was found between performance on an auditory frequency pattern judgment task for the left ear ($r = 0.75$, $p < 0.05$) and performance on the Word Identification subtest of the *WRMT-R* in adults with reading disorders. This relationship may have been due to the fact that while the Word Identification subtest is used to measure sight-word reading skills, the word stimuli of this subtest are comprised of both nonphonetic and phonetic words. As previously described, nonphonetic words may only be decoded via the visual-lexical strategy since these words cannot be decoded by being sounded out. However, phonetic words, even in a seemingly rapid single word decoding task (as in the Word Identification subtest of the *WRMT-R*), may be decoded using a visual-lexical or phonological decoding strategy. This observation may explain the significant relationships between the Word Identification subtest and the auditory temporal processing experimental tasks. Further, simple linear regression analyses revealed a significant predictive nature ($p < 0.05$) of performance on all but one (i.e., within-channel gap paradigm) of the auditory tasks to performance on the Word Identification subtest of the *WRMT-R*. Thus, the lower the threshold on a gap detection task or auditory duration discrimination task, as well as higher accuracy on an auditory temporal order judgment task, the better the performance on the Word Identification subtest of the *WRMT-R*.

When examining the relationship between visual temporal processing and performance on a sight-word reading task (*WRMT-R*, Word Identification), a significant positive correlation was observed only between the mean ($r = 0.63$, $p < 0.05$) and best performances ($r = 0.46$, $p < 0.05$) on the visual duration discrimination task and the Word Identification subtest of the *WRMT-R*. These significant correlations suggest that visual temporal processing may have been taxed when the reading tasks were administered with forced rate and cued presentation during pre-experimental testing. The administration of the experimental visual duration discrimination task was similar to the administration of the pre-experimental reading tasks. In the visual duration discrimination task, before the nonlinguistic stimuli (*) were presented, a cross-hair appeared on the screen to cue the participant that the test sequence was about to begin. The rate of presentation of the test sequence was predetermined and presented rapidly (300 ms for the short duration and 600 ms for the fast duration). As with the *WRMT-R* Word Identification subtest, where the readers were required to visually decode word patterns quickly before moving on to the next word, the readers also had to quickly recognize and discriminate subtle differences to visual stimuli presented rapidly and in succession during the visual discrimination task. Thus, lower visual discrimination thresholds on the visual duration discrimination task were correlated to higher standard and raw scores on the sight-word pre-experimental reading tasks (*WRMT-R*, Word Identification subtest). Furthermore, a simple linear regression revealed a significant ($p < 0.05$) predictive nature of performance on the visual duration discrimination task to performance on the Word Identification subtest of the *WRMT-R*. That is, the better the threshold on the visual duration discrimination task, the higher (better) the standard score on the Word Identification subtest of the *WRMT-R*.

As with the correlational analyses for the Word Attack subtest, it is important to note that both auditory and visual tasks revealed strong relationships to the sight-word reading strategy. That performance on the auditory tasks were strongly related to performance on the Word Identification subtest is not surprising. The Word Identification subtest, while assumed to assess sight-word decoding abilities, is not a purely non-phonetic assessment. Due to the fact that some words on the Word

Identification list may be decoded phonetically, the reader may choose which reading strategy to employ during testing. Therefore, low-level auditory processing skills are still involved when the reader opts to decode via the phonological route. The correlational analyses between performance on the experimental tasks and the Word Identification subtest of the *WRMT-R* provide further support for a pansensory (auditory and visual) relationship to reading.

Additional correlations were also examined between and across the experimental tasks. When examining correlations between auditory tasks, several negative correlations were found between performance on both the auditory between-channel gap detection task and the auditory duration discrimination task to performance on the auditory duration temporal order judgment task. The correlations support the hierarchical nature of the experiments utilized in the current investigation as temporal order judgment first requires the ability to identify and discriminate differences within acoustic events, which then serve as precursors for accurately sequencing those events according to order of presentation. Also supporting the use of hierarchical experimental tasks was the significant negative correlation found between performance on the visual duration discrimination task and the visual duration temporal order judgment task. The design of the visual discrimination and temporal order judgment tasks mimicked those of the auditory tasks assessing discrimination and temporal patterning abilities. The significance of the correlation found between the visual duration discrimination task and the visual temporal order judgment task used in the current investigation suggests that the processes involved in the discrimination task serves as a precursor to the visual temporal order judgment task.

Finally, a significant negative correlation ($r = -0.42$, $p < 0.05$) was found between performance on the auditory duration discrimination task and the visual duration discrimination task utilized in the current investigation. While the visual tasks designed and utilized in the current investigation did not reveal visual temporal processing deficits in individuals with reading disorders, the correlation between the auditory duration discrimination and visual duration discrimination tasks suggests that the design of the visual duration discrimination task was analogous to that of the auditory duration discrimination task. Thus, it is inferred that the processes tasked during auditory duration discrimination were of a similar nature to those tasked during visual duration discrimination.

Limitations

Low participant numbers for the dyseidetic RD group (sight-word reading deficit only) may have been affected by inclusionary age criteria, recruitment methods, and a small participant pool, which may have limited the identification of more children with a primary deficit in sight-word decoding skills. The use of rapid automatized naming tasks (RAN) may have helped to identify this RD subtype.

A possible limitation specific to the experimental tasks employed in this investigation was the efficiency of visual experimental tasks used to assess visual temporal processing. It is possible that the visual duration discrimination and visual temporal order judgment tasks may have been too difficult for all experimental groups.

The visual stimuli were presented at 300 ms for the short stimulus and 600 ms for the long stimulus, approximately 50 to 100 ms longer than the stimuli used for auditory duration discrimination and auditory temporal order judgment. While a ceiling effect was not observed in the current study, it was observed that participants needed more practice with the familiarization trials before meeting the criteria to continue on to the experimental trials. Increasing the stimulus duration during familiarization trials and initial presentations during experimental trials may alleviate initial demand on attention, reduce participant mistakes, and increase the rate of desired responses during the experimental task, thus increasing the possibility for more significant differences to be observed between experimental groups. Therefore, lengthening the presentation duration of the visual stimuli utilized on both the visual discrimination and visual duration pattern tasks should be taken under consideration.

Conclusions

The purpose of the current investigation was to determine if a relationship existed between reading disorders and deficits in auditory and/or visual temporal processing. As mentioned previously, the Double Deficit Hypothesis suggests that difficulty with both phonological decoding and naming speed independently contribute to overall reading difficulty in children with reading disorders (Wolf & Bowers, 1999). Thus, difficulty in decoding the written word via the phonological and/or the visual/lexical routes suggests impairment in low-level perceptual processing in either of the two sensory modalities (auditory and visual). Using this rationale, the present study focused on the temporal processing deficit hypothesis of reading disorders by assessing auditory and visual temporal processing through a series of analogous hierarchical tasks designed to examine detection, discrimination, and temporal patterning abilities in both normal readers and children with reading disorders. The current investigation did not find evidence of a pansensory temporal processing deficit in children with reading disorders on experimental tasks across modality when the reading groups were dichotomized, which did not support the initial hypothesis that children with reading disorders would exhibit greater difficulty in performance on all experimental tasks in both the auditory and visual domains. Furthermore, the findings of the current investigation failed to support the hypothesis that individuals with particular subtypes of RD (dysphonetic and dysphoneidetic) would display different patterns of performance on the experimental tasks as a function of sensory system (auditory and visual). That is, it was hypothesized that children having both a dysphonetic and mixed reading disorder would perform poorer on all auditory temporal processing tasks, but that only the dysphoneidetic group would perform poorer on visual temporal processing tasks due to the presence of an additional sight-word deficit. However, an analysis of performance on all experimental tasks in regards to reading skill revealed significant findings that both confirmed and contributed to the relationship between auditory and visual temporal processing and reading in general.

The current investigation revealed a significant relationship between single word decoding skills, in both sight-word and phonological decoding strategies, and auditory and visual temporal processing abilities. Specifically, significant correlations were found between performance on the Word Attack subtest of the *WRMT-R* and performance on auditory temporal processing tasks involving gap detection, discrimination, and temporal ordering. These correlations suggest that auditory temporal processing is related to efficiency of phonological decoding skills as measured by reading nonwords. Additionally, and importantly, a significant association was found between performance on the Word Attack subtest and performance on the visual duration discrimination task. This finding suggests that low-level visual temporal processing in addition to lower-level auditory temporal processing is involved when using the phonological decoding strategy, as this strategy requires the ability of the reader to discriminate between graphemes and phonemes in order to utilize grapheme/phoneme associations. This finding provides evidence that pansensory temporal processing skills are related to reading skills, specifically regarding decoding abilities.

Similarly, the current investigation also revealed a significant relationship between word recognition skills and auditory and visual temporal processing. Specifically, significant associations were found between performance on the Word Identification subtest of the *WRMT-R* and performance on auditory temporal processing tasks involving detection, discrimination, and temporal ordering. These correlations suggest that, while the Word Identification subtest is used to measure sight-word decoding skills, the word stimuli are not purely non-phonetic, which allow for some words to be decoded using a phonological decoding strategy. As mentioned previously, correlational analyses revealed an association between auditory temporal processing skills and nonlexical reading abilities. Additionally, a significant association was observed between performance on the Word Identification subtest and the visual duration discrimination task. The association between visual temporal processing and word recognition skills may suggest that visual temporal processing skills are employed during sight-word reading, as the reader is required to quickly recognize and discriminate word patterns before quickly moving to the next word. As with the Word Attack subtest, a significant correlation was found between performance on the auditory duration discrimination task and performance on the visual duration discrimination task, which provides further support of low-level pansensory processing during reading. However, as mentioned earlier, results from the current investigation, when analyzing performance on the auditory and visual experimental tasks as a function of reading ability, did not support the pansensory deficit in reading disorders.

Despite the lack of evidence yielded by the current investigation to clearly determine a relationship between low-level visual temporal processing and reading disorders on visual experimental tasks, the findings from the auditory experiments in the current investigation confirmed previous research supporting the relationship between auditory temporal processing deficits and reading disorders (Rey et al., 2002; Tallal, 1980; Walker et al., 2001; Walker et al., 2006). As mentioned previously, it has been suggested that basic perceptual processing of acoustic stimuli serves as a prerequisite skill for active perception of continuous speech, which directly affects phonological processing (a higher-level linguistic skill), which subsequently impacts the development of reading and spelling (Schulte-Körne et al., 1999). It has been argued that the negative impact of auditory temporal processing deficits in relation to reading disorders is only affected by perception of linguistic stimuli, suggesting that reading disorders stemming from deficits in auditory processing is language specific (Mody et al., 1997). However, data obtained from the current investigation, in support of previous research (Tallal, 1980; Walker et al., 2001; Walker et al., 2006; Wright et al., 1997), found that children with reading disorders exhibited poorer performance on auditory tasks utilizing nonlinguistic stimuli, specifically the between-channel gap paradigm task. Elevated thresholds on the auditory between-channel gap detection task were significantly correlated to performance on the Word Attack subtest of the *WRMT-R*, suggesting a relationship between detecting and discriminating temporal changes within an acoustic signal and the ability to determine phonetic distinctions during isolated speech perception. Furthermore, the nature of nonlinguistic auditory temporal order judgment tasks require participants to focus attention on each acoustic stimulus presented, discriminate fragments of meaningless sound, and retain each fragment in short-term memory while simultaneously performing same-different operations, all of which have been suggested to "impose demands of a metalinguistic nature," similar to those used during phoneme segmentation (Share et al., 2002, p. 174). Thus, the findings of the current study indicated the presence of a nonlinguistic auditory deficit in children with reading disorders. It is, therefore, argued that insensitivity to temporal changes in a nonlinguistic signal during auditory processing would be the suggested source of a possible causal nature to deficits in higher-order phonological processing abilities (Boets et al., 2008; Share et al., 2002; Talcott et al., 2000).

The fact that the current investigation did not find evidence of an underlying visual temporal processing deficit in children with dysphoneidetic reading disorders on the visual experiments utilized was only somewhat surprising. It has been argued that the magnocellular pathway is responsible for transient motion detection, which is demonstrated in the saccadic eye movement during continuous reading (Eden et al., 1996; Lovegrove, 1997, Skottun, 2000). It has been hypothesized that individuals with primary deficits in visual/lexical access have difficulty transitioning from one letter to the next in printed text. These difficulties may be due to longer visual persistence, poor visuospatial attention, and impaired letter position encoding, all of which require a sensitivity of the visual system to rapidly transitioning stimuli (Boets et al., 2008; Talcott et al., 2000). Individuals with dyseidetic or dysphoneidetic reading deficits rely heavily on phonological decoding skills and fail to establish automatic reading patterns. Thus, these individuals tend to be slower readers. While some of these behaviors seem linguistic in nature, several studies have found visual temporal processing deficits in individuals with reading disorders using a variety of nonlinguistic tasks, such as coherent motion and flicker sensitivity (Cornelisson et al., 1998; Demb et al., 1998; Talcott et al., 2000). Therefore, it was expected that an inability to detect rapid temporal changes of nonlinguistic visual stimuli designed and utilized in the current investigation should have been observed in the children with reading disorders, if the nature of the visual processing deficit was at a sensory level. Although the data obtained on the low-level visual temporal processing tasks, used the current investigation, did not support a relationship between nonlinguistic visual temporal processing and reading disorders, it may be the case that visual temporal processing deficits would be more apparent using higher-order linguistic stimuli. Therefore, visual temporal processing deficits in individuals with dyseidetic or dysphoneidetic reading disorders may be more related to higher level visual processing deficits and lexical access or retrieval difficulties. In other words, visual temporal processing disorders exhibited by individuals with reading disorders may be more linguistic in nature rather than nonlinguistic. This was suggested by the significant correlations, found in the current investigation, between performance on the visual duration discrimination task and the Word Attack and Word Identification subtests of the *WRMT-R*. Decoding encompasses a variety of processes during visual word recognition such as sequential processing of letters, perceived pronunciation of letter strings, and the application of rules regarding grapheme-to-phoneme correspondences within words (Habib, 2000; Talcott et al., 2000; Witton et al., 1998). Therefore, tasks assessing visual temporal processing using linguistic stimuli involving lexical access should be addressed in experimental tasks in future research.

As mentioned previously, this study, in conjunction with previous literature, found a relationship between auditory and phonological processing when auditory nonlinguistic stimuli were utilized. Examination of correlational data revealed significant negative correlations between performance on the within- and between-channel auditory gap detection tasks and the Word Attack subtest of the *WRMT-R*. That is, lower thresholds (i.e. better performance) on the auditory within- and between-channel gap detection tasks were correlated to better performance on the Word Attack subtest. Likewise, a significant positive correlation was found between accuracy data on the auditory duration pattern judgment task and performance on the Word Attack subtest of the *WRMT-R*. The nonlinguistic nature of auditory temporal processing deficits, specifically those involving gap detection or temporal order patterning, provide support for the argument favoring an interdisciplinary approach in the diagnosis and management of individuals with reading disorders. The data obtained in the current study suggest that underlying deficits in the auditory sensory system may lie at the root of reading disorders, in particular those reading disorders where the primary deficit is in phonological decoding. Therefore, the administration of a comprehensive auditory processing evaluation could identify children at risk for reading disorders. While hyperactivity, inattention, and cognitive factors cannot be factored out of interpretational analysis, it would be appropriate to refer those children identified with auditory temporal processing deficits in the temporal domain for a speech and language evaluation. Alternatively, those children diagnosed with reading disorders should be referred for a comprehensive auditory processing evaluation. The inability to correctly perceive and process the subtleties of any acoustic event or speech may lead to misrepresentations of information stored in the mental lexicon, thereby negatively affecting phonological decoding and visual/lexical processing while reading. Thus, results of an auditory processing evaluation may further shed light on the nature of reading disorder and may aid in appropriate subtyping. Due to the apparent nonlinguistic relationship auditory processing deficits and reading disorders, as particularly exhibited by those individuals with a dysphonetic and dysphoneidetic reading patterns, the current study is in favor of treating reading disorders as a heterogeneous disorder and, therefore, supports subtyping individuals with reading disorders as dysphonetic, dyseidetic, or dysphoneidetic based on characteristic reading behaviors.

No other significant differences were revealed between groups on measures assessing visual temporal processing (i.e. critical flicker fusion, duration discrimination, and duration pattern judgment). Results from the analyses revealed large variances in performance between groups, suggesting either poor sensitivity of the visual tasks utilized in this study as visual analogs to the auditory tasks or that visual temporal processing deficits exhibited by individuals with a primarily dyseidetic reading behavior is more variable than auditory temporal processing deficits exhibited by individuals with a primary dysphonetic reading behavior. The dyseidetic subtype is characterized by heavy reliance on phonological decoding abilities during continuous reading due to an inability to rapidly retrieve lexical information stored in the lexicon. This may suggest that a visual temporal processing deficit is more linguistic in nature rather than a more general sensory deficit. Future studies are warranted to continue examining the relationship of visual temporal processing and reading disorders and to investigate tasks more sensitive to (i.e. linguistic in nature) visual temporal processing in both normal readers and individuals with reading disorders.

Future Research

In the current investigation, the finding that there was a strong relationship between lexical ability and auditory processing, utilizing nonlinguistic stimuli, suggests that reading disorders can arise from breakdowns in both bottom-up and top-down processing. It has been argued that reading disorders stem from a language-specific disorder rather than from an auditory temporal processing deficit (Mody et al., 1997). However, previous investigations have also supported the hypothesis that a strong relationship exists between auditory temporal processing of nonlinguistic stimuli and reading abilities (Bellis et al., 2008; Breznitz & Misra, 2003; Walker et al., 2002 & 2006). Due to the nonlinguistic nature of the relationship between lower-level auditory temporal processing deficits and reading disorders, it may be safe to assume that lower-level auditory perceptual deficits may then extend to higher-level linguistic and phonological processing difficulties. Therefore, future research should focus on using linguistic tasks in the auditory temporal domain, such as categorical perception of acoustically similar stop consonants (i.e. /b/ and /d/ or /b/ and /g/) or voice onset time oppositions (i.e. /b/ and /p/) in both words and nonwords, and compare performances on these tasks to various measures of reading, primarily those assessing phonological decoding and sight-word reading abilities.

Furthermore, implications from this study suggest a need for further investigation of the magnocellular theory of reading disorder. Previous research examining the role of underlying deficits in the visual system in RD has produced inconclusive results. The current investigation did not yield significant results indicating a magnocellular deficit in reading disorders using nonlinguistic stimuli, thereby failing to support the relationship between pansensory temporal processing deficits and reading disorders at a nonlinguistic level. However, it should be noted that this investigation failed to find children with primarily sight-word decoding deficits. As mentioned previously, this study supports the use of subtyping of reading disorders (dysphonetic, dyseidetic, dysphoneidetic) based on characteristic deficits exhibited by individuals with reading disorders. The pre-experimental testing measures failed to identify the dyseidetic subtype of reading disorders. The lack of representation of a dyseidetic subtype could be attributed to: insensitivity of the pre-experimental tasks to the dyseidetic subtype or a general lack of representation of the dyseidetic subtype among the participants as a whole due to a low participant pool or an overwhelming primary deficit in phonological decoding exhibited by all participants with reading disorders. To date, no study has used nonlinguistic visual discrimination and visual temporal order judgment tasks in the same manner as those designed and administered by the present investigation. Correlational analyses performed on the visual tasks found a significant correlation between the visual duration discrimination task and the visual duration pattern judgment task, suggesting that the participants used similar temporal processing strategies for both visual tasks. Further investigation into the design of the visual duration discrimination and visual duration pattern judgment tasks in normal readers to establish normative data and then extending the investigation to individuals with reading disorders is warranted.

As mentioned previously, some individuals with reading disorders experience difficulty rapidly transitioning from one word to the next in printed text. Reading involves brief fixations followed by saccadic eye movements. Information is processed, retrieved, and stored during these brief fixations allowing the skilled, or automatic, reader to move quickly from one word to the next without diminishing comprehension. However, it has been suggested that individuals with dyseidetic (sight-word) or dysphoneidetic (mixed) deficits of reading disorders exhibit longer visual persistence and possible letter transposition while reading due to information carried during one fixation to the next during saccadic eye movement (Boets et al., 2008; Talcott et al., 2000).

Therefore, further exploration of linguistic and nonlinguistic tasks that assess visual temporal processing utilizing saccadic eye movement is warranted.

In regards to the nonlinguistic nature of the visual temporal processing tasks, it is argued that perhaps visual temporal processing deficits in individuals with reading disorders would be more apparent using linguistic stimuli. The dyseidetic group is characterized by a primary deficit in sight-word reading. That is, these individuals rely heavily on phonological decoding abilities during continuous reading. The inability to rapidly retrieve lexical information stored in the mental lexicon may suggest that a visual temporal processing deficit is language-specific rather than a more general deficit. The ability to identify familiar letter sequences with little to no help from phonological decoding is necessary for orthographic processing of exception words. As difficulty with accurate visual/lexical access is the primary deficit exhibited by individuals with the dyseidetic subtype of reading disorders, future research investigating the relationship between visual temporal processing and reading disorders should treat reading disorders as a heterogeneous group and continue to look for specific patterns of performance in the identification of reading disorder. Additionally, as the results of the inferential and correlational analyses in the current investigation suggest, further research is needed to examine the relationship between auditory and visual temporal processing when reading abilities are viewed along a continuum, rather than as distinct categories of reading deficits or subtypes. That is, the current investigation failed to find evidence on a pansensory deficit as a function of reading ability when reading groups were dichotomized across experimental tasks, yet did find evidence to support underlying pansensory perceptual processing relative to reading ability when the association between performance on all experimental tasks and reading strategies was examined with reading groups collapsed together. Furthermore, future studies directed toward how visual temporal processing of linguistic stimuli (such as anagrams or graphically similar isolated letters) relate to naming speed tasks while examining the relationship between visual temporal processing deficits and reading disorders is also warranted.

The question whether a visual task is truly analogous to an auditory task continues to remain in question and should be further examined. Correlational analysis between auditory and visual experimental tasks revealed a significant negative correlation (r = -0.44, $p < 0.05$) between the auditory duration pattern judgment task and the visual duration discrimination task, suggesting that the visual analogs designed in the present investigation assessed similar temporal processing abilities. Therefore, the need to continue investigations into analogous auditory and visual temporal processing tasks is also warranted.

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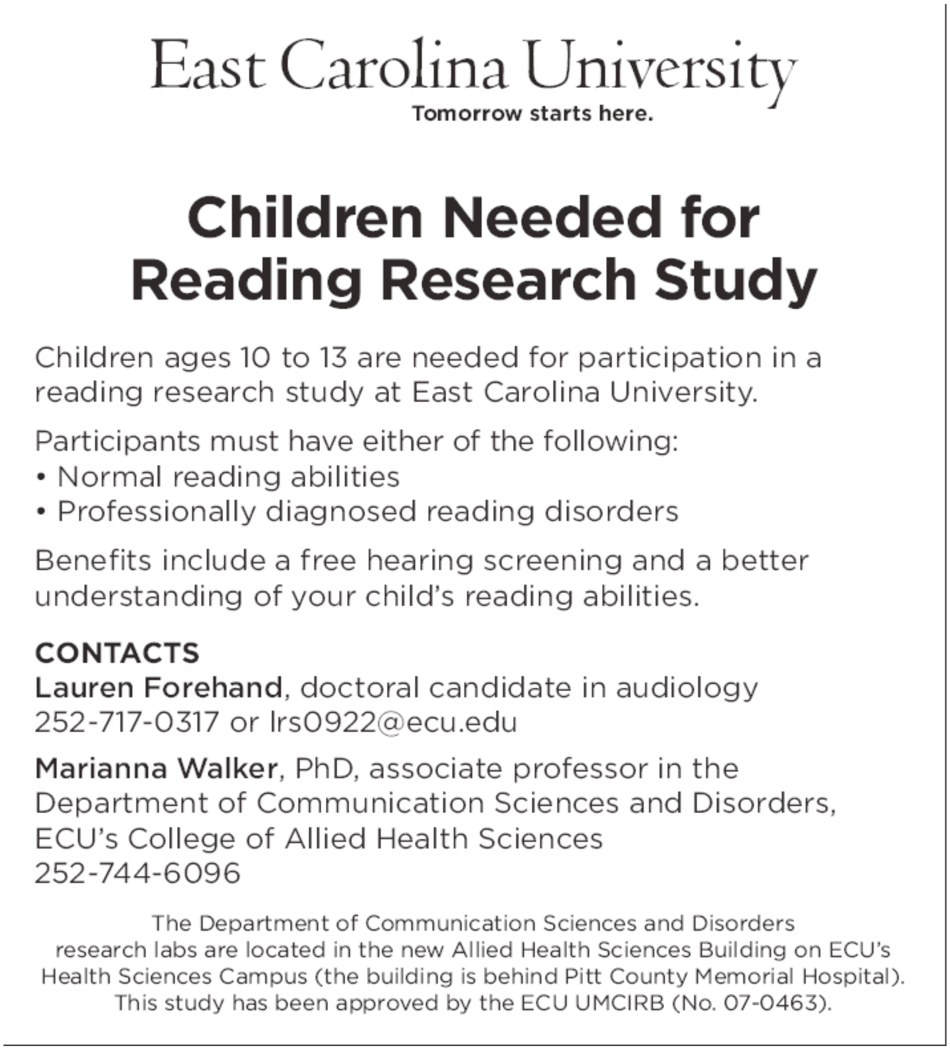
APPENDIX A: ADVERTISEMENTS FOR PARTICIPANTS



East Carolina University
Tomorrow starts here.

Children Needed for Reading Research Study

Children ages 10 to 13 are needed for participation in a reading research study at East Carolina University.

Participants must have either of the following:

- Normal reading abilities
- Professionally diagnosed reading disorders

Benefits include a free hearing screening and a better understanding of your child's reading abilities.

CONTACTS
Lauren Forehand, doctoral candidate in audiology
252-717-0317 or lrs0922@ecu.edu

Marianna Walker, PhD, associate professor in the
Department of Communication Sciences and Disorders,
ECU's College of Allied Health Sciences
252-744-6096

The Department of Communication Sciences and Disorders research labs are located in the new Allied Health Sciences Building on ECU's Health Sciences Campus (the building is behind Pitt County Memorial Hospital). This study has been approved by the ECU UMCIRB (No. 07-0463).

East Carolina University
Tomorrow starts here.

Children Needed for Participation in Reading Research Study

"Timing is Everything: An Investigation of Auditory and Visual Temporal Processing in Children with Reading Disorders"

Children ages 10–13 years old with professionally diagnosed reading disorders are needed to participate in the study.

Benefits include:
- Free hearing screening
- Better understanding of your child's reading abilities

The study will be conducted in the Department of Communication Sciences and Disorders research labs at East Carolina University. Involvement in the study will consist of pre-experimental testing to determine study eligibility and two experimental testing sessions, which will assess auditory and visual processing abilities. The purpose of this study is to determine if a relationship exists between auditory and visual temporal processing skills and reading disorders, primarily in decoding and comprehension abilities.

If interested, please contact Lauren Forehand, doctoral candidate in audiology, at 252-717-0317 or lrs0922@ecu.edu, or Marianna Walker, PhD, associate professor, Department of Communication Sciences and Disorders, School of Allied Health Sciences, at 252-744-6096.

The Communication Sciences and Disorders research labs are located in the new Health Sciences Building located behind Pitt County Memorial Hospital. This study has been approved by the UMCIRB (#07-0463).

APPENDIX B: INFORMED CONSENT AND MINOR ASSENT FORMS

INFORMED CONSENT DOCUMENT

Title of Research Study: Timing is Everything: An Investigation of Auditory And Visual Temporal Processing in Children with Reading Disorders

Principal Investigators:

Gregg D. Givens, Ph.D.
Chair of Department of Communication Sciences and Disorders
School of Allied Health Sciences
East Carolina University
(252) 744-6080

Marianna Walker, Ph.D.
Associate Professor, Department of Communication Sciences and Disorders
School of Allied Health Sciences
East Carolina University
(252) 744-6096

Student Investigator:

Lauren Smith Forehand, BA, Audiology Doctoral Candidate
Department of Communication Sciences and Disorders
School of Allied Health Sciences
East Carolina University
(252) 717-0317

INTRODUCTION

Your child has been asked to participate in a research study being conducted by Dr. Gregg Givens, Chair of the Department of Communication Sciences and Disorders and Lauren Forehand, graduate student in audiology in the Department of Communication Sciences and Disorders at East Carolina University. This research study is designed to investigate the relationship between auditory and visual temporal processing and reading disorders. Four groups of 15 children (one group of normal readers and three subgroups of children with reading disorders) will complete this experimental study. Results from this study will supplement the literature and further our understanding of how multi-modal temporal processing relates to reading disorders.

PLAN AND PROCEDURES

Your child will be one of approximately 60 children recruited to participate in this study. Your child will undergo pre-experimental testing, in which a variety of reading and language tests will be administered to determine your child's reading, language, and nonverbal abilities. These tests include subtests of the *Woodcock Reading Mastery Test – Revised* (WRMT-R), the *Word/Nonword Reading Test*, the *Peabody Picture Vocabulary Test – III* (PPVT-III), and the *Ravens Progressive Matrices*. Results from these tests will provide a reading profile on your child and will aid in determining which of the four groups he or she will be classified under for data analysis.

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Your child's participation will most likely consist of three testing sessions: a pre-experimental testing session, in which your child will be administered reading and language assessment tests, an auditory experimental testing session, and a visual experimental testing session. Each testing session will last approximately 1 hour. Pre-experimental testing and visual testing will be conducted at your child's school. You will be asked to bring your child to the research lab in the Department Communication Sciences and Disorders at the new Health Sciences building located behind the hospital to complete the auditory testing session.

In the auditory experimental testing session, your child will be asked to sit in a sound attenuated booth. All auditory tasks will be presented at comfortable loudness levels. For two of the three auditory tasks, your child will be instructed to listen carefully to the sounds presented through the headphones and to indicate which sound was different by pushing a button on a response pad. The final auditory test will consist of a series of patterns of sounds, in which your child will have to indicate which pattern they heard by pointing to the pattern represented on a piece of paper. Your child will receive periodic breaks during testing.

The visual experimental testing session will be similar to the auditory experimental testing session. Your child will be asked to look through a viewing chamber at two circles of light. These lights will flicker (or flash) or will appear to remain steady. Your child will be asked to indicate if the light flickers or remains steady by pushing a button. For the other two tasks, your child will be seated in front of a computer. For the second visual task, three asterisks (*) will appear on the screen, one right after the other. Your child will be instructed to carefully watch how the asterisks (*) appear on the screen and to indicate which asterisk was different by pushing the appropriate button on a keyboard. The final visual task will be similar to the second, in which three asterisks (*) will appear on the screen but in a particular pattern. Your child will be instructed to watch all three asterisks (*) and then determine the pattern in which they were presented by pushing the appropriate key on the computer keyboard. Your child will receive periodic breaks during testing.

POTENTIAL RISKS AND DISCOMFORTS

Although it is not possible to predict all possible risks or discomforts that volunteer participants may experience in any research study, the present investigators anticipate that no major risks or discomforts will occur in the present project.

POTENTIAL BENEFITS

Willingness to allow your child to participate in this study helps East Carolina University researchers and other scientists develop a better understanding of how deficits in the auditory and visual sensory systems relate to reading disorders. Also, your child will receive a free reading assessment using a variety of standardized tests and a free clinical hearing screening during the auditory testing session. You will be given the results of these screenings for your records, if you so choose.

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SUBJECT PRIVACY AND CONFIDENTIALITY OF RECORDS

All data collected from this study will remain confidential and will only be available to the principal investigators and myself. Your child's name will not be used to identify the information or results in any public presentations of research findings or published research articles. Data will be coded to conceal your child's identity.

TERMINATION OF PARTICIPATION

Participation is voluntary and may be terminated at any time without penalty.

COSTS OF PARTICIPATION

There will be no cost for participating in this study.

COMPENSATION AND TREATMENT FOR INJURY

The policy of East Carolina University and/or Pitt County Memorial Hospital does not provide for payment or medical care for research participants because of physical or other injury that result from this research study. Every effort will be made to make the facilities of the School of Medicine and Pitt County Memorial Hospital available for care in the event of physical injury.

VOLUNTARY PARTICIPATION

Participating in this study is voluntary. If you decide not to be in this study after it has already started, you may stop at any time without losing benefits that you should normally receive. You may stop at any time you choose without penalty, loss of benefits, or without causing a problem with your medical care at this institution.

PERSONS TO CONTACT WITH QUESTIONS

The investigators will be available to answer any questions concerning this research, now or in the future. You may contact the investigators, Dr. Gregg Givens at (252) 744-6080, Dr. Marianna Walker at (252) 744-6096, or Lauren Forehand at (252) 717-0317. If you have questions about your rights as a research subject, you may call the Chair of the University and Medical Center Institutional Review Board at phone number (252) 744-2914 (days).

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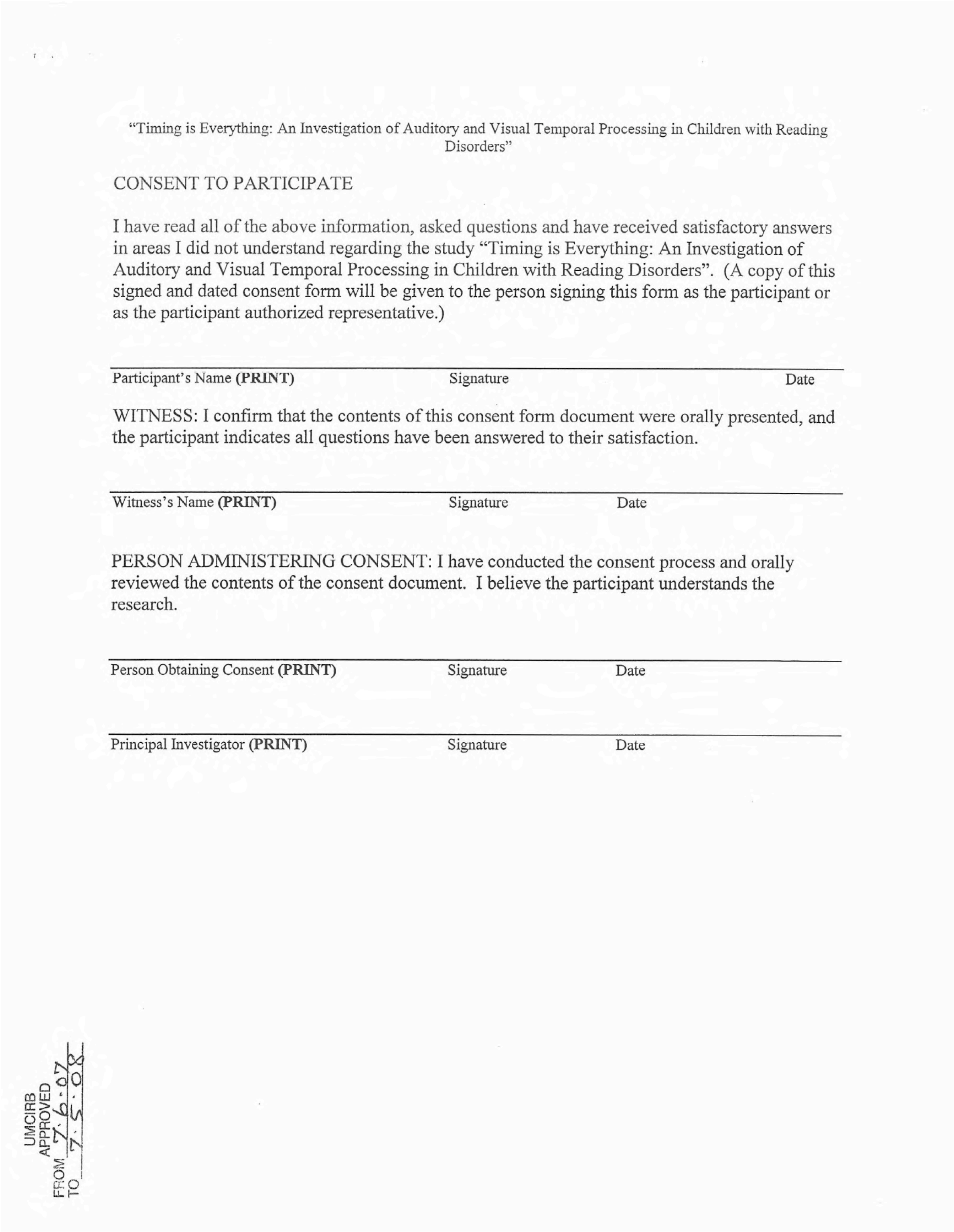

"Timing is Everything: An Investigation of Auditory and Visual Temporal Processing in Children with Reading Disorders"

CONSENT TO PARTICIPATE

I have read all of the above information, asked questions and have received satisfactory answers in areas I did not understand regarding the study "Timing is Everything: An Investigation of Auditory and Visual Temporal Processing in Children with Reading Disorders". (A copy of this signed and dated consent form will be given to the person signing this form as the participant or as the participant authorized representative.)

Participant's Name **(PRINT)** Signature Date

WITNESS: I confirm that the contents of this consent form document were orally presented, and the participant indicates all questions have been answered to their satisfaction.

Witness's Name **(PRINT)** Signature Date

PERSON ADMINISTERING CONSENT: I have conducted the consent process and orally reviewed the contents of the consent document. I believe the participant understands the research.

Person Obtaining Consent **(PRINT)** Signature Date

Principal Investigator **(PRINT)** Signature Date

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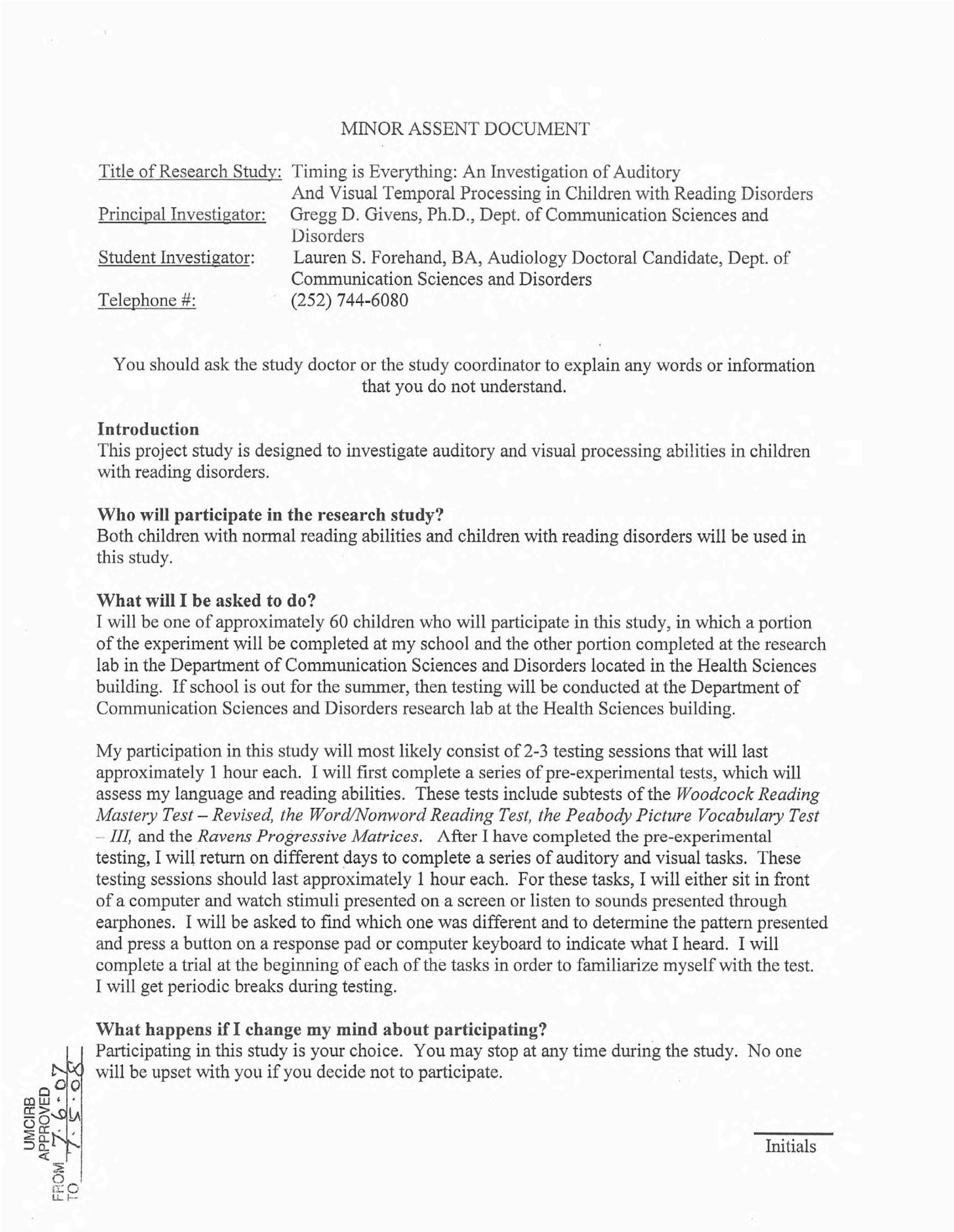

MINOR ASSENT DOCUMENT

Title of Research Study: Timing is Everything: An Investigation of Auditory And Visual Temporal Processing in Children with Reading Disorders
Principal Investigator: Gregg D. Givens, Ph.D., Dept. of Communication Sciences and Disorders
Student Investigator: Lauren S. Forehand, BA, Audiology Doctoral Candidate, Dept. of Communication Sciences and Disorders
Telephone #: (252) 744-6080

You should ask the study doctor or the study coordinator to explain any words or information that you do not understand.

Introduction

This project study is designed to investigate auditory and visual processing abilities in children with reading disorders.

Who will participate in the research study?

Both children with normal reading abilities and children with reading disorders will be used in this study.

What will I be asked to do?

I will be one of approximately 60 children who will participate in this study, in which a portion of the experiment will be completed at my school and the other portion completed at the research lab in the Department of Communication Sciences and Disorders located in the Health Sciences building. If school is out for the summer, then testing will be conducted at the Department of Communication Sciences and Disorders research lab at the Health Sciences building.

My participation in this study will most likely consist of 2-3 testing sessions that will last approximately 1 hour each. I will first complete a series of pre-experimental tests, which will assess my language and reading abilities. These tests include subtests of the *Woodcock Reading Mastery Test – Revised, the Word/Nonword Reading Test, the Peabody Picture Vocabulary Test – III,* and the *Ravens Progressive Matrices*. After I have completed the pre-experimental testing, I will return on different days to complete a series of auditory and visual tasks. These testing sessions should last approximately 1 hour each. For these tasks, I will either sit in front of a computer and watch stimuli presented on a screen or listen to sounds presented through earphones. I will be asked to find which one was different and to determine the pattern presented and press a button on a response pad or computer keyboard to indicate what I heard. I will complete a trial at the beginning of each of the tasks in order to familiarize myself with the test. I will get periodic breaks during testing.

What happens if I change my mind about participating?

Participating in this study is your choice. You may stop at any time during the study. No one will be upset with you if you decide not to participate.

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How can I participate?
You may call Lauren Forehand (252) 717-0317 to schedule a time to participate in this study.

Who can answer my questions that I might have later on?
You can talk to Dr. Gregg Givens (252) 744-6080, Dr. Marianna Walker at (252) 744-6096, or Lauren Forehand (252) 717-0317 if you have more questions at any time during the study. You can also call the university office at (252) 744-2914 if you are concerned about how you have been treated in the study.

If I put my name at the end of this form it means I agree to be in this study. I will be given a copy of this form to keep after I sign it and so will my parents.

Print your name ________________________________

Sign your name ________________________________

Date ____

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APPENDIX C: TASK INSTRUCTIONS

Task Instructions

Instructions for the Gap Detection Test:

You will hear three sequences of noise that sound like static. Two will be the same and one will be different. Listen carefully. Some of the noises will sound like one burst of static and some will sound like two bursts of static. I want you to find the noise that sounds like two bursts of static and press the button on the response box. On the response box, you will see little lights flash above the buttons letting you know if you're hearing the first, second, or third noise. Pay attention because these lights will help you figure out what button to push. So, for example, if the noise that sounds different happens first, then I want you to press the first button. This test will gradually get harder, which means it will be harder for you to tell which one has two static noises in it, so if you're not sure which noise sounds different, then it's alright to take a guess. [Verbally demonstrate the task and ask for a response. Do two or three times before running the practice trail.] Before the test begins, we will do a practice. You will see all the lights flash on the box to let you know we are about to start the test. Push any button to start. We will do this test three times. Do you have any questions?

Instructions for the Auditory DL Test:

You will hear three tones. Two will sound the same and one will sound different. Listen carefully. I want you to find the tone that sounds different from the other two and push the right button on the response box. The tone that sounds different will sound shorter than the other two sounds. One the response box, little lights will flash over the buttons letting you know which tone you're hearing: first, second, or third. So, for example, if the tone that sounds different is the last one, then press the third button. This task will gradually get harder, which means it will be harder for you to tell which tone was different from the other two. If you are not sure which tone is different, then take a guess. [Verbally demonstrate test and ask for a response. Demonstrate two or three times before beginning practice trial.] Before the test begins, we will do a practice. You will see all the lights flash on the box to let you know the test is about to start. Push any button to start. We will do this test three times. Do you have any questions?

Instructions for the Auditory Duration Pattern Test:

You will hear a sequence of three tones that will make a pattern of sound. Two of the tones will be the same and one will be different. Listen carefully. After you hear all three tones, I want you to find the pattern on the paper and point to it. For example, if you hear short-long-short, I want you to find the pattern on the piece of paper and point to it. The symbol for short will be (-) and the symbol for long will be (----). So short-long-short would look like (- ---- -) on the piece of paper. [Verbally demonstrate three of the six patterns and have child demonstrate the remaining three. Verbally demonstrate a pattern and ask for a response before beginning practice trial.] If you are not sure what the pattern is that you heard, then it's alright to guess. Before we start the test we will practice. We will only do this test one time. Do you have any questions?

Instructions for the Critical Flicker Fusion Test:

Inside the box you will see two circles of light. At first, the lights will flash. Whenever you see the lights flash, I want you to press the (-) on the clicker. These lights will flash faster and faster every time you press the (-). At some point, these lights will flash so fast that they will seem to have stopped flashing and become a solid light. Whenever you think the lights are no longer flashing and are completely solid, I want you to press the (+) on the clicker. Watch the lights carefully. Remember, every time you think the lights flash, press the (-) and every time you think you think they are solid, press the (+). Before we begin the test, I will show you what the lights will look like and ask you to tell me if you think they're flashing or not. Once we start the test, we will do it 3 times. Do you have any questions?

Instructions for the Visual DL Test:

You will first see some instructions on the screen. These instructions will tell you that you will see three (*)'s flash on the screen, one right after the other. Two (*)'s will flash on the screen for the same amount of time and one (*) will flash for a different length of time. Watch carefully. I want you to find which (*) flashed on the screen for a different amount of time from the other two and press the correct button on the computer keyboard. For example, if the (*) flashed on the screen for a different amount of time happened first, then press #1 on the keyboard. [Manually and verbally demonstrate the task. Use hands to indicate the flash but use voice to aid in identifying short versus long. Demonstrate two or three times and ask for a response before beginning practice trial.] This test will gradually get harder and it will be more difficult to tell which (*) was different. If you are unsure, you may guess. Before we begin the test, we will practice. Do you have any questions?

Instructions for the Visual Duration Pattern Test

You will see three (*)'s appear on the computer screen that will make up a pattern. Two of the (*)'s will be the same and one will be different. Watch carefully. After you see all three (*)'s, I want you to find the pattern on the paper and then press the correct button on the computer keyboard. The symbol for short will be (-) and the symbol for long will be (----). For example, if you see short-long-short, I want you to find (- ---- -) on the piece of paper and then press the keyboard button for SLS. [Verbally demonstrate three of the six patterns and ask participant to demonstrate remaining three. Manually demonstrate patterns and ask for a response. Do several times before beginning practice trial.] If you are not sure what the pattern is that you saw, then guess. Before we start the test we will practice. We will only do this test one time. Do you have any questions?

APPENDIX D: INDIVIDUAL READING AND LANGUAGE SCORES BY GROUP (I.E., CONTROL, DYSPHONETIC, AND DYSPHONEIDETIC)

Individual Reading and Language Scores by Subgroup
(i.e., Control [C], Dysphonetic [DP] and Dysphoneidetic [M])

Standard Scores for *Woodcock Reading Mastery Test – Revised*

Control Group

Participant	Word Identification	Word Attack
C1	95	103
C2	100	104
C3	120	127
C4	132	122
C5	108	112
C6	105	119
C7	113	123
C8	98	101
C9	92	105
C10	110	110
C11	94	105
C12	114	113
Mean (SD)	106.8 (11.9)	112.0 (8.9)

Dysphonetic Group

Participant	Word Identification	Word Attack
DP1	95	92
DP2	91	107
DP3	94	88
DP4	85	84
DP5	88	87
DP6	99	102
Mean (SD)	92.0 (5.1)	93.3 (9.2)

Dysphoneidetic Group

Participant	Word Identification	Word Attack
M1	85	94
M2	86	94
M3	89	107
M4	77	83
M5	72	78
M6	85	73
M7	75	81
M8	85	89
M9	83	87
Mean (SD)	81.9 (5.8)	87.3 (10.2)

Raw Scores for *Word/Nonword Test*

Control Group

Participant	Reg. Word	Irreg. Word	Nonwords
C1	29	20	27
C2	27	20	23
C3	30	30	26
C4	30	30	29
C5	29	23	26
C6	30	29	30
C7	29	28	29
C8	26	23	21
C9	25	24	25
C10	30	23	28
C11	28	25	23
C12	28	24	28
Mean (SD)	28.4 (1.7)	24.9 (3.6)	26.3 (2.8)

Dysphonetic Group

Participant	Reg. Word	Irreg. Word	Nonwords
DP1	27	25	19
DP2	28	23	19
DP3	25	22	15
DP4	26	20	11
DP5	23	19	12
DP6	23	19	14
Mean (SD)	25.3 (2.1)	21.3 (2.4)	15.0 (3.4)

Dysphoneidetic Group

Participant	Reg.Word	Irreg. Word	Nonwords
M1	21	13	20
M2	28	21	20
M3	28	21	18
M4	18	13	9
M5	16	17	8
M6	20	16	9
M7	14	8	4
M8	25	18	18
M9	22	13	3
Mean	21.3 (5.0)	15.6 (4.2)	12.1 (6.9)

Language Scores for the Peabody Picture Vocabulary Test – IV

Participant	Control	DP	M
1	96	111	105
2	103	96	123
3	138	109	95
4	146	108	109
5	129	102	87
6	129	104	109
7	126	-	86
8	103	-	94
9	104	-	101
10	108	-	-
11	96	-	-
12	103	-	-
Mean (SD)	115.1 (17.4)	105.0 (5.5)	101.0 (11.9)

APPENDIX E: INDIVIDUAL THRESHOLDS (MS) AND ACCURACY SCORES (%) ON EXPERIMENTAL TASKS BY GROUP (I.E., CONTROL, DYSPHONETIC, AND DYSPHONEIDETIC)

Individual Thresholds (ms) and Accuracy Scores (%) on Experimental Tasks by Group (i.e., Control [C], Dysphonetic [DP], and Dysphoneidetic [M])

Mean and Best Thresholds (ms) for Within-Channel (WC) and Between-Channel (BC) Auditory Gap Detection Tasks

	Control Group			
Participant	WC Average	WC Best	BC Average	BC Best
C1	7.8	5.0	46.5	36.5
C2	5.8	5.0	27.3	14.0
C3	5.1	3.8	26.5	19.0
C4	5.5	3.8	8.3	5.0
C5	5.0	2.5	*	*
C6	10.4	6.3	13.3	12.5
C7	8.8	8.8	25.5	24.0
C8	6.3	5.0	5.0	5.0
C9	8.0	6.3	65.0	54.0
C10	10.0	6.3	28.5	26.5
C11	3.8	2.5	13.3	5.0
C12	5.0	2.5	8.3	7.5
Mean (SD)	6.9 (2.2)	5.0 (1.9)	24.3 (18.2)	19.0 (15.5)

*This child was unable to complete the between-channel gap detection task.

	Dysphonetic Group			
Participant	WC Average	WC Best	BC Average	BC Best
DP1	7.5	5.0	56.5	34.0
DP2	6.7	3.8	89.0	69.0
DP3	2.9	2.5	22.2	14.0
DP4	18.8	10.0	25.2	16.5
DP5	8.3	7.5	59.8	44.0
DP6	10.0	6.3	61.8	45.0
Mean (SD)	9.0 (5.3)	5.8 (2.7)	52.4 (25.1)	37.1 (20.5)

Dysphoneidetic Group

Participant	WC Average	WC Best	BC Average	BC Best
M1	5.5	3.8	40.7	39.0
M2	5.8	5.0	46.5	34.0
M3	8.3	3.8	23.5	21.5
M4	7.0	4.8	*	*
M5	6.3	3.8	144.0	144.0
M6	28.9	27.5	32.0	30.0
M7	40.8	25.0	70.3	64.0
M8	5.9	3.8	125.3	116.5
M9	9.6	7.5	67.3	51.5
Mean (SD)	13.9 (13.4)	10.0 (10.1)	68.7 (44.0)	62.6 (44.4)

*This child was unable to perform the between-channel gap detection task.

Mean and Best Thresholds (ms) on the Auditory Duration Discrimination (ADD) Task as a Function of Group (Control [C], Dysphonetic [DP], and Dsyphoneidetic [M])

Control Group

Participant	ADD Average	ADD Best
C1	8.8	5.0
C2	21.3	16.3
C3	15.0	12.5
C4	10.4	8.8
C5	20.0	16.3
C6	15.4	12.5
C7	8.3	3.8
C8	14.2	10.0
C9	24.6	22.5
C10	9.2	7.5
C11	10.0	8.8
C12	13.3	8.8
Mean (SD)	14.2 (5.4)	11.0 (5.3)

Dysphonetic Group

Participant	ADD Average	ADD Best
DP1	19.6	12.5
DP2	13.8	11.3
DP3	10.8	8.8
DP4	11.7	10.0
DP5	14.2	10.0
DP6	30.0	20.0
Mean (SD)	16.7 (7.2)	12.1 (4.1)

Dysphoneidetic Group

Participant	ADD Average	ADD Best
M1	33.8	27.5
M2	17.9	16.3
M3	7.1	6.3
M4	23.8	20.0
M5	24.4	13.8
M6	36.3	32.5
M7	18.3	16.3
M8	15.4	12.5
M9	16.7	13.8
Mean (SD)	21.5 (9.2)	17.6 (8.0)

Accuracy (Percent Correct) on the Auditory Duration Patten Judgment Task as a Function of Group (Control, Dysphonetic [DP], and Dysphoneidetic [M])

Participant	Control	DP	M
1	43	53	43
2	96	77	80
3	93	77	77
4	100	66	60
5	87	80	57
6	100	70	37
7	90	-	80
8	73	-	43
9	63	-	67
10	67	-	-
11	83	-	-
12	77	-	-
Mean (SD)			

Mean and Best Thresholds (Hz) on the Visual Critical Flicker Fusion (CFF) Task as a Function of Group (Control [C], Dysphonetic [DP], and Dsyphoneidetic [M])

	Control Group	
Participant	CFF Average	CFF Best
C1	41.8	41.8
C2	44.9	50.7
C3	45.1	56.7
C4	43.4	46.9
C5	42.8	44.0
C6	41.8	42.9
C7	41.5	41.6
C8	34.9	37.8
C9	37.4	39.7
C10	43.6	47.2
C11	42.6	44.8
C12	37.6	39.3
Mean (SD)	41.4 (3.2)	44.5(5.3)

Dysphonetic Group

Participant	CFF Average	CFF Best
DP1	41.9	42.2
DP2	38.2	41.2
DP3	40.2	40.8
DP4	32.9	41.0
DP5	36.1	38.0
DP6	38.5	39.3
Mean (SD)	38.0 (3.2)	40.4 (1.5)

Dysphoneidetic Group

Participant	CFF Average	CFF Best
M1	46.3	46.7
M2	46.2	47.1
M3	34.0	34.6
M4	36.2	36.6
M5	37.5	40.6
M6	37.1	41.0
M7	33.1	35.3
M8	31.2	34.6
M9	59.2	67.4
Mean (SD)	40.1 (8.9)	42.7 (10.5)

Mean and Best Thresholds (ms) on the Visual Duration Discrimination (VDD) Task as a Function of Group (Control [C], Dysphonetic [DP], and Dsyphoneidetic [M])

Control Group

Participant	VDD Average	VDD Best
C1	29.1	56.2
C2	62.5	112.5
C3	65.6	75.0
C4	137.5	237.5
C5	110.6	116.7
C6	39.6	56.3
C7	77.1	131.3
C8	*	*
C9	25.0	31.3
C10	77.1	106.3
C11	54.2	100.0
C12	45.8	68.8
Mean (SD)	65.8 (34.1)	99.2 (55.2)

*This child was unable to perform the between-channel gap detection task.

Dysphonetic Group

Participant	VDD Average	VDD Best
DP1	43.8	75.0
DP2	110.4	181.3
DP3	70.8	118.8
DP4	47.9	68.8
DP5	45.8	87.5
DP6	54.2	75.0
Mean (SD)	62.2 (25.6)	101.0 (43.2)

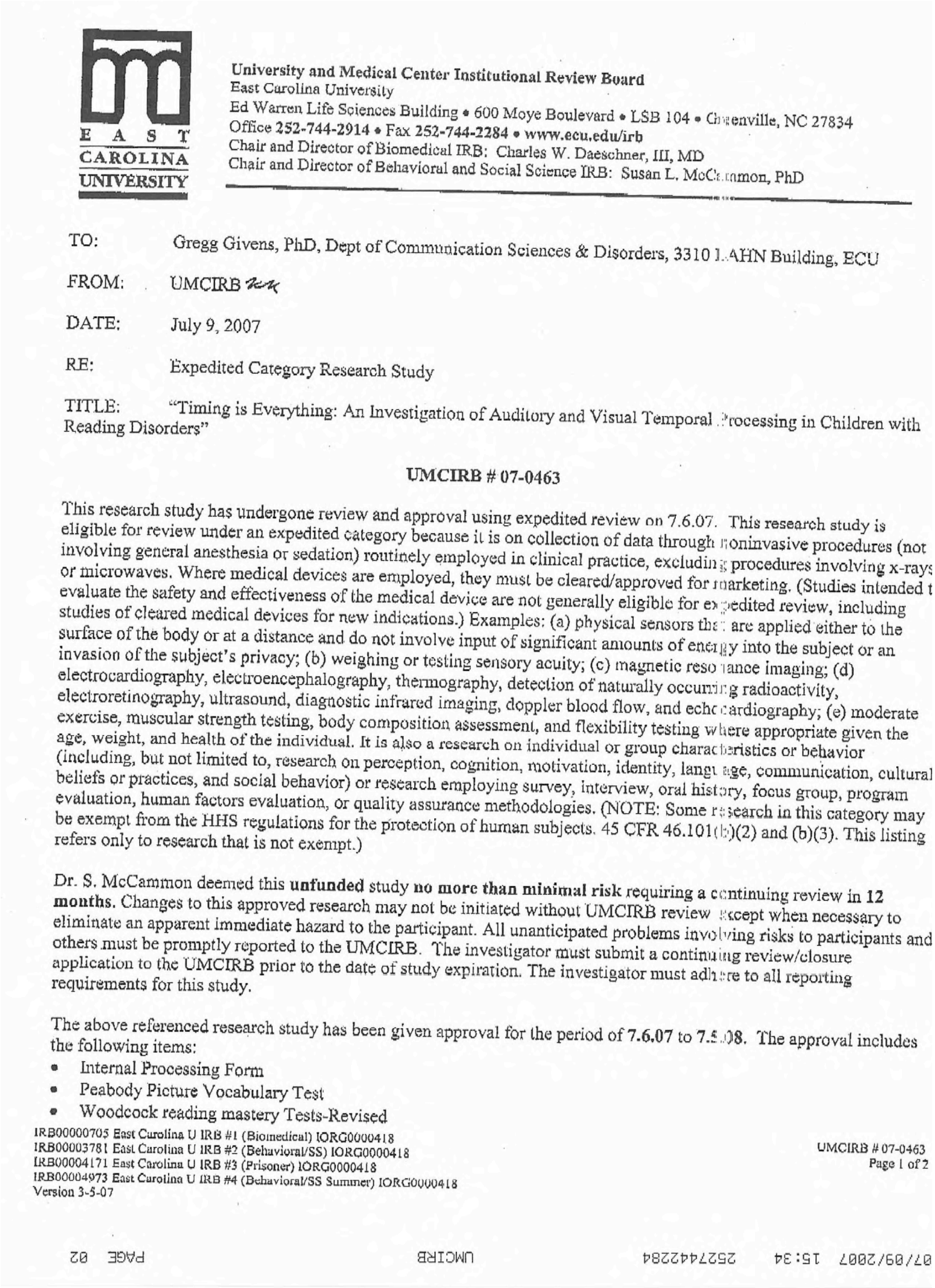
Dysphoneidetic Group

Participant	VDD Average	VDD Best
M1	12.5	18.8
M2	52.1	68.8
M3	87.5	225.0
M4	37.5	50.0
M5	29.2	56.3
M6	45.8	81.3
M7	14.6	18.8
M8	50.0	56.3
M9	25.0	25.0
Mean (SD)	39.4 (23.1)	66.7 (63.4)

Accuracy (Percent Correct) on the Visual Duration Patten Judgment Task as a Function of Group (Control, Dysphonetic [DP], and Dysphoneidetic [M])

Participant	Control	DP	M
1	30	80	63
2	50	87	80
3	73	47	50
4	80	37	47
5	60	17	50
6	30	67	73
7	73	-	37
8	63	-	27
9	43	-	43
10	37	-	-
11	50	-	-
12	67	-	-
Mean (SD)			

APPENDIX F: IRB APPROVAL LETTER



E A S T
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University and Medical Center Institutional Review Board
East Carolina University
Ed Warren Life Sciences Building • 600 Moye Boulevard • LSB 104 • Greenville, NC 27834
Office 252-744-2914 • Fax 252-744-2284 • www.ecu.edu/irb
Chair and Director of Biomedical IRB: Charles W. Daeschner, III, MD
Chair and Director of Behavioral and Social Science IRB: Susan L. McCammon, PhD

TO: Gregg Givens, PhD, Dept of Communication Sciences & Disorders, 3310 LAHN Building, ECU

FROM: UMCIRB

DATE: July 9, 2007

RE: Expedited Category Research Study

TITLE: "Timing is Everything: An Investigation of Auditory and Visual Temporal Processing in Children with Reading Disorders"

UMCIRB # 07-0463

This research study has undergone review and approval using expedited review on 7.6.07. This research study is eligible for review under an expedited category because it is on collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving x-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing. (Studies intended t evaluate the safety and effectiveness of the medical device are not generally eligible for expedited review, including studies of cleared medical devices for new indications.) Examples: (a) physical sensors that are applied either to the surface of the body or at a distance and do not involve input of significant amounts of energy into the subject or an invasion of the subject's privacy; (b) weighing or testing sensory acuity; (c) magnetic resonance imaging; (d) electrocardiography, electroencephalography, thermography, detection of naturally occurring radioactivity, electroretinography, ultrasound, diagnostic infrared imaging, doppler blood flow, and echocardiography; (e) moderate exercise, muscular strength testing, body composition assessment, and flexibility testing where appropriate given the age, weight, and health of the individual. It is also a research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies. (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(2) and (b)(3). This listing refers only to research that is not exempt.)

Dr. S. McCammon deemed this **unfunded** study **no more than minimal risk** requiring a continuing review in **12 months.** Changes to this approved research may not be initiated without UMCIRB review except when necessary to eliminate an apparent immediate hazard to the participant. All unanticipated problems involving risks to participants and others must be promptly reported to the UMCIRB. The investigator must submit a continuing review/closure application to the UMCIRB prior to the date of study expiration. The investigator must adhere to all reporting requirements for this study.

The above referenced research study has been given approval for the period of **7.6.07** to **7.5.08.** The approval includes the following items:

- Internal Processing Form
- Peabody Picture Vocabulary Test
- Woodcock reading mastery Tests-Revised

IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418
IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418
IRB00004171 East Carolina U IRB #3 (Prisoner) IORG0000418
IRB00004973 East Carolina U IRB #4 (Behavioral/SS Summer) IORG0000418
Version 3-5-07

UMCIRB # 07-0463
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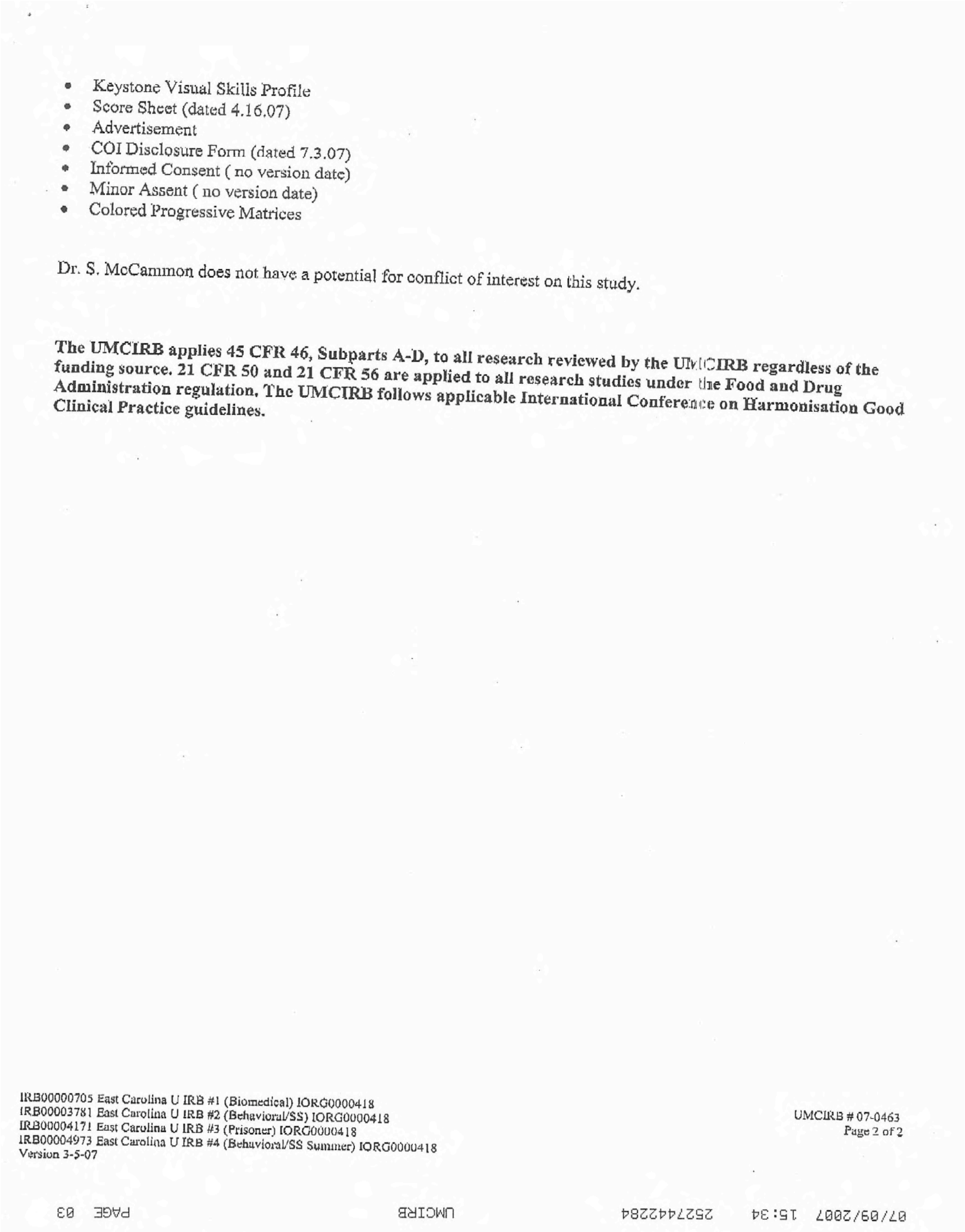

- Keystone Visual Skills Profile
- Score Sheet (dated 4.16.07)
- Advertisement
- COI Disclosure Form (dated 7.3.07)
- Informed Consent (no version date)
- Minor Assent (no version date)
- Colored Progressive Matrices

Dr. S. McCammon does not have a potential for conflict of interest on this study.

The UMCIRB applies 45 CFR 46, Subparts A-D, to all research reviewed by the UMCIRB regardless of the funding source. 21 CFR 50 and 21 CFR 56 are applied to all research studies under the Food and Drug Administration regulation. The UMCIRB follows applicable International Conference on Harmonisation Good Clinical Practice guidelines.

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Version 3-5-07