PHONOLOGY, PROSODY, AND READING SKILLS: A MISMATCH NEGATIVITY EXPERIMENT

by

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A Dissertation Submitted in Partial Fulfillment
of the Requirements for the Degree of
Doctor of Philosophy in Literacy Studies

Middle Tennessee State University
May 2020

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This work is dedicated to my daughter, Josètte Raven,

who is the brightest ray of sunshine to have ever warmed this Earth.

I also dedicate this work to my partner, Shane,

who has been my rock through it all.

I love you both to the moon and back.

ACKNOWLEDGEMENTS

I would like to take this opportunity to express my sincerest gratitude to my dissertation committee members, several members of the Literacy Studies PhD program, and to all my beloved people. First, I wish to thank my committee members, Dr. Laura Barquero, Dr. Amy Elleman, and Dr. Cyrille Magne. Dr. Barquero made me feel immediately comfortable and welcomed at the Education and Brain Sciences Research Lab at Vanderbilt University. I am very grateful to have had the experience of completing my research practicum under Dr. Barquero's guidance, and am so fortunate to have her expertise on my dissertation committee. I very much look forward to our continued collaborations together. Dr. Elleman's vast expertise, high expectations, and rigorous, intensive coursework helped me gain the background skills necessary to conduct high quality research. I have never worked harder than in her courses, and as a result I am prepared to continue important work in this field. I am so lucky to have had Dr. Elleman as a professor and feel honored to have her on my committee, as I value her input greatly. (And perhaps someday, we will open up that dream charter school we've talked so often about!). I wish to also express my deepest gratitude to my dissertation chair, Dr. Magne, for his excellent guidance, continuous support, eternal patience, as well as for helping me in countless ways to complete my research during very challenging times. After my accident and the long recovery, during my pregnancy and after the birth of my daughter, Dr. Magne has been a supportive advisor, a model researcher, and most of all, a good friend. His dedication to my success means so much to me, and without his support this work would have been impossible. I am very grateful to have had the opportunity to study under him and look forward to future collaborations.

I would also like to thank Dr. Jwa Kim, for being a great first advisor in the program. Although my research interests led me towards a path closer to neuroscience, I

am very thankful to have had the opportunity to work under Dr. Kim. During that time, Dr. Kim helped me develop a better understanding and appreciation for psychometrics and its important role in validating education testing instruments. In addition, I would like to express my gratitude for Angela Morrell. Angela helps to keep the program running smoothly, and I appreciate her willingness to always answer all of my questions. (And Angela's general interest in all things "Josètte" warms my heart and helps me spread the joy and cheer that Josie brings to the world!).

It would also be remiss of me not to mention my deep gratitude for Dr. Eric Oslund. Despite my original trepidation towards anything statistics related, I can honestly say that because of Dr. Oslund's comprehensive coursework in statistics, I can understand and even *enjoy* statistics. I also greatly appreciate his willingness to answer all of my pestering questions related to stats. (And I have Dr. Oslund to thank for ruining my social life, because I question everything and forever now "want to see the stats on that!")

I feel very fortunate to have been a part of the Literacy Studies PhD program. I could not have successfully completed my dissertation without the dedicated guidance and support of all these committee and program members.

In addition, I am thankful to all my colleagues in the Auditory and EEG laboratory at MTSU, for helping me collect EEG data. Specifically, I would like to thank Heechun Moon, who first helped me learn how apply the EEG net properly. I enjoyed the many conversations we had while in the windowless AMG lab, and missed him dearly when he graduated. I would also like to thank Jessica Steele for the countless hours she spent helping to collect and clean my EEG data. She was a wonderful help and through the *very* many hours we spent together, I am happy to call her a very dear friend, as well. I am also thankful to Dr. Alan Musicant, for his advice, suggestions, support, and humor, and for teaching me how to administer the hearing test in my study.

My deepest thanks extend to my family, as well. My partner, Shane Minter, stood by me throughout the entire difficult journey, and encouraged me when things were trying and I wanted to throw in the towel. I could not have kept going towards the end without the daily snuggles and limitless giggles and smiles from my beloved daughter, Josètte Raven, who has been a ray of sunshine in my life since her birth. My sister, Trea Fotidzis, has been an invaluable friend and I know that no matter what the situation, I can always count on her grounded advice and unconditional support. Finally, I wish to thank my parents, Gregory and Halina Fotidzis. Without their encouragement and support in various ways, I would not have been able to achieve this goal of mine. I owe everything to them, and I love them with all my heart.

ABSTRACT

Reading is a fundamental skill for success in everyday life. Unfortunately, 5-20% of all children in the U.S. experience some form of reading difficulty (RD), such as dyslexia. Prosody—i.e., the suprasegmental features of phonology—helps to convey the meaning of speech beyond actual spoken words and has been implicated to facilitate language comprehension. Increasing evidence supports a link between prosodic sensitivity (PS) and reading skills and suggests PS may be predictive of reading outcomes. However, the role of PS in reading comprehension has not been well established. Likewise, research remains sparse on the interactions of the neurocognitive systems underlying the components of prosody and reading. Furthermore, the majority of studies that have examined prosodic sensitivity primarily focused on the rhythmic or metrical aspects, while intonation is not always accounted for.

As such, the current dissertation research addresses this specific gap in the literature by focusing specifically on the intonation aspect of prosody and how it relates to reading comprehension skills in adult readers, after controlling for phoneme perception and vocabulary. To this end, the mismatch negativity (MMN) was recorded using the audio-morphing paradigm developed by Sammler and colleagues (2015) to measure neural sensitivity to auditory cues of phonemic or prosodic contrasts. Participants were also administered standardized behavioral measures of vocabulary knowledge and silent reading comprehension skills.

Results showed that the intonation aspect of prosody statistically significantly relates to reading; however, the behavioral-EEG relationship was less clear, as there still are quite a few ways to examine the data before a behavioral-EEG relationship can be ruled out with any certainty. Findings of this study have potentially important implications for early identification and possible intervention for students at risk for RD. Most early reading interventions focus on the segmental aspects of phonology, while few programs specifically address this suprasegmental aspect. As such, these study findings fill this gap and contribute to a better understanding of what role these particular segmental and suprasegmental features of phonology play in reading and provide merit for subsequent EEG studies to further examine the relationship between the prosodic feature of intonation and reading.

Keywords: phonology, prosody, intonation, voice-onset time, mismatch negativity

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CHAPTER I: INTRODUCTION

Reading with comprehension is arguably the single most important skill for success in academics, financial security, and for social acceptance (Connor, Alberto, Compton, & O'Connor, 2014; Rapp, van den Broek, McMaster, Kendeou, & Espin, 2007). Yet many students struggle to learn to read, with 32% of fourth graders and 24% of eighth graders struggling to read at even a basic level (National Center for Education Statistics, 2018). Further, some students are "late-emerging poor readers," and despite getting off to a good start in learning to read, exhibit difficulties at the upper elementary levels and beyond (Catts, Compton, Tomblin, & Bridges, 2012; Chall, 1983; Leach, Scarborough, & Rescorla, 2003). These difficulties even persist well into high school and adulthood, with 14 % of U.S. adults (individuals aged 16 and older living in households or prisons) having below basic prose literacy reading skills, and only 29% being at a basic level (NCES, 2007). These statistics, as harrowing as they are, serve to exemplify the complexity of the reading process itself.

Converging research evidence indicates that successful reading acquisition is typified by robust phonological representations that accurately encode the phoneme sequences of spoken words in the mental lexicon (e.g., Fowler, 1991; Snowling, 2000; Stanovich, 1998; Vellutino, 1977; Vellutino & Fletcher, 2008). Phonological sensitivity (i.e., detecting and manipulating speech-sounds; Lonigan, Burgess, & Anthony, 2000) has also been shown to have a causal effect on children's normal reading development (e.g., Byrne & Fielding-Barnsley, 1991; Stanovich, 1992; Wagner et al., 1987). Indeed, considerable evidence documents that children with reading difficulty (RD) experience deficits in phonological processing (McBride-Chang, 1995), which are often also accompanied by speech perception deficits (Melby-Lervag, Lyster, & Hulme, 2012). However, a growing body of evidence now suggests that sensitivity to the suprasegmental features of language (i.e., prosody) is implicated in children's successful reading development, independently of phonological awareness (Magne & Brock, 2012; see also Wade-Woolley & Heggie, 2016). Yet, unlike the attention that the role of segmental phonological awareness in reading development has received (see Snowling, 2000 for review), the role of prosodic sensitivity in reading development has not been as well established and remains to be better elucidated.

Purpose

Prosody refers to the rhythmic patterns of stress and intonation in speech and is a key component of language processing. Prosody is multidimensional in that it operates at different phonological levels and as such, can be implicated in reading in various ways (Wade-Woolley & Heggie, 2016). For example, at the lexical level, prosody can alter a word's grammatical category from a verb to a noun, and vice versa, based on the location of stress assignment across the syllables (e.g., initial stress pattern of the noun ‘CONflict,’ versus the final stress pattern in the verb ‘conFLICT'). Intonation is important because it helps build contexts for the proper decoding of speech (House 2006) and is used for language discrimination by infants (Chong, Vicenik & Sundara, 2018). Intonation is also used for conveying emotions (Rodero, 2011; Scherer, Johnstone, & Klasmeyer, 2003), detecting irony (Wilson, 2013), and signaling attitude (Estebas-Vilaplana, 2014) in speech. Sensitivity to the prosodic structure of speech has been demonstrated to be a strong predictor of later reading skills (e.g., Holliman, Wood, & Sheehy, 2010), while deficits in speech rhythm sensitivity have been associated with some forms of RD (e.g., Goswami, Fosker, Huss, Mead, & Szucs, 2011).

Despite the numerous studies on prosody in the neuroscience literature to date, few have explored the relationship between prosody sensitivity and reading, and most of the literature on prosody sensitivity has focused mainly on the rhythm component, such as stress patterns (e.g., Wade-Woolley & Wood, 2006; Whalley & Hansen, 2006). In addition, most studies examining prosodic sensitivity (PS) have been conducted with children despite evidence that the role of prosody not only aids in learning to read, but is still used by skilled readers and present well into adulthood (Mundy & Carroll, 2016).

Another far less studied feature of prosody, known as intonation, involves the rising and falling pitch contours in speech. However, as previously mentioned, studies on PS focus mainly on the component of rhythm, particularly of stress patterns, and the majority of studies examining intonation have dealt with speech and have been conducted in tonal languages where intonation modifies the semantic categories of the spoken words (Kung, 2018). The few studies in English that have looked at intonation used tasks designed to test PS in which intonation was not specifically isolated from other prosodic characteristics, such as speech rhythm, thus making it difficult to tease their respective effects apart (e.g., prosodic sensitivity: Holliman et al., 2017; prosodic phrase boundaries: Geiser, Kjelgaard, Christodoulou, Cyr, Gabrieli, 2014). Furthermore, few studies to date have directly looked at how reading skills directly relate to prosodic skills at the individual difference level. Likewise, research on how the neurocognitive systems underlying the different components of prosody, phonemic awareness, and reading interact with one another, particularly in adults, remains sparse. As such, this study addresses these specific gaps in the research on the component of prosody known as intonation.

Research Questions, Design, and Hypotheses

A mismatch negativity (MMN) paradigm was employed to investigate sensitivity to suprasegmental (intonation) and segmental (phonemic) aspects of phonology simultaneously. The MMN is a component of the event-related potentials (ERPs) observed in response to deviant stimuli in a series of frequent stimuli. This paradigm is particularly well suited to examine speech processing skills because it can be measured without participants needing to focus their attention toward the stimuli or perform any task (Sussman, Chen, Sussman-Fort, & Dinces, 2014). The MMN has been mainly used as an index of "pre-attentive" acoustic change detection. However, the MMN has also been found to be sensitive to selective attention (Szymanski, Yund, & Woods, 1999), language experience (e.g., Chandrasekaran, Krishnan, & Gandour, 2007; Näätänen et al., 1997), and long-term linguistic representations (e.g., Alexandrov, Boricheva, Pulvermüller & Shtyrov, 2011; Näätänen, 2001). Thus, by using an MMN paradigm, I was able to account for individual differences using a non-explicit task, thereby controlling for potential confounding variables that may be more related to task performance, such as working memory and decision making.

Following the design and approach proposed by Sammler, Grosbras, Anwander, Bestelmeyer, and Belin (2015), the present study used an MMN paradigm in combination with prosody and phoneme categorization tasks and several behavioral assessments to examine the relationship between prosody perception, phoneme perception, and reading comprehension. Specifically, this study used spoken monosyllabic words manipulated along a prosodic pitch contour (from statement to question) and a phoneme continuum (from /p/ to /b/) respectively. Two identification tasks were performed to measure each participant's prosodic and phonemic categorical perception (CP) skills indexed by the standard deviation between the data and the fit to the slope of their response functions (see O'Brien, McCloy, Kubota, & Yeatman, 2018), along the prosodic and phonemic dimensions (here on out referred to as "intonation/phoneme quality," respectively, for the "quality of fit). The MMN was then recorded while participants passively listened to prosodic or phonemic deviant words. For each participant, the within- and between-category deviant stimuli was selected based on their individual point of subjective equality (i.e., PSE) for each dimension (i.e., prosodic or phonemic).

Previous studies with children and adults show that between-category phoneme CP is weaker in individuals with RD (e.g., O'Brien, Kubota, & Yeatman, 2018; Serniclaes & Seck, 2018). By contrast, the finding that individuals with RD show better discrimination ability and larger MMN responses than controls for within-category variations of the same phoneme support the "allophonic mode of speech perception" (Serniclaes, Van Heghe, Mousty, Carré & Sprenger-Charolles, 2004). According to this theory, individuals with RD have an enhanced sensitivity to small phonetic variations that are not linguistically relevant, which leads to weaker phonemic representations and thus make the entire speech perception process quite complex. While diminished prosody sensitivity has also been reported in individuals with RD, it remains to be determined whether such deficit is due to similar CP difficulty. To address this issue in regard to the intonation aspect of prosody, this study aimed to answer the following research questions:

- Q_1: What is the relationship between performances on the prosodic CP task and the MMN responses to the prosodic deviants?
    - H_1: I predicted that individuals with the smaller value for the quality of fit on their CP response function would demonstrate larger MMN to between-category deviant stimuli and smaller MMN to within-category deviant stimuli, compared to the standard stimulus.
- Q_2: How does PS to different intonation contours in spoken American English correlate with reading performance?
    - H_2: If individuals with the lowest reading skills show an enhanced sensitivity for within-category variations in intonation contours (as previously shown for within-category phoneme CP), I predicted that the MMN elicited by within-category deviants would be negatively correlated with reading comprehension scores, after controlling for vocabulary and phonemic perception.
- Q_3: How does prosody CP correlate with reading performance?
    - H_3: I predicted that higher scores on the reading comprehension measure would positively correlate with the quality of fit of the participants' response function on the prosodic CP task, after controlling for vocabulary and phonemic perception.

Significance of the Study

Findings from this study have potentially important implications for early identification and possible intervention for students at risk for RD. Most early reading interventions focus primarily on the segmental aspects of phonology, while few programs—to the best of my knowledge—specifically address this suprasegmental aspect. As such, this study aims to fill this gap and contribute to a better understanding of what role these particular segmental and suprasegmental features of phonology play in reading.

CHAPTER II: LITERATURE REVIEW

Categorical Perception of Phonemes

Categorical perception (CP) is a perceptual phenomenon first observed for speech sound units, also known as phonemes (e.g., Liberman, Harris, Hoffman, & Griffin, 1957). CP occurs when an individual perceives a sensory stimulus which varies continually along some specific dimension as one of two discrete categories (Crystal, 1987; Fugate, 2013). In other words, within a particular part of the continuum, the sensory stimuli are perceived as the same, with a distinct change of perception at the point along the continuum where there is a perceptible identity change (Myers et al., 2009).

Phonetic CP is general and related to how neural networks detect the features that allow us to automatically classify things—phonemes, in this case—into separate categories by adjusting for perceived similarities and differences; some speech sounds are compressed into the same category, while others are separated into different ones (Holt & Lotto, 2010; Myers, et al., 2009). This is why, despite individual variations inherent in the human speech signal, humans are able to understand speech as language and comprehend this auditory code (Holt & Lotto, 2010; Lotto & Holt, 2015). CP of phonemes has been demonstrated to affect speech perception for both native (Holt & Lotto, 2010), and second language speakers (Bialystok & Hakuta, 1995). Phonemes in natural speech are unsegmented and coarticulated as a continuous acoustic speech signal (Moats, 2000). However, the perception of phonemes is categorical (Carlo & Bengochea, 2011). How phonemes are categorically perceived has classically been illustrated using the acoustic feature of voice-onset timing (VOT), which is a feature of the production of stop consonants, defined—broadly—as the length of time that elapses between the release of a stop consonant (i.e., output of air on the lips), and the onset of voicing or of vocal cords vibration (e.g., Lisker & Abramson, 1964).

VOT allows for the contrasting of particular phonemes, namely the voiced bilabial stop /*b*/ (i.e., [b] as in [ˈb̬ɛ(ə)r]), and the unvoiced bilabial stop /*p*/ (i.e., [p] as in [ˈp̥ɛ(ə)r]). In fact, /*b*/ fades to /*p*/ as VOT increases. However, perceptually, /*b*/ changes into /*p*/ at a specific point in time within the VOT, and the point this change in perception occurs at, varies by language (Bialystok & Hakuta, 1994; Moats, 2000), and can vary perceptually by individual speakers within a language (e.g., ‘t Hart, 1981). For instance, Spanish speakers perceive the switch earlier than English speakers (Bialystok & Hakuta, 1994), but other languages remain to be more fully examined. Furthermore, the boundaries for the perception of phonemes are set very early during development and can have an influence on the speech perception of both native and second language speakers alike (e.g., Bialystok & Hakuta, 1994).

Categorical Perception and Reading Difficulty

Given the link between phonological awareness and reading acquisition, several studies have examined the relationship between phoneme CP skills and learning to read (e.g. Adlard & Hazan, 1998; Manis et al., 1997; Messaoud-Galusi, Hazan, & Rosen, 2011; Nittrouer, 1999). Furthermore, there is some evidence that supports the view that speech perception is causally related to learning to read (e.g., Snowling, Lervåg, Nash, & Hulme, 2018). In short, these evidences demonstrate a link between phonemic representations and categorical perception, and further suggest that some of these features are also related to reading skills.

Impaired phonemic awareness has been well documented in individuals with dyslexia (see Snowling, 2001 for a review). Well-defined phonemic categories are required in order for proper grapheme-phoneme correspondences to become established (Ehri, 1998). As such, some evidence suggests that the phonological reading difficulties observed in dyslexia might actually arise from a deficit in phonemes CP (e.g., Banai, & Ahissar, 2018; Hornickel, Skoe, Nicol, Zecker, & Kraus, 2009). These deficits are particularly seen for place of articulation and VOT contrasts, which reflect spectral and dynamic temporal contrasts, respectively (Adlard & Hazan, 1998; Hornickel et al., 2009; Maassen, Groenen, Crul, Assman-Hulsmans, & Gabreels, 2001). For example, when compared to typically developing (TD) peers, children with dyslexia have demonstrated difficulty in discriminating pairs of spoken syllables contrasting in their place of articulation, such as /*ba*/ and /*da*/ (Adlard & Hazan, 1998; Masterson, Hazan & Wijayatilake, 1995; Mody, Studdert-Kennedy & Brady, 1997; Reed, 1989). Individuals with dyslexia have also been found to perform more poorly than TD children on discrimination tasks with phonemes sharing the same place of articulation but differing in their VOT (e.g. between-category phonemes /*p*/ vs. /*b*/). Surprisingly, they perform better on tasks requiring discrimination of acoustic variants within the same phoneme category (e.g., Godfrey, Syrdal-Lasky, Millay & Knox, 1981; Serniclaes, Sprenger-Charolles, Carré & Démonet, 2001; Werker & Tees, 1984). This difference in phonetic discrimination skills between within- and between-phoneme categories has led to the allophonic theory of dyslexia (Serniclaes et al., 2004). Allophones are contextual phonetic variants of the same phoneme that result from co-articulation effects with surrounding phonemes during speech production. During language development, allophonic variants are progressively integrated into phonemic categories relevant for the native language (Hoonhorst et al., 2011). According to the allophonic theory, children with dyslexia do not fully integrate these allophonic variants into phonemic categories, and thus processing of phonemic and allophonic units compete with one another during speech perception (Serniclaes & Seck, 2018).

In addition, unlike TD children, children with RD are less able to benefit from stimulus repetition, thereby suggesting a deficit in forming a perceptual anchor or memory trace (i.e., anchoring deficit; e.g., Ahissar, Lubin, Putter-Katz, & Banai, 2006; see also: Ahissar, 2007; Banai & Ahissar, 2018). Specifically, when compared to TD individuals, dyslexic individuals' implicit memory of previously presented stimuli decays faster and their stimulus-specific adaptation processes are shorter (Ahissar et al., 2006). This faster decay may limit the temporal window over which they implicitly calculate stimulus distributions, thus yielding somewhat weakened speech categories (Ahissar et al., 2006; Banai & Ahissar, 2018).

Prosody and Reading

In addition to categorically perceiving phonemes in spoken language, vocal tone, or prosody, also helps to convey the meaning of speech beyond the actual spoken words (Wade-Woolley & Heggie, 2016), and the suprasegmental features of phonology have been implicated in facilitating comprehension (e.g., Bolinger, 1986; Calet, Gutiérrez-Palma, Simpson, González-Trujillo, & Defior, 2015). Recent findings demonstrate the importance of both prosodic sensitivity for children's reading development (Whalley & Hansen, 2006), and "prosodic fluency" for reading comprehension among native English readers (Benjamin & Schwanenflugel, 2010; Miller & Schwanenflugel, 2006, 2008; Schwanenflugel, Hamilton, Kuhn, Wisenbaker, & Stahl, 2004). While reading aloud with appropriate rhythm, stress, and intonation (i.e., prosodic fluency) can be viewed as features of fluent reading, demonstrating prosodic reading is considered a distinction of reading fluency (Dowhower, 1991; Kuhn & Stahl, 2003; Schwanenflugel et al., 2004). For instance, Schwanenflugel and colleagues (2004) showed that having an adult-like prosodic contour while reading aloud—which includes appropriate intonation, phrasing, and pauses (see Cutler, Dahan & van Donselaar, 1997, cf. Tong, Tsui, & Fung, 2018, for findings related to pauses applied during children's reading)—was positively correlated with reading comprehension ability.

Likewise, using hierarchical multiple regression analyses, Whalley and Hansen (2006) found that phrase-level prosodic skills predicted unique variance in 4th graders' reading comprehension, after controlling for word reading accuracy, phonological awareness, and general rhythmic sensitivity. In addition, prosodic sensitivity is predictive of later reading outcomes, even after accounting for phonological awareness (e.g., Holliman et al., 2014; Holliman, Wood, & Sheehy, 2012).

By contrast, research on how the neurocognitive systems underlying the different components of prosody and reading interact with one another remains sparse. In addition, studies on prosodic sensitivity focus mainly on the component of rhythm—particularly of stress patterns—and the selected few studies that *have* looked at English intonation used pseudowords in a typical /*DEE dee*/ forced-choice task paradigm, in which intonation was not specifically isolated from the other prosodic characteristics (e.g., Ashby & Clifton, 2005; Wade-Woolley & Wood, 2006; Whalley & Hansen, 2006), such as speech rhythm, (e.g., Holliman, Wood & Sheehy, 2010; Huss, Verney, Fosker, Mead, & Goswami, 2011; Mundy & Carroll, 2012; see also Männel, Schaadt, Illner, van der Meer, & Friederici, 2017), thus making it difficult to tease apart their respective effects.

Lexical Quality and Prosody

Along these lines in a different, albeit potentially germane body of literature, the lexical quality hypothesis (LQH) maintains that differences in characteristics of words and their respective representations, affect reading skills, thereby affecting comprehension, and suggests that skilled reading requires high lexical quality representations (Perfetti, 2007; Perfetti & Hart, 2002). According to the LQH, high lexical quality involves, to some extent, knowledge of well-specified representations of word forms (i.e., orthography and phonology), as well as the flexible manipulation of word meanings, thus allowing for rapid and reliable meaning retrieval, while low-quality representations of a word lead to specific word-related difficulties in comprehension of a text (Perfetti, 2007). Similarly, high PS facilitates phonological processing (Holliman et al., 2014; Whalley & Hansen, 2006) and contributes to more precise phonological representation (Goswami et al., 2002), thereby enabling automatic word retrieval, which facilitates comprehension as well.

In addition, according to the automaticity theory first posited by LaBerge and Samuels (1974), when readers achieve word decoding automaticity, more cognitive resources can be allocated to higher level comprehension processes, including making inferences (e.g., Cain, Oakhill, Barnes & Bryant, 2001; see also Elleman, 2017, for a meta-analytic review), retrieving word knowledge (e.g., Oslund, Clemens, Simmons, Smith, & Simmons, 2016; Perfetti, 2007; Perfetti & Adlof, 2012; Perfetti & Stafura, 2014), and activating relevant background knowledge (e.g., Kendou & O'Brien, 2014; Kintsch, 1988; McNamara, DeVega, & O'Reilly, 2007).

Mismatch Negativity and Speech Perception

The neurophysiological correlates of CP have been reliably studied using the Mismatch negativity (MMN) paradigm. In psycho- and neurolinguistics, the MMN has been frequently used to test memory traces at the subconscious level, that is, whether participants neurologically distinguish between certain kinds of sounds (e.g., phonological processing; Phillips, et al., 2000). Brain responses to a repeated stimulus are recorded via electroencephalography (EEG) and averaged to calculate an event-related potential (ERP). MMN is one of the components of the ERPs and reflects the mismatch of a standard to a deviant stimulus (Bishop, 2007). When a series of repeating stimuli are presented aurally, the brain unconsciously detects the regularity of the stimuli in the auditory stream. Any subsequent stimulus that deviates from the regularity of previously perceived stimuli thus causes a mismatch of the standard and the deviant, which can be observed as a negative peak in the ERP—hence a "mismatch negativity". The MMN usually has a maximum amplitude over the fronto-central regions of the scalp, and a peak latency of 100-250 ms after the stimulus onset (e.g., Garrido, Kilner, Stephan, & Friston, 2009; Kujala et al., 2000; Sams, Paavilainen, Alho, & Näätänen, 1985). In some studies, an additional ERP component, known as the “late” MMN, has also been observed in response to small auditory deviant stimuli, which may reflect additional auditory processing required when the acoustic features of the stimuli are hard to discriminate (e.g., Halliday, Barry, Hardiman, & Bishop, 2014).

Because the MMN reflects a passive auditory change detection neural mechanism, one of the main advantages of this method is that stimuli can be presented passively without necessitating any active response from a participant (Ramsøy, Balsev & Paulson, 2010). However, in order to trigger an MMN, a memory trace must exist to begin with. For instance, when a deviant non-native phoneme is presented in a stream of native phonemes, individuals do not have a strong MMN because a memory trace for that phoneme does not exist in their native language repertoire (e.g., Näätänen, 1992; Winkler & Näätänen, 1992). Similarly, within a native phoneme continuum, the MMN is elicited by both within-category deviants (Kasai et al., 2001; Sharma & Dorman, 1999), and between-category deviants (Dehaene-Lambertz, 1997; Phillips et al., 2000; Sharma & Dorman, 1999). However, the MMN is usually larger for between- than for within-category deviants (e.g., Sharman & Dorman, 1999). In addition, a few studies found differences in scalp distribution between within- and between-category responses, suggesting both hemispheres are involved in between-category phoneme perception while within-category phonetic differences are processed primarily by the right hemisphere (e.g., Kasai et al., 2001).

In addition, MMN has been used to study prosodic representations, such as lexical stress (e.g., bilingual children with autism spectrum disorder: Zhang et al., 2018) and intonation (e.g., pitch direction in non-native tonal contrasts: Liu, Ong, Tuninetti, &

Escudero, 2018; boundary effects in Mandarin: Shen & Froud, 2018). However, MMN research on the latter has been largely conducted examining musical pitch (e.g., Chen, Peter, Wijnen, Schnack, & Burnham, 2018), examining the semantic role of intonation in tonal languages (e.g., Xiao et al., 2018), or MMN in relationship to the emotional role of prosody (Jiang, Yang, & Yang, 2014; Kostilainen et al., 2018), thus creating a dearth in the literature-base on English intonation studies (e.g., to mark non-emotional prosody such as in interrogative or directive sentences).

In sum, the MMN paradigm can be used to test the strength of a memory trace in regard to the phoneme category status or prosody of the speech stimulus (e.g., Maiste, Wiens, Hunt, Scherg, & Picton, 1995), as well as the language experience of the listener (e.g., Brandmeyer, Farquhar, Mcqueen, & Desain, 2013).

Mismatch Negativity and Reading Disability

Given the sensitivity of the MMN to phoneme discrimination skills (Männel, Schaadt, Illner, van der Meer, & Friederici, 2017), it has been used in numerous studies of reading and RD in both children and adults (e.g., children: Chobert, François, Habib, & Besson, 2012; Huttunen, Halonen, Kaartinen, & Lyytinen, 2007; Noordenbos, Segers, Serniclaes, Mitterer, & Verhoeven, 2012; Zaric, González, Tijms, van der Molen, Blomert, & Bonte, 2014; Zhang et al., 2012; Zuijen, Plakas, Maassen, Maurits, & Leij, 2013; adults: Kujala, Belitz, Tervaniemi, & Näätänen, 2003; Schaadt, Pannekamp, & van der Meer, 2014; Schulte-Korne, Deimel, Bartling, & Remschmidt, 2001). For instance, MMNs to VOT phoneme deviants have been found to be smaller and developed later in children with dyslexia than in typical readers (e.g., Chobert et al., 2012; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998).

In line with these results, a recent systematic review of studies examining MMNs elicited by speech or non-speech deviants in children at risk for dyslexia found a positive correlation between the size of the MMN and later reading performance (Volkmer & Schulte-Körne, 2018). By contrast, the MMN elicited by within-category deviant phonemes appears to be larger in individuals with dyslexia than controls (e.g., Noordenbos, Segers, Serniclaes, & Verhoeven, 2013). Children with RD have also demonstrated deficits in discriminating several acoustic features underlying prosodic variations, such as frequency changes (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999; Kujala, Lovio, Lepistö, Laasonen, & Näätänen, 2006), duration changes (Corbera, Escera, & Artigas, 2006), and complex tone patterns (Kujala, et al., 2000).

Summary

Collectively, the research evidence discussed in the preceding sections demonstrates a link between phonological processing and CP, and further provides support for the hypothesis that prosody and reading are based, to some extent, on shared neural resources (e.g., Chobert et al., 2012; Männel et al., 2017; Schulte-Korne, 2001; Hämäläinen, Landi, Loberg, Lohvansuu, Pugh, & Leppänen, 2018). Furthermore, having greater prosodic sensitivity enhances the lexical quality of words and facilitates decoding (Whalley & Hansen, 2006), so that greater cognitive resources can be applied towards higher-level cognitive processes necessary for comprehension. As such, this empirical evidence provides a solid theoretical basis for further experimental investigation into the role of phonology, prosody, and reading skills.

CHAPTER III: METHOD

Participants

A total of 34 adult participants (ages 18 and above) were recruited via flier posted around the campus of a regional state university in the Southeast United States as well as from the Psychology Research Pool. Participants from the research pool received course credits while those recruited by flier received a gift card. The study was approved by the university's Institutional Review Board (IRB), and written informed consent was obtained from each participant prior to the start of the experiment.

The following criteria were used to determine participant eligibility: they must be right-handed based on widely reported variability in hemispheric specialization for language in left-handed individuals. Handedness was assessed during signing of the consent form. Participants must have normal or corrected-to-normal vision, and no hearing deficit (see screening procedure below), and must be native speakers of English. In addition, they must have a non-verbal IQ score of at least 85 (see screening procedure below). Participants also needed to score between 35 and 70 for intonation and VOT, respectively, on the behavioral CP task to ensure there was an audio stimulus matching their individual PSE for each condition, that would be presented during the EEG recording (see Procedure section below). After removing movement and bad channel EEG artefacts (*n* = 5 removed), participants scoring outside of the required range for PSE (*n* = 4 removed), and outliers based on Cook's *d* values (*n* = 2 removed), the remaining participant pool (*N* = 23) was used in the final analyses (male = 13; *M* age = 20, *SD* = 2.35, min age = 19, max age = 28).

Screening Measures

Hearing Screening. A Pure-Tone Threshold Audiometry hearing screening was conducted in order to ensure participants meet a minimum criterion of normal hearing at 20 dB for frequencies between 250 – 8000 Hz. This test consists of a series of pure tones between 250 and 8000 Hz presented in succession in the left ear and then the right ear. The test starts at 30 dB and then goes down in intensity level. The duration of this test was 5 minutes. If a participant failed to pass this screening, she/he was excluded from the rest of the experiment.

Kaufman Brief Intelligence Test, 2nd edition (KBIT-2; Kaufman & Kaufman, 2004). Participants' non-verbal intelligence was assessed using the non-verbal IQ component of the KBIT-2 in order to screen out those whose poor language skills might be due to general cognitive impairment. To this end, only data from participants with a score of 85 or above were included in the study. This test consists of a series of images, whereby the participant must indicate the next most logical sequence in the pattern. The duration of this test was untimed and took approximately 15-20 minutes to administer. The KBIT-2 test reports reliability and validity coefficients in the .90s range.

Language Test Battery

Participants received the following two behavioral measures which were counterbalanced across participants in terms of test order administration.

Peabody Picture Vocabulary Test - Fourth Edition (PPVT-4; Dunn & Dunn, 2007). The PPVT-4, which measures receptive vocabulary of Standard American English, was administered as a control to ensure that poorer comprehension skills are not due to weaker vocabulary knowledge. During the test, participants hear a spoken word and must indicate which one of four pictures best exemplifies the given word. This test is untimed, and typically takes approximately 15-20 minutes to administer. The PPVT-4 test reports reliability and validity coefficients in the .90s range.

Wechsler Individual Achievement Test-Third Edition (WIAT-III; Wechsler, 2009)**.** The Enhanced Reading Comprehension subtest from the WIAT-III was administered to measure participants' reading comprehension levels. The WIAT-III was chosen because the design of this subtest allows individuals to demonstrate their reading comprehension skills on passages at a lower readability level, thereby controlling for potentially confounding weaknesses in decoding and vocabulary knowledge. This subtest requires participants to silently read –which is more adapted to adults – several short passages that vary in content and difficulty, and verbally respond to questions spoken by the proctor with access to the passage in question. The questions range in difficulty and test literal and inferential comprehension skills. The test is untimed and typically takes 20-30 minutes to administer. The WIAT-III is normed for adults through age 50:11, and the average reliability coefficients for the WIAT–III composite scores range between .91–.98. However, reliability is not reported for component scores of subtests which includes the Enhanced Reading Comprehension subtest

CP and MMN Speech Stimulus Preparation

The two monosyllabic nouns *pear* and *bear* were selected because they are minimal pairs, which only differ in their initial phoneme (/p/ vs. /b/, respectively; e.g., see Sammler et al., 2015). These words were manipulated to be intoned as statements (i.e., falling pitch contour), or as questions (i.e., rising pitch contour), and were morphed along a phonological continuum from */bear/* to */pear/*. An adult female native speaker of English was recorded uttering the monosyllabic word “pear” or “bear,” with rising (question), or falling (statement) pitch contour to then create two continua: a prosody continuum, and a phoneme continuum.

Prosody continuum. The recordings were first fed into an audio morphing algorithm implemented in the TandemSTRAIGHT toolbox (Kawahara, 2006) for Matlab (MathWorks, Inc., Natick, MA, USA). The statement to question continuum, henceforth known as "prosody continuum" (see Figure 1), was constructed by creating two 21-step continua for “bear” and “pear” from 4 original utterances (i.e. “Bear**.**”, “Bear**?**”, “Pear**.**”, “Pear**?**”).

Figure 1. Sample pitch contours from statement (falling contour) to question (rising contour). This figure illustrates examples of seven contour steps along the prosodic continuum.

Spectro-temporal anchors were set to the 1st through 4th formants at onsets and offsets of formant transition, and to pitch rise/drop in statements and in questions to minimize distortion of the speech signal (see Figure 2). Additionally, temporal anchor points were set to onsets and offsets of phonation and word-final “r” (see Figure 3).

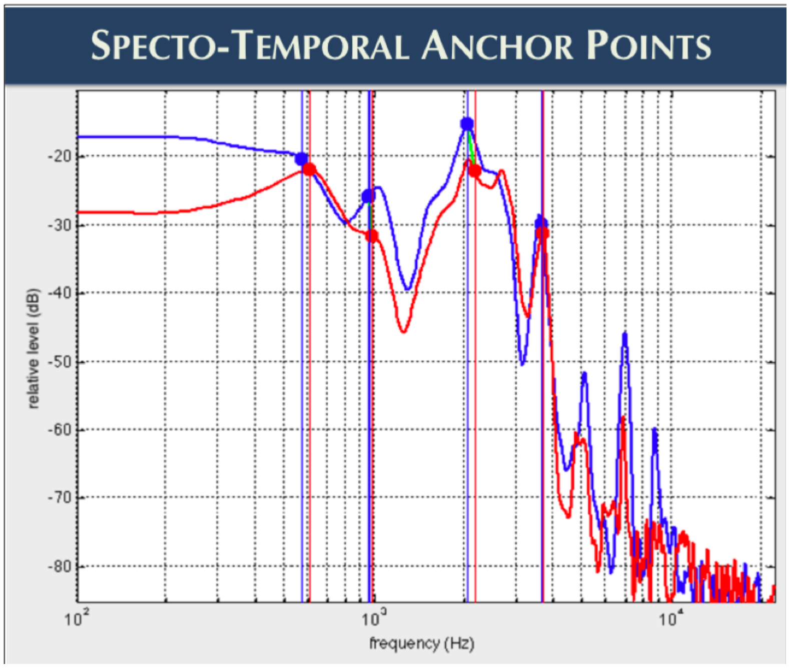


Figure 2. Spectro-temporal anchor points. The figure illustrates the frequency spectrum of the word *bear* spoken as a statement (blue trace) or question (red trace). The spectro-temporal anchors (dots) were set to 1st – 4th formants (peaks) at onsets and offsets of formant transitions as well as at pitch rises and drops.

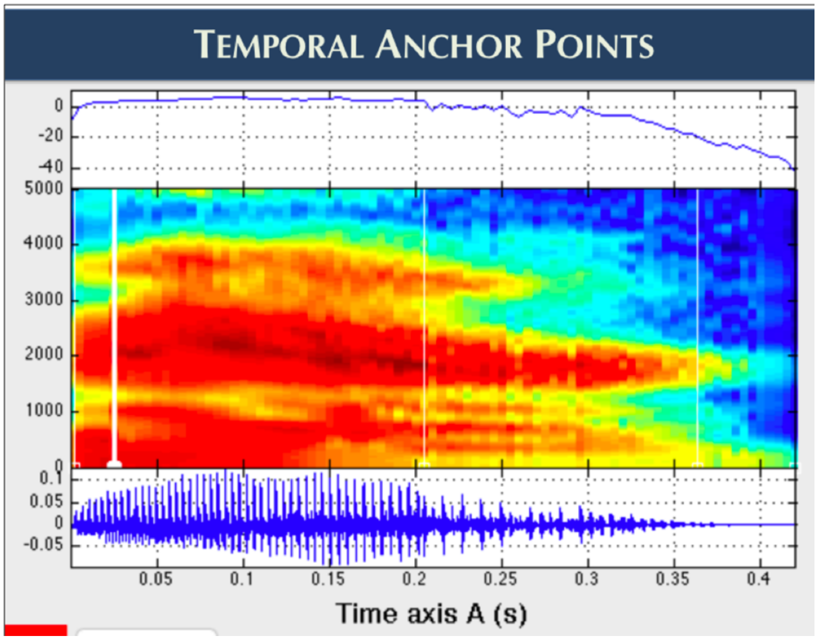


Figure 3. Temporal anchor points. The figure illustrates the spectrogram (middle panel) and waveform (bottom panel) of the word *bear*. The temporal anchors were set to the onsets and offsets of phonation (darkest red area) and word-final “r.”

Then, based on logarithmic interpolation of these anchor templates and the spectrogram, the morphed stimuli were resynthesized in 5% steps to create prosodic contours such as those presented in Figure 1.

Phoneme continuum. The VOT phoneme continuum from *bear* to *pear* was created using PRAAT 5.3.01 (http://www.praat.org).The stop-consonants /*b*/ and /*p*/ were first clipped from each original recording. A total of 21 VOT steps were then created using a +3-ms (i.e., 5%) increment of aspiration noise from the corresponding */p/* in *pear* inserted between the release burst and phonation onset of */b/* in *bear*. The first step in the continuum had a VOT of 0 ms (perceived as a */b/*) and the last steps had a maximum VOT of 60 ms (perceived as a */p/*, see Figure 4). The size of the VOT increments was determined based on the design and approach proposed by Sammler et al. (2015).

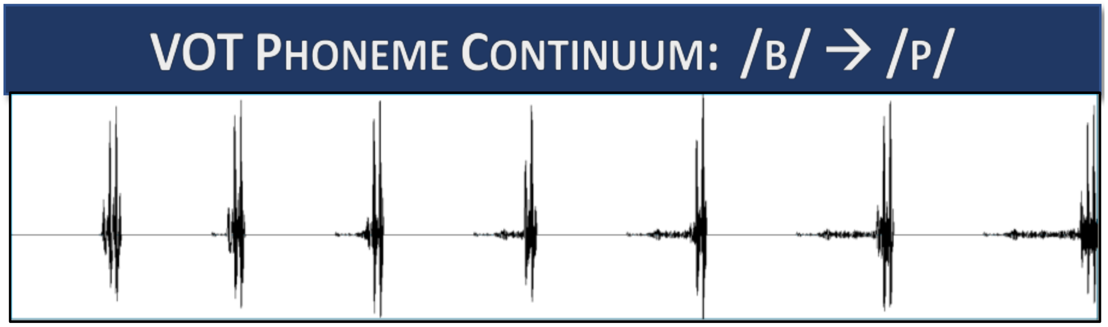


Figure 4. Sample VOT steps from /b/ to /p/. The figure illustrates examples of spoken words with VOT of the initial consonant ranging between 0 and 60 ms, with +3 ms increments of aspiration noise between tokens.

Procedure

The experiment took place in the EEG lab located on the university campus. Prior to the start of the experiment, participants were given a consent form and were asked to read it carefully. Participants then had the opportunity to ask any questions regarding the experimental procedure. After written consent was obtained, participants received a hearing screening in order to ensure they met a minimum criterion of normal hearing at 20 dB for frequencies between 250 – 8000 Hz.

To account for perceptual variability between listeners, the stimuli used in the MMN paradigm were chosen individually for each participant from the pool of 441 stimuli (i.e., 21-step prosody continua × 21-step VOT continua) based on his/her individual point of subjective equality (PSE) for prosody and VOT, respectively. In order to determine each person's PSEs, participants performed separate phoneme CP and prosodic CP tasks on a subset of 49 "pear/bear" stimuli chosen from the pool of 441 stimuli. These 49 stimuli vary along a 7-step VOT continuum between "pear" and "bear" as well as along a 7-step continuum of prosodic contour between declarative and interrogative intonations, and represents all possible combinations of stimuli with a: 5/95% – 20/80% – 35/65% – 50/50% – 65/35% – 80/20% – 95/5% question/statement, and "bear"/"pear" ratio. The same 49 stimuli were used for each participant and each CP task. In the prosodic CP task, participants judged whether each word was spoken as a question or a statement, while in the phonemic CP task, they judged whether they heard "pear" or "bear" (see Figure 5). In addition to measuring each participant's prosodic and phonemic PSEs, the behavioral responses on the two CP tasks were also used to calculate their individual phonemic and prosodic CP identification functions, which allowed me to measure their phoneme and prosody CP skills. The order of administration of the two CP tasks were counter-balanced across participants. Completion of the two tasks took approximately 8 minutes.

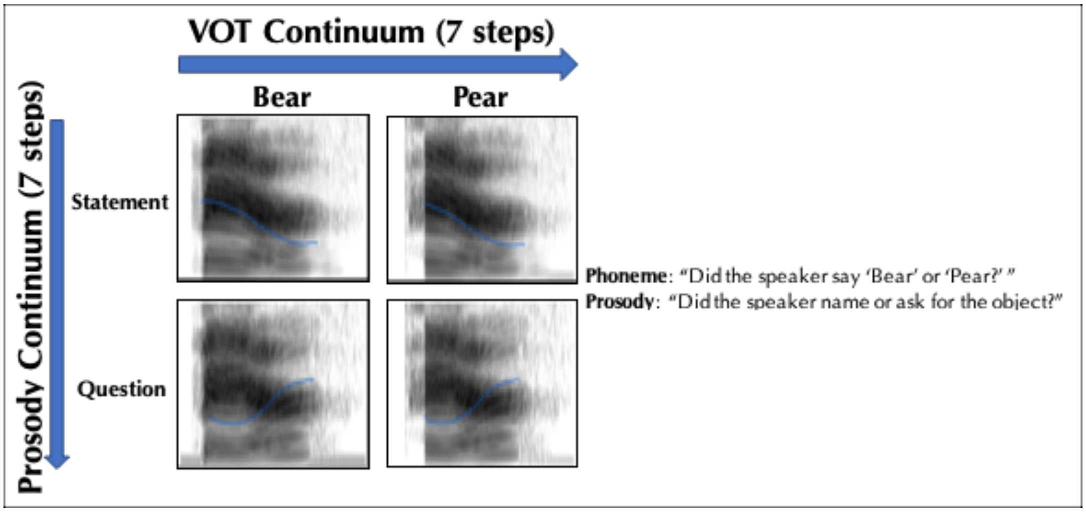


Figure 5. Prosodic and phonemic CP tasks. A subset of seven steps along the VOT (x axis) and prosodic (y axis) continua were selected for the CP tasks, resulting a total of 49 stimuli.

After completing the CP tasks, participants took part in the MMN paradigm. Participants were fitted with an EEG electrode net and comfortable headphones, and seated in a chair in front of a computer screen in the soundproofed chamber. For each participant, the stimuli located three steps below (i.e., -15%) and three steps above (i.e., +15%) their individual phonemic PSE in the 21-step VOT continuum were used as their within-phoneme exemplar and between-phoneme exemplar, respectively. Likewise, the stimuli located three steps below (-15%) and three steps above (+15%) their individual prosodic PSE in the 21-step VOT continuum were used as their within-prosody exemplar and between-prosody exemplar, respectively. Stimuli were presented using a multi-feature paradigm, during which every other stimulus is a standard (*p* = .5), and every other is one of four types of deviant (*p* = .125). The order of presentation of each type of successive deviant was random. The word “bear” spoken as a statement was used as the standard while the within-category prosody, between-category prosody, within-category phoneme and between-category phoneme stimuli specifically selected for each participant were used as the deviants. To minimize movements, the participant’s EEG was recorded while they watched a PG-rated wordless and silent animated movie. Participants were presented with a total of 960 stimuli (i.e., 480 stand repetitions and 120 repetitions of each of the four deviants). The total duration of the EEG acquisition lasted 24 min.

While the CP tasks were always administered prior to the MMN paradigm, the order of administration of the CP-MMN portion and behavioral test battery (i.e., vocabulary and reading comprehension) were counter-balanced in order to minimize potential confounding effects of attention and fatigue on the behavioral performances and EEG data. Overall duration of the entire experimental session (including screening measures, language test battery, and CP-MMN portion) was approximately 2.5 hours.

EEG Data Acquisition and Preprocessing

Continuous EEG was recorded from 128 electrodes embedded in a Hydrocel Geodesic Sensor Net (EGI, Eugene, OR) connected to a NetAmps 300 amplifier, and using the software NetStation 4 on a MacBook Pro. Six of the 128 electrodes were used to record the vertical and horizontal electrooculograms so that blinks and eye movements can be identified. During recording, the EEG was sampled at 500 Hz and referenced to the vertex (Cz). EEG data were then re-referenced offline to the average of the left and right mastoid electrodes and filtered with a bandpass between 0.1 and 20Hz. Electrode impedances were kept below 50 kΩ.

For each participant, the continuous EEG were segmented into 600 ms long epochs time-locked to the presentation of each stimulus, starting 100 ms prior to the onset of the words. EEG epochs containing artefacts such as electrode drifting or muscle activity were discarded. Eye artefacts (blinks or movements) were removed from the EEG epochs using a second-order blind identification (SOBI) procedure as implemented in the AAR plug-in for the EEGLAB toolbox (Gómez-Herrero *et al.*, 2006) for MATLAB. ERPs were then computed separately for each participant, electrode and condition (i.e., within-phoneme, between-phoneme, within-prosody, between-prosody) by averaging together the remaining artefact-free EEG epochs relative to a 100 ms pre-word-onset baseline.

Power Analysis

A power analysis was conducted in G-Power (Faul, Erdfelder, Lang, & Buchner, 2007) to determine the minimum sample size needed to achieve adequate power of 80% using an alpha of .05. Based on the existing behavioral literature on the relationships between prosody sensitivity and reading skills in adults (Chan & Wade-Woolley, 2018; Fotidzis, Moon, Steele, & Magne, 2018; Heggie & Wade-Woolley, 2018), power analysis indicated that a sample size of 28 participants with usable data (i.e., post-attrition) would be adequate for detecting an effect size of Cohen's $f^2 \geq .4$. Cohen (1998) classifies $f^2 \geq$

.02, $f^2 \geq .15$, and $f^2 \geq .35$ as representing small, medium and larger effect sizes, respectively. The final sample size with usable data was 23 participants.

CHAPTER IV: RESULTS

This dissertation research addresses a particular gap in the literature by focusing specifically on the intonation aspect of prosody and how it relates to reading comprehension skills in adult readers, after controlling for phoneme perception and vocabulary. To this end, 34 participants were recruited and their MMN was recorded to measure neural sensitivity to auditory cues of phonemic or prosodic contrasts. Participants were also administered standardized behavioral measures of IQ, vocabulary knowledge, and silent reading comprehension skills, and were given a researcher-created auditory CP task on the computer. After removing movement and bad channel EEG artefacts (*n* = 5 removed), participants scoring outside of the required range for PSE (*n* = 4 removed), and outliers based on Cook's *d* values (*n* = 2 removed), the remaining participant pool (*N* = 23) was used in the final analyses (male = 13; *M* age = 20, *SD* = 2.35, min age = 19, max age = 28).

Event-Related Potentials

The ERPs elicited by deviants were analyzed using the cluster-based permutation approach implemented in the FieldTrip toolbox (Oostenveld Fries, Maris, & Schoffelen, 2011). Using nonparametric statistics, this procedure allows for identification of significant effects without prior assumptions about their latency or spatial distribution over the scalp. In addition, this approach deals with the multiple comparisons problem due to the large number of (channel, timepoint)-pairs by controlling for the family-wise error rate (Maris & Oostenveld, 2007). Separately for the phoneme and prosody conditions, pairwise comparisons were conducted between the ERPs elicited by deviant and standard stimuli to measure the time course and scalp distribution of the brain responses elicited by within-category stimuli (within-category deviants *vs.* between-category standards) and between-category stimuli (between-category deviant *vs.* within-category standard).

Phonemic Deviants. Pairwise comparisons were conducted between the ERPs elicited by standard stimuli and the ERPs elicited by within-category VOT deviants (Figure 6) or between-category-VOT deviants (Figure 7). Results showed that within-category VOT deviants were associated with an increased positivity between 76 and 116 ms (p = 0.006) followed by an increased negativity between 122 and 176 ms post word onset (p = .001). Both ERP effects showed a cluster of significant differences that was more pronounced over centro-frontal regions of the scalp.

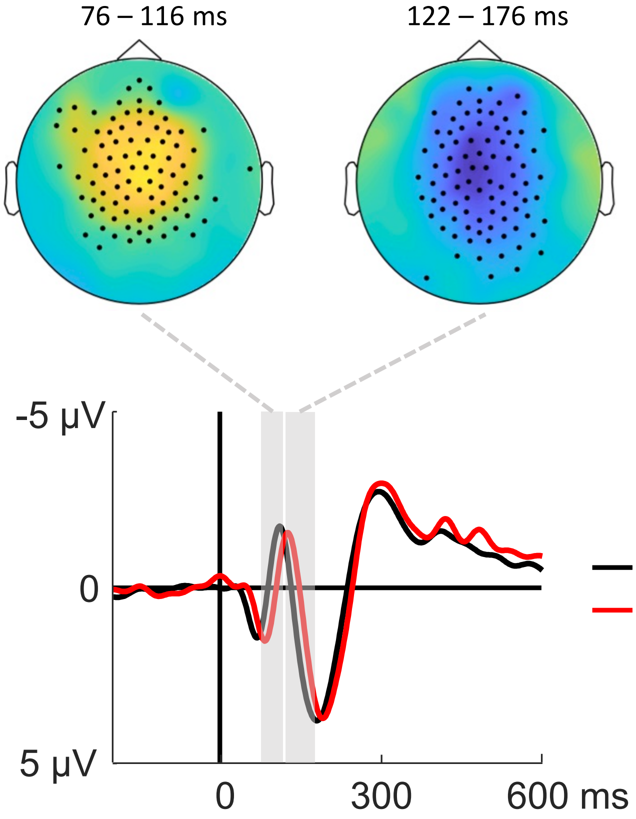


Figure 6. Within-category VOT effect. Grande-average ERPs elicited by standard stimuli (black trace) and within-category deviant stimuli (red trace). The gray rectangles indicate the time window of the clusters of significant ERP differences. Topographic maps at the top of the figure show the average amplitude difference between the ERPs for the standard and deviant conditions in the time windows of each cluster (black dots represent the electrodes part of the cluster).

Similarly, between-category VOT deviants elicited both an increased positivity between 66 and 124 ms ($p < 0.001$), and an increased negativity between 128 and 180 ms ($p = 0.001$). In addition, between-category VOT deviants showed a second increased positivity between 166 and 286 ms ($p < 0.001$). These three significant ERP differences were centro-frontally distributed.

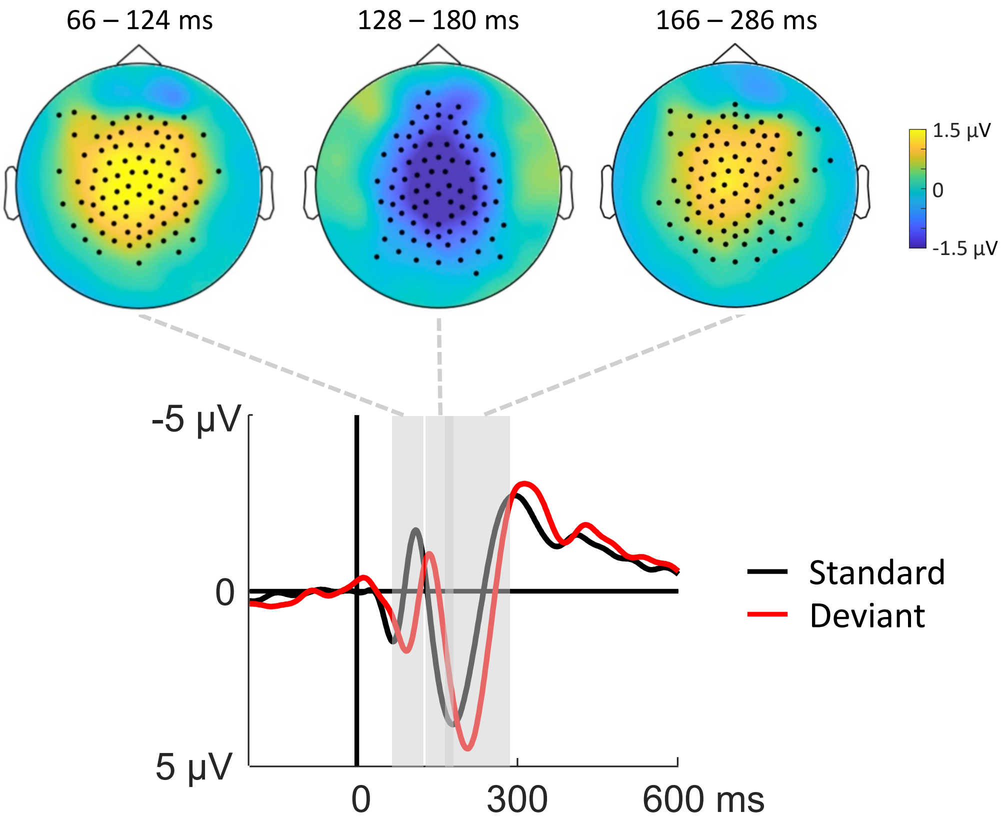


Figure 7. Between-category VOT effect. Grande-average ERPs elicited by standard stimuli (black trace) and between-category deviant stimuli (red trace). The gray rectangles indicate the time window of the clusters of significant ERP differences. Topographic maps at the top of the figure show the average amplitude difference between the ERPs for the standard and deviant conditions in the time windows of each cluster (black dots represent the electrodes part of the cluster).

Prosodic Deviants. Pairwise comparisons were conducted between the ERPs elicited by the standard stimuli and the ERPs elicited by within-category intonation deviants (Figure 8) or between-category intonation deviants (Figure 9). Within-category intonation deviants elicited an increased negativity between 128 and 190 ms post word onset ($p = .044$). This negative ERP effect was centro-frontally distributed.

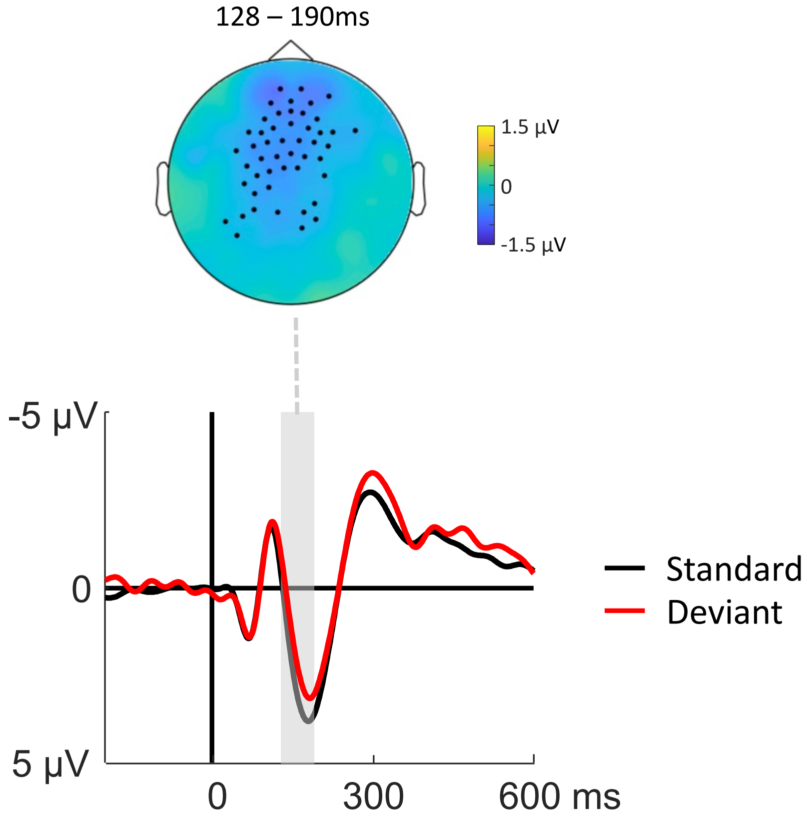


Figure 8. Within-category intonation effect. Grande-average ERPs elicited by standard stimuli (black trace) and within-category deviant stimuli (red trace). The gray rectangle indicates the time window of the cluster of significant ERP differences. Topographic maps at the top of the figure show the average amplitude difference between the ERPs for the standard and deviant conditions in the time windows of the cluster (black dots represent the electrodes part of the cluster).

Between-category intonation deviants also elicited an increased centro-frontal negativity, but in a slightly different time window starting from 118 and lasting until 234 ms post word onset ($p = .044$).

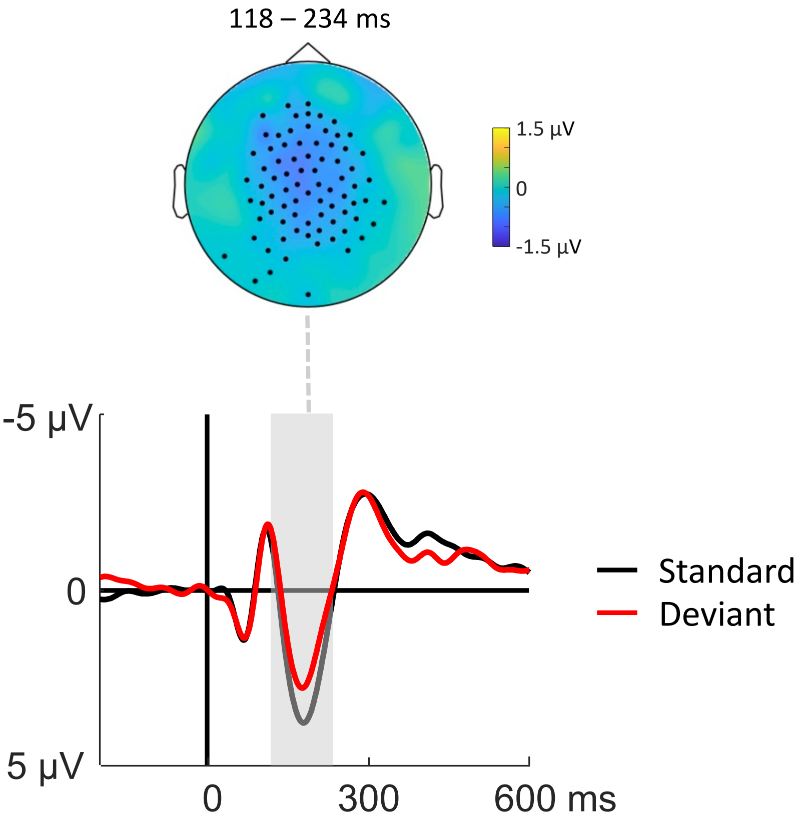


Figure 9. Between-category intonation effect. Grande-average ERPs elicited by standard stimuli (black trace) and within-category deviant stimuli (red trace). The gray rectangle indicates the time window of the cluster of significant ERP differences. Topographic maps at the top of the figure show the average amplitude difference between the ERPs for the standard and deviant conditions in the time windows of the cluster (black dots represent the electrodes part of the cluster).

Brain-Behavior Relationships

Table 1 presents the descriptive statistics of the participants for all variables included in the study.

Table 1. *Descriptive statistics of participants (N = 23)*

Measure	Mean	Standard Deviation
PPVT-4	102.78	14.73
WIAT-III	111.78	9.54
VOT CP quality	0.023	0.019
Intonation CP quality	0.061	0.039
MMN difference VOT	-0.266	0.950
MMN difference intonation	0.035	1.112

Note: WIAT-III is the reading comprehension measure; PPVT-4 is the vocabulary measure; CP = categorical perception; MMN difference = MMN within minus MMN between

To address research questions Q_1 and Q_2, phonemic sensitivity and prosodic sensitivity were measured separately using the mean of the ERP amplitude at each channels and time points belonging to the clusters of significant negative difference (i.e., MMN) in the four deviant conditions (see Lense, Gordon, Key, & Dykens, 2014; Magne, Jordon & Gordon, 2016 for similar approaches). The phonemic sensitivity index (i.e., MMN difference VOT) was calculated by subtracting the mean within-phoneme MMN from the mean between-phoneme MMN. The prosodic sensitivity index (i.e., MMN difference intonation) was calculated by subtracting the mean within-prosody MMN from the mean between-prosody MMN.

The three research questions addressed in the present study were used as guides in the data analysis presented in the rest of this section.

Q1: What is the relationship between performances on the prosodic CP task and the MMN responses to the prosodic deviants? An analysis of the data and visual inspection of histograms, P-P plots, and scatterplots revealed that the MMN prosody differences had no outliers and met the assumptions of linearity and normality. The

Kolmogorov-Smirnov test was statistically non-significant, *D*(23) = 0.128, *p* = .20, indicating the MMN prosody differences did not deviate significantly from normal.

A Pearson product-momentum correlation was conducted to test whether there is a statistically significant linear relationship between the MMN prosody difference and CP intonation quality.

Based on the results, MMN prosody difference and CP intonation quality have a non-significant inverse relationship, *r*(23) = -.26, *p* = .23. Figure 10 shows the relationship between individual MMN prosody differences and intonation quality. While this relationship was not significant, it represents a small-to-moderate effect size according to Cohen (1988).

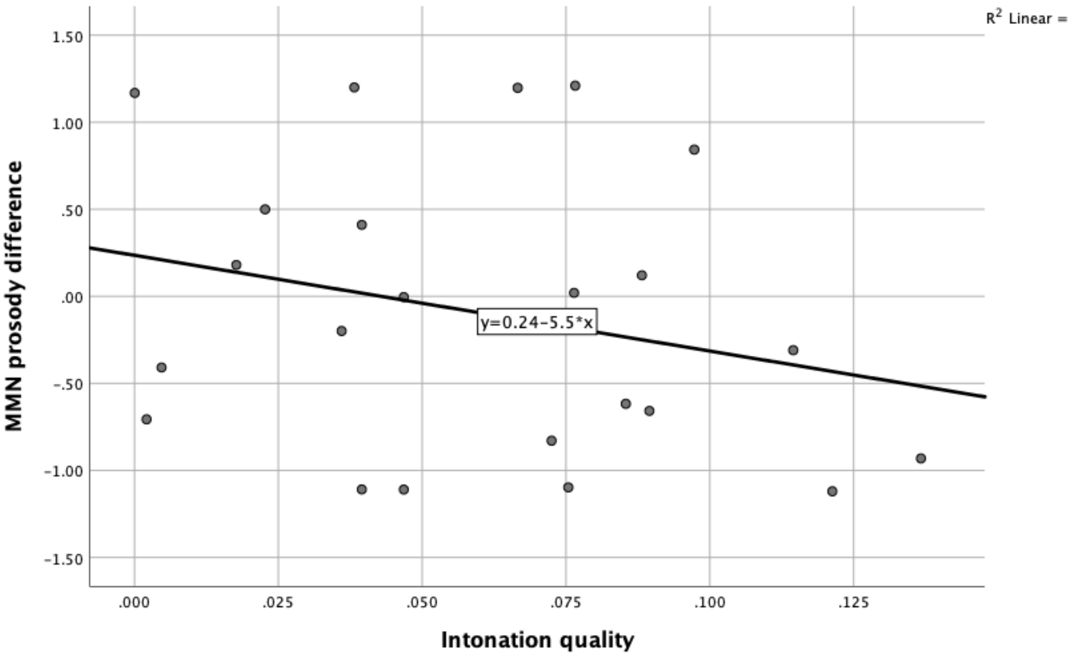


Figure 10. Relationship between individual MMN prosody differences and intonation quality. The line of best fit is represented by a solid gray line.

Q2: How does PS to different intonation contours in spoken American English correlate with reading performance? An analysis of standard residuals was conducted, which revealed the data contained no outliers (*Std. Residual Mi*n = -1.40, *Std. Residual Max* = 1.96). Tests to determine whether data met the assumption of collinearity were met (all *Tolerance* < 10, all *VIF* > 0.1), as was the assumption of independent errors (Durbin-Watson value = 2.49). Visual inspection of the standardized residuals via histograms, P-P plots, and scatterplots all indicated the data contained normally distributed errors and met the assumptions of homogeneity of variance and linearity. Table 2 summarizes the correlations between MMN differences for intonation and VOT, respectively, and vocabulary performance variables on reading comprehension.

Table 2. *Pearson product-momentum correlation values between MMN differences for intonation and VOT, respectively, and vocabulary performance variables on reading comprehension.*

	WIAT-III	MMN difference intonation	MMN difference VOT	PPVT-4
WIAT-III	1.00	.044	.140	.109
MMN difference intonation		1.00	.631**	.125
MMN difference VOT			1.00	.124
PPVT-4				1.00

Note: The Benjamini-Hochberg procedure was used to control for multiple comparisons. WIAT-III is the reading comprehension measure; PPVT-4 is the vocabulary measure; CP = categorical perception; MMN difference = MMN within minus MMN between

** Correlation coefficient statistically significant at *p* < .01 level (2-tailed)

A bootstrapped multiple regression analysis was conducted to investigate whether the variability in the reading comprehension scores on the WIAT-III ($M = 111.78$, $SD = 9.54$) could be predicted from vocabulary scores on the PPVT-4 ($M = 102.78$, $SD = 14.73$), the MMN difference for within and between conditions for intonation ($M = 0.04$, $SD = 1.11$), and the MMN difference for within and between conditions for VOT ($M = -0.27$, $SD = 0.95$). The linear combination of all three variables in the regression model (reading comprehension = b_0 + .18[MMN difference VOT] + .10[vocabulary] – .08[MMN difference Intonation]) was not statistically significantly related to reading comprehension, $F(3, 19) = 0.21$, $p = .89$, Cohen's $f^2 = .03$, indicating the overall model has a small effect size and does not account for statistically significant variance explained in reading comprehension. Table 3 summarizes the results of the multiple regression analysis.

Table 3. *SPSS Bootstrapped Multiple Regression Analysis - Linear model of MMN predictors of reading comprehension.*

Model	Predictor	*b*	*SE*	*ß*	R^2	ΔR^2	*p*
3					.032	.004	.79
	Constant	105.65	11.96				.000***
	MMN difference VOT	1.96	4.36	.178			.60
	Vocabulary	0.06	0.12	.097			.62
	MMN difference Intonation	-0.83	4.15	-.080			.80

Note: Dependent variable: reading comprehension scores on WIAT-III

*** Statistically significant at $p < .001$

MMN difference for VOT variable (*ß* = .178, *p* = .60) was statistically non-significant indicating it did not influence reading comprehension scores on the WIAT-III. The vocabulary scores on the PPVT-4 variable (*ß* = .097, *p* = .62) was statistically non-significant indicating it also did not influence reading comprehension scores on the WIAT-III. The MMN difference for intonation variable (*ß* = -.08, 95% *CI* [-5.23, 10.23], *p* = .80), was statistically non-significant indicating it did not influence reading comprehension scores on the WIAT-III (see also Figure 11). There was, however, a statistically significant positive correlation between the MMN difference for VOT and the MMN difference for intonation variables, *r*(23) = .63, *p* = .006. This indicates that as values increase in one variable, they also increase in the other.

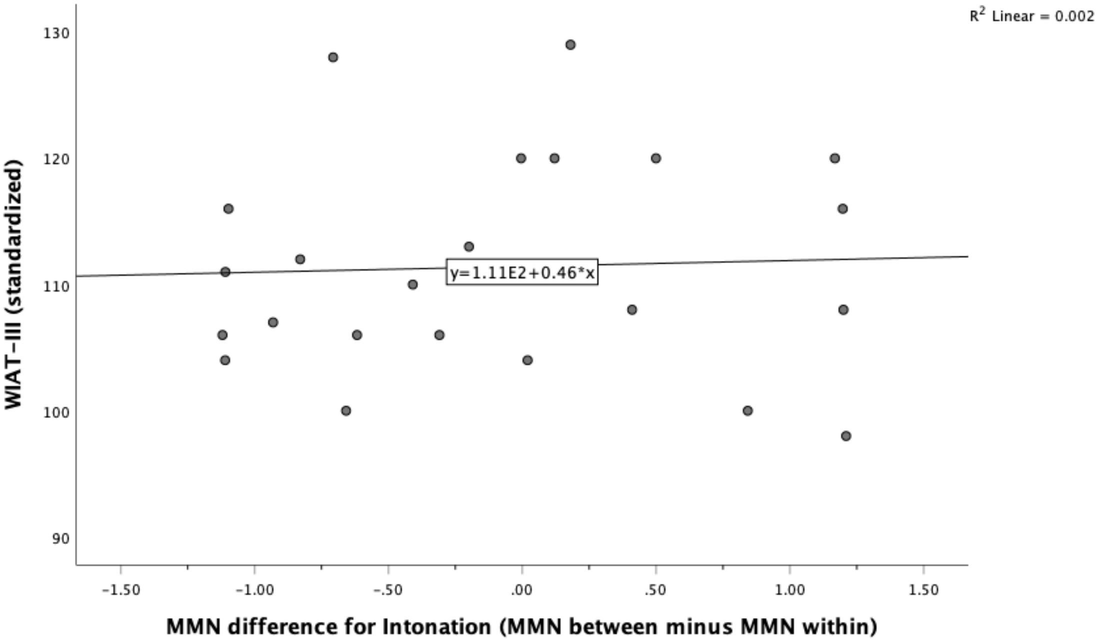


Figure 11. Relationship between individual MMN prosody differences and WIAT-III scores. The line of best fit is represented by a solid gray line.

Q3: How does prosody CP correlate with reading performance? An analysis of standard residuals was conducted, which revealed the data contained no outliers (*Std. Residual Mi*n = -1.69, *Std. Residual Max* = 1.72). Tests to determine whether data met the assumption of collinearity were met (all *Tolerance* < 10, all *VIF* > 0.1), as was the assumption of independent errors (Durbin-Watson value = 1.99). Visual inspection of the standardized residuals via histograms P-P plots, and scatterplots all indicated the data contained normally distributed errors and met the assumptions of homogeneity of variance and linearity. Table 4 summarizes the correlation values between intonation and phoneme CP quality, and vocabulary performance variables on reading comprehension.

Table 4. *Pearson product-momentum correlation values between intonation and phoneme CP quality, and vocabulary performance variables on reading comprehension.*

	WIAT-III	Intonation quality	Phonemic perception	PPVT-4
WIAT-III	1.00	-.582**	-.296	.109
Intonation quality		1.00	.098	-.405
Phonemic perception			1.00	.026
PPVT-4				1.00

Note: The Benjamini-Hochberg procedure was used to control for multiple comparisons. WIAT-III is the reading comprehension measure; PPVT-4 is the vocabulary measure; CP = categorical perception

** Correlation coefficient statistically significant at $p < .01$ (2-tailed)

WIAT-III scores and CP intonation quality have a statistically significant inverse relationship, $r(23) = -.58$, $p = .03$, meaning that as the performances on the WIAT-III decreases, the standard deviation between the empirical data and the linear fit for CP intonation increases (see Figure 12).

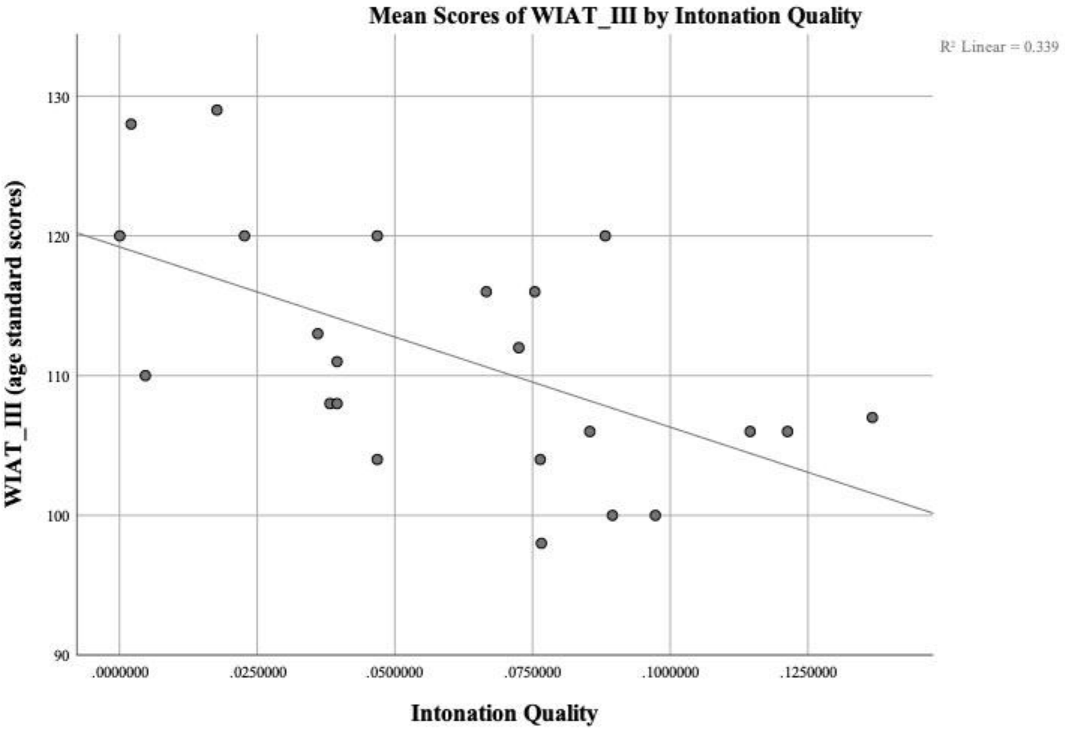


Figure 12. Relationship between WIAT-III mean scores and intonation quality. The line of best fit is represented by a solid gray line.

A bootstrapped multiple regression analysis was conducted to investigate whether the variability in the reading comprehension scores on the WIAT-III (11.39*, SD* = 8.55) could be predicted from vocabulary scores on the PPVT-4 (*M* = 102.48*, SD* = 14.05), CP quality intonation (*M* = .061*, SD* = .039), and CP quality phoneme scores (*M* = .023*, SD* = .019). The linear combination of all three variables in the regression model (reading comprehension = b_0 – .232[phonemic perception] – .133[vocabulary] – .613[intonation quality] was statistically significantly related to reading comprehension, *F*(3, 19) = 4.42, *p* = .016, indicating the overall model accounts for statistically significant variance explained in reading comprehension, Cohen's f^2 = .70. The beta values tell us to what degree each predictor variable affects the outcome of reading comprehension, if the effects of all other variables are held constant. Table 5 summarizes the relative strength of the individual predictors on the reading comprehension outcome.

Table 5. *SPSS Bootstrapped Multiple Regression Analysis - Linear model of predictors of reading comprehension.*

Model	Predictor	*b*	*SE*	*ß*	R^2	ΔR^2	*p*
3					.411	.310	.005**
	Constant	130.25	13.64				.001***
	Phonemic perception	-102.68	77.71	-.232			.19
	Vocabulary	-.081	0.11	-.133			.44
	Intonation quality	-135.93	43.62	-.613			.01**

Note: Dependent variable: reading comprehension scores on WIAT-III

** Statistically significant at $p < .01$; *** Statistically significant at $p < .001$

After controlling for phonemic perception and vocabulary scores, the model 3 including the intonation quality variable (R^2 = .41, *ß* = -.613, 95% *CI* [-223.16, -51.53], $p = .01$), accounted for 41% of the variance in reading comprehension. This means that for each unit increase in standard deviation between the empirical data and the fit, reading comprehension scores decreased by .613 of a standard deviation unit.

Hypothesis 3 states that higher scores on the reading comprehension measure would positively correlate with the CP intonation quality value of the participants' response function on the prosodic CP task, after controlling for vocabulary and phonemic perception. In terms of the direction of the correlation observed, it is negative. However, this makes sense, given that the smaller the intonation quality value the better individuals are able to detect slight changes in pitch, which has been implicated in better reading comprehension.

CHAPTER V: DISCUSSION

This dissertation research addresses a gap that exists in the literature by specifically addressing the intonation aspect of prosody and how it relates to reading comprehension skills in adult readers, after controlling for phoneme perception and vocabulary. To this end, the mismatch negativity (MMN) was recorded to measure neural sensitivity to auditory cues of phonemic or prosodic contrasts. Participants were also administered standardized behavioral measures of vocabulary knowledge and silent reading comprehension skills. The findings revealed there were no statistically significant correlations between the behavioral measures and the MMNs; however, statistically significant ERPs were found for all between and within CP conditions. In addition, a statistically significant relationship was found for CP of intonation and reading comprehension. The following section discusses the findings and their implications in relation to each of the research questions for this study.

Q_1: What is the relationship between performances on the prosodic CP task and the MMN responses to the prosodic deviants?

Categorical perception was measured with identification and discrimination of spoken stimuli varying along a minimal-pair continuum for phoneme (i.e., /bear/-/pear/), and intonation (e.g., question or statement). The standard deviation between the data and the quality of the fit to the slope of the identification responses as a function of the continuum step, indicates boundary precision between phonemic or prosodic categories with smaller values reflecting a closer approximation to the actual categorical step (O’Brien et al., 2018). Whereas, the ability to discriminate neighboring continuum steps within categories (e.g., incremental steps for [/b/ → /p/], and [question? → statement.], respectively), which is typically more difficult, and between categories (e.g., /pear/ vs. /bear/; question? vs. statement.), which is typically easier, can reflect sensitivity to phonemic and subphonemic features (e.g., Serniclaes, 2006, Li et al., 2019).

The statistically significant MMN observed for within and between VOT deviants is in line with similar results observed by others (e.g., O'Brien et al., 2018; Serniclaes & Seck, 2018; Serniclaes et al., 2004). Regarding prosody, the finding of significant MMNs for both within- and between-category deviants is important because, to the best of my knowledge, intonation has not been examined in a non-tonal language using an MMN paradigm. In addition, MMNs observed for both prosody and VOT were larger for the between-category than for the within-category deviant (Serniclaes et al., 2004). This thus indicates that phonetic and pitch changes in speech stimuli can elicit an MMN (Maiste et al., 2005), and that the MMN appears to be more sensitive to the acoustic cues of VOT and intonation, rather than the category (Li et al., 2019; Maiste et al., 2005). Interestingly, the MMNs for both VOT and prosody manipulations had similar fronto-central distributions over the scalp, potentially suggesting similar neurocognitive mechanisms (see Figures 6 through 9). By contrast, the MMN occurred slightly later for prosody than for VOT (i.e., 118-234 ms intonation vs. 66-286 ms VOT for between; 128-190 ms intonation vs. 76-176 ms VOT for within). This time difference could be due to the temporal characteristic of the acoustic cues underlying intonation versus VOT.

According to the first hypothesis (H_1), I predicted that individuals with the smaller value for the quality of fit on their prosody CP response function (i.e., smaller standard deviation between the empirical data and the fit) would demonstrate larger

MMN to between-category prosodic deviant stimuli, and smaller MMN to within-category prosodic deviant stimuli, compared to the standard stimulus. The MMN prosody difference and CP intonation quality have an inverse relationship, albeit statistically non-significant. Despite the lack of statistical significance, the effect size and direction of the correlation lend marginal support to H_1, which predicted that individuals with a smaller CP intonation quality value on their response function would demonstrate larger MMNs differences. This implies that the larger the MMN difference, the better they are able to discern differences in intonation changes, although further investigation is warranted to determine if a statistically significant relationship does indeed exist.

Several possibilities exist for the lack of a statistically significant correlation between the MMN difference for intonation and the CP intonation quality. It could be that the sample tested were all adults with typical reading skills, whereas significant group differences have been shown for individuals with RD compared to controls (e.g., Schulte-Körne et al., 2001). In addition, contrary to what one would expect—that the larger the acoustical difference between the standard and deviant, the larger the MMN amplitude (e.g., Tiitinen, May, Reinikainen, & Näätänen, 1994)—another reason for a lack of correlation could be because the deviant stimuli were created from native language prototypes, which have been shown to influence the MMN amplitude via acoustical and phonetic processes (Näätänen et al, 1997; Cheour, Ceponiene, Lehtokoski, Luuk, Allik, Alho, & Näätänen, 1998). Finally, a small sample size may have contributed to a non-significant result, as the power analysis indicated a sample of 28 to sufficiently detect an effect, and the final usable sample was 23.

In short, despite that there were statistically significant findings for the ERPs, there was not a discernable brain-behavior relationship, but future studies with an RD sample and slightly modified stimuli could reveal a different outcome.

Q_2: How does PS to different intonation contours in spoken American English correlate with reading performance?

Regarding the second hypothesis (H_2), The multiple regression analysis conducted to investigate whether the variability in the reading comprehension scores on the WIAT-III could be predicted from vocabulary scores on the PPVT-4), the MMN difference for within and between conditions for intonation, and the MMN difference for within and between conditions for VOT, was statistically non-significant, yielding a small effect size (Cohen's $f^2 = .03$). The correlation between the MMN and reading variables was also not in the hypothesized direction (H_2).

In terms of the MMN findings, previous research suggests that speech deviants can generate more than just one MMN response—at least for phonemes. For example, a phoneme deviant may elicit an early MMN and a late MMN, sometimes called a late discriminative negativity (LDN) that appears around 400 – 500 ms (e.g., Cheour et al., 2001). Additional findings have shown even three MMNs (e.g., Shulte-Körne et al., 2001), while in other studies, they have early negativities and positivity followed by a late MMN (e.g., Hommet et al., 2009; Maiste et al., 1995). Thus, the results are quite heterogeneous in regard to phonemic manipulations, and even more scarce in regard to prosody.

Studies examining the relationship between the MMN responses and reading skills suggest distinct contributions of the early and late MMN responses. Indeed, the early MMN responses are not very sensitive to reading abilities nor categorical perception, and they seem to reflect more acoustical differences among stimuli (Maiste et al., 1995). In contrast, in several instances, it seems that the late responses (i.e., late MMNs [Korpilahti, Lang, & Aaltonen, 1995], or also referred to as N2-P3 complex [O'Donnell & Cohen, 1988]), do seem to be more likely related to CP or reading skills. Similarly, in the present study, the MMN appears to be sensitive to the acoustic cues (VOT and intonation) rather than phonemic or prosodic categories, since there is an observed MMN here even for within-category deviants, as well as a statistically significantly correlation between the two MMN differences for VOT and intonation.

Q_3: How does prosody CP correlate with reading performance?

In line with the third hypothesis (H_3), there was a statistically significant correlation between CP intonation and reading comprehension. In addition, in the regression model, CP intonation quality was found to be a significant predictor of reading comprehension (i.e., WIAT-III), even after controlling for vocabulary (PPVT) and CP phonemic quality. In contrast, the WIAT-III and phonemic perception variables were not statistically significantly correlated, and the phonemic perception variable had a negative beta value in the regression model ($\beta = -.232$). This negative beta value, albeit non-significant, may simply be because the sample tested was adults and the contribution of phonological processing skills to reading decreases in adults (e.g., Castles, Rastle, & Nation, 2018; Ehri, 1995; Frith, 1985; but see also, Milledge & Blythe, 2019).

Not surprisingly, the correlation between intonation quality and vocabulary scores on the PPVT-4 were approaching statistical significance ($p = .06$). However, what is surprising is that the addition of the vocabulary variable to the regression model did not explain a statistically significant amount of variance in reading comprehension. Furthermore, the vocabulary variable had a negative beta value in the regression model, $\beta = -.133$. Despite being non-significant, this negative beta value for a variable that has historically been known to be predictive of reading comprehension (e.g., Cain & Oakhill, 2014), is puzzling and seems to even potentially have a suppressive effect on the overall model. However, this assumption requires further investigation in order to fully understand the nature of the vocabulary finding.

Still, the finding that CP intonation quality significantly contributes to reading comprehension skills stands in stark contrast to the lack of significant relationship between the prosodic MMNs and reading (i.e., Hypothesis H_2). However, Mundy and Carroll (2016) make an argument that prosody awareness, not prosody sensitivity, contributes to reading skills in adults. The participants in the current study were asked to discriminate between two stimuli on the basis of the acoustic dimensions of phoneme (/p/ or /b/), or intonation (statement or question). The fact that the quality of fit for prosody predicts reading comprehension, but the MMN sizes do not, suggests that the poorer fit cannot be attributed to a fundamental deficit in the perception and encoding of the prosodic cues, but rather is more related to what to make of these cues (i.e., consciously comparing and contrasting the different auditory stimuli), which is related to awareness (i.e., the ability to identify and manipulate these cues; Mundy & Carroll, 2016).

The finding that reading comprehension can be predicted by CP of intonation is important for several reasons. One reason is that the factors accounting for all of the considerable variability in reading skills are still unaccounted for and a much-debated topic today. The fact that CP of intonation was predictive of reading comprehension means that there are definitely prosodic features of pitch at play in the reading skills of typical adult readers (REF). Secondly, if prosodic features of pitch are involved in the reading skills of typically reading adults, there is reason to investigate how this looks in a dyslexic or RD population. Thirdly, to date, no studies have specifically examined the predictive nature of CP of intonation in a non-tonal language, and as such, this study represents an important addition to the literature.

Limitations and Future Directions

Several factors could potentially have affected the results of the present study. To start, the CP behavioral task might not have been sensitive enough to capture all the subtle differences in participant's categorical perception. The stimuli were created by replicating the procedures outlined by Sammler and colleagues (2015). However, further investigations utilizing smaller incremental steps for the within-condition stimuli could potentially be useful for capturing a more robust representation of individuals' PSEs.

An unexpected finding was that the relationship between vocabulary scores on the PPVT-4 and WIAT-III comprehension scores was not statistically significant. This could very likely be due to the fact that the words used on the PPVT-4 are not related to the passages used in the WIAT-III. The reading comprehension subtest of the WIAT-III was designed to include high frequency, highly decodable words in order to control for any potentially confounding weaknesses in decoding or vocabulary. Whereas the PPVT-4 is designed to measure receptive vocabulary of children and adults, and the words increase in difficulty. As a result, by design, the difficulty of the words on the PPVT-4 exceed those on the WIAT-III, which is likely the reason for the lack of correlation observed between the two measures.

On the MMN side, in auditory oddball paradigms, MMNs can be detected even when the subject is not paying attention, which demonstrates the brain's capacity to carry out complex comparisons between a stream of sounds automatically (Näätänen, 2001). However, even though the MMN is seldomly affected by a subject's attention, some studies suggest that the MMN is attenuated when their attention is directed outside of the location of the auditory stimulus (Arnott and Allan, 2002). In contrast, the MMN can also be elicited when the subject pays attention to stimuli, but it is difficult to measure in this condition because of the overlapping N2 component (Müller, Achenbach, Oades, Bender, & Schall, 2002). As such, it has generally been recommended to direct subjects' attention away from the auditory stimulus (Näätänen, 2000).

With these aforementioned points in mind, the results of the current study could have been influenced based on whether the participant's attention was directed toward some other distractor, or whether they did not ignore the auditory stimuli as instructed. In addition, participant arousal and attention state have been found to affect the amplitudes of the MMN response (Garrido et al., 2009). The participants in this study could have experienced varying states of relaxation and/or attention while watching the silent movies. Consequently, their relative state of consciousness could have affected the amplitude of the observed MMNs.

With regard to the ERPs recorded, if you look at all the comparisons of interest (see Figures 6 through 9), you can actually see that there seems to be another negative difference between deviant and standards for all comparisons except for the Intonation between condition. This late MMN / LDN starts around 300 ms, which is after the statistically significant MMN and positivity for VOT and after the significant MMN for intonation within. Although this late negative difference was statistically non-significant, it appears to be approaching significance in some instances (*p* =.079 for within-category intonation). As such, there could be an alternative way to characterize this late MMN and further research is needed to see if it is indeed a good predictor of reading and/or CP performances. Furthermore, Hommet and colleagues (2009) found that the differences in MMN and LDN profiles between individuals with developmental dyslexia and typically developing controls appears to be a consistent finding across the ages in their samples, and suggests there may potentially be a defect at both early and late phases of speech sounds processing in RD.

Another aspect that can be examined in future studies is the latency of the MMN. Some studies suggest that it is not the amplitude of the MMN peak, but rather the latency that is related to reading. For instance, both reduced amplitudes and delayed latencies have been observed in the general auditory processing ability of children with reading problems (e.g., Alonso-Búa, Díaz, & Ferraces, 2006; Shulte-Körne et al., 1998; Shulte-Körne, Bartling, Deimel, & Remschmidt, 1999).

In summary, there still are quite a few ways to look at the data before a behavioral-EEG relationship can be ruled out with any certainty. Taken together, the findings of this study contribute to the literature base, and also furnish a solid springboard for subsequent EEG studies into the relationship between the prosodic feature of intonation and reading.

REFERENCES

Adlard, A., & Hazan, V. (1998). Speech perception in children with specific reading difficulties (Dyslexia). *The Quarterly Journal of Experimental Psychology*, *51A*(1), 153–177. Retrieved from https://journals.sagepub.com/doi/pdf/10.1080/713755750

Ahissar, M. (2007). Dyslexia and the anchoring-deficit hypothesis. *Trends in Cognitive Sciences*, *11*(11), 458–465. http://doi.org/10.1016/J.TICS.2007.08.015

Ahissar, M., Lubin, Y., Putter-Katz, H., & Banai, K. (2006). Dyslexia and the failure to form a perceptual anchor. *Nature Neuroscience*, *9*(12), 1558–1564. http://doi.org/10.1038/nn1800

Alexandrov, A. A., Boricheva, D. O., Pulvermüller, F., & Shtyrov, Y. (2011). Strength of word-specific neural memory traces assessed electrophysiologically. *PLoS ONE*, *6*(8), e22999. http://doi.org/10.1371/journal.pone.0022999

Alonso-Búa, B., Díaz, F., & Ferraces, M. J. (2006). The contribution of AERPs (MMN and LDN) to studying temporal vs. linguistic processing deficits in children with reading difficulties. *International Journal of Psychophysiology*, *59*(2), 159–167. https://doi.org/10.1016/j.ijpsycho.2005.03.020

Arnott, S. R., & Allan, C. (2002). Stepping out of the spotlight: MMN attenuation as a function of distance from the attended location. *NeuroReport*, *13*(17), 2209–12.

Ashby, J., & Clifton, C. J. (2005). The prosodic property of lexical stress affects eye movements during silent reading. *Cognition*, *96*(3), B89-100.

Baldeweg, T., Richardson, A., Watkins, S., Foale, C., & Gruzelier, J. (1999). Impaired auditory frequency discrimination in dyslexia detected with mismatch evoked potentials. *Annals of Neurology*, *45*(4), 495–503. doi: 10.1002/1531-8249(199904)45:4<495::AID-ANA11>3.0.CO;2-M

Banai, K., & Ahissar, M. (2018). Poor sensitivity to sound statistics impairs the acquisition of speech categories in dyslexia. *Language, Cognition and Neuroscience*, *33*(3), 321–332. http://doi.org/10.1080/23273798.2017.1408851

Benjamin, R. G., & Schwanenflugel, P. J. (2010). Text complexity and oral reading prosody in young readers. *Reading Research Quarterly*, *45*(4), 388–404. http://doi.org/10.1598/RRQ.45.4.2

Bialystok, E., & Hakuta, K. (1995). *In other words: The science and psychology of second language acquisition*. New York, NY: Basic Books. http://doi.org/10.1177/027046769501500412

Bishop, D. V. M. (2007). Using mismatch negativity to study central auditory processing in developmental language and literacy impairments: Where are we, and where should we be going? *Psychological Bulletin*, *133*(4), 651–672. http://doi.org/10.1037/0033-2909.133.4.651

Bolinger, D. (1986). *Intonation and its parts: Melody in spoken English*. Stanford, CA: Stanford University Press.

Brandmeyer, A., Farquhar, J. D. R., Mcqueen, J. M., & Desain, P. W. M. (2013). Decoding speech perception by native and non-native speakers using single-trial electrophysiological data. *PLoS ONE*, *8*(7), 68261. http://doi.org/10.1371/journal.pone.0068261

Breen, M., Kaswer, L., Van Dyke, J. A., Krivokapić, J., & Landi, N. (2016). Imitated prosodic fluency predicts reading comprehension ability in good and poor high school readers. *Frontiers in Psychology*, *7*. http://doi.org/10.3389/fpsyg.2016.01026

Braze, D., Tabor, W., Shankweiler, D. P., & Mencl, W. E. (2007). Speaking up for vocabulary: Reading skill differences in young adults. *Journal of Learning Disabilities*, *40*(3), 226–43. http://doi.org/10.1177/00222194070400030401

Byrne, B., & Fielding-Barnsley, R. (1991). Evaluation of a program to teach phonemic awareness to young children. *Journal of Educational Psychology*, *83*(4), 451–455. Retrieved from http://psycnet.apa.org/buy/1992-10755-001

Cain, K., & Oakhill, J. (2014). Reading comprehension and vocabulary: Is vocabulary more important for some aspects of comprehension. *L'Année Psychologique, 114,* 647–662.

Cain, K., Oakhill, J. V, Barnes, M. A., & Bryant, P. E. (2001). Comprehension skill, inference-making ability, and their relation to knowledge. *Memory & Cognition*, *29*(6), 850–859. http://doi.org/10.3758/BF03196414

Calet, N., Gutiérrez-Palma, N., Simpson, I. C., González-Trujillo, M. C., & Defior, S. (2015). Suprasegmental phonology development and reading acquisition: A Longitudinal Study. *Scientific Studies of Reading*, *19*(1), 51–71. http://doi.org/10.1080/10888438.2014.976342

Carlo, M. S., & Bengochea, A. (2011). Best practices in literacy instruction for English language learners. In L. M. Morrow & L. B. Gambrell (Eds.), *Best practices in literacy instruction,* (Fourth Edition, pp. 117–137). New York, NY: The Guilford Press.

Castles, A., Rastle, K., & Nation, K. (2018). Ending the reading wars: Reading acquisition from novice to expert. *Psychological Science in the Public Interest*, *19*(1), 5–51. https://doi.org/10.1177/1529100618772271

Catts, H. W., Compton, D., Tomblin, J. B., & Bridges, M. S. (2012). Prevalence and nature of late-emerging poor readers. *Journal of Educational Psychology*, *104*(1), 166–181. http://doi.org/10.1037/a0025323

Chall, J. S. (1983). *Stages of reading development*. New York, NY: McGraw-Hill.

Chan, J. S., & Wade-Woolley, L. (2018). Explaining phonology and reading in adult learners: Introducing prosodic awareness and executive functions to reading ability. *Journal of Research in Reading*. http://doi.org/10.1111/1467-9817.12083

Chandrasekaran, B., Krishnan, A., & Gandour, J. T. (2007). Mismatch negativity to pitch contours is influenced by language experience. *Brain Research*, *1128*, 148–156. http://doi.org/10.1016/J.BRAINRES.2006.10.064

Chen, A., Peter, V., Wijnen, F., Schnack, H., & Burnham, D. (2018). Are lexical tones musical? Native language's influence on neural response to pitch in different domains. *Brain and Language*, *180–182*, 31–41. http://doi.org/10.1016/J.BANDL.2018.04.006

Cheour, M., Korpilahti, P., Martynova, O., & Lang, A. (2001). Mismatch negativity and late discriminative negativity in investigating speech perception and learning in children and infants. *Audiology & Neurotology*, *6*, 2–11.

Cheour, M., Ceponiene, R., Lehtokoski, A., Luuk, A., Allik, J., Alho, K., & Näätänen, R. (1998). Development of language-specific phoneme representations in the infant brain. *Nature Neuroscience, 1*, 351-353.

Chobert, J., François, C., Habib, M., & Besson, M. (2012). Deficit in the preattentive processing of syllabic duration and VOT in children with dyslexia. *Neuropsychologia*, *50*(8), 2044–2055. http://doi.org/10.1016/j.neuropsychologia.2012.05.004

Chong, A. J., Vicenik, C., & Sundara, M. (2018). Intonation Plays a Role in Language Discrimination by Infants. *Infancy*, *23*(6), 795–819. http://doi.org/10.1111/infa.12257

Connor, C. M., Alberto, P. A., Compton, D. L., & O'Connor, R. E. (2014). *Improving reading outcomes for students with or at risk for reading disabilities: A synthesis of the contributions from the Institute of Education Sciences Research Centers. NCSER 2014-3000. National Center for Special Education Research*.

Corbera, S., Escera, C., & Artigas, J. (2006). Impaired duration mismatch negativity in developmental dyslexia. *NeuroReport*, *17*(10), 1051–1055. http://doi.org/10.1097/01.wnr.0000221846.43126.a6

Crystal, D. (1987). *The Cambridge encyclopedia of language* (2nd ed.). New York, NY: Cambridge University Press.

Cutler, A., Dahan, D., & van Donselaar, W. (1997). Prosody in the comprehension of spoken language: A literature review. *Language and Speech*, *40*(2), 141–201.

Dehaene-Lambertz, G. (1997). Electrophysiological correlates of categorical phoneme perception in adults. *NeuroReport*, *8*, 919–924. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.147.8605&rep=rep1&type=pdf

Dowhower, S. L. (1991). Speaking of prosody: Fluency's unattended bedfellow. *Theory Into Practice*, *30*(3), 165–175. doi: 10.1177/002383099704000203

Ehri, L. C. (1995). Phases of development in learning to read words by sight. *Journal of Research in Reading*, *18*(2), 116–125. https://doi.org/10.1111/j.1467-9817.1995.tb00077.x

Ehri, L.C. (1998). Grapheme-phoneme knowledge is essential for learning to read words in English. In J. L. Metsala & L. C. Ehri (Eds.). *Word recognition in beginning literacy*, (pp. 3-40). Mahwah, NJ: Erlbaum

Elleman, A. M. (2017). Examining the impact of inference instruction on the literal and inferential comprehension of skilled and less skilled readers: A meta-analytic review. *Journal of Educational Psychology*, *109*(6), 761-781. https://doi.org/10.1037/edu0000180

Estebas-Vilaplana, E. (2014). The evaluation of intonation: Pitch range differences in English and in Spanish. In G. Thompson & L. Alba-Juez (Eds.), *Pragmatics & Beyond New Series* (pp. 179–194). http://doi.org/10.1075/pbns.242.09est

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. http://doi.org/10.3758/BF03193146

Fotidzis, T. S., Moon, H., Steele, J. R., & Magne, C. L. (2018). Cross-Modal Priming Effect of Rhythm on Visual Word Recognition and Its Relationships to Music Aptitude and Reading Achievement. *Brain Sciences, 8*(12), 210. https://doi.org/10.3390/brainsci8120210

Fowler, A. E. (1991). *How early phonological development might set the stage for phoneme awareness*. *Haskins Laboratories Status Report on Speech Research, SR-105|106*. Retrieved from https://pdfs.semanticscholar.org/02fe/e364e13ca6b271e4d9fb9f89adca2530150f.pdf

Frith, U. (1985). Beneath the surface of developmental dyslexia. In K. E. Patterson, J. C. Marshall, & M. Coltheart (Eds.), *Surface Dyslexia: Neuropsychological and Cognitive Studies of Phonological Reading* (pp. 301–330). Hillsdale, NJ: Erlbaum.

Fugate, J. M. B. (2013). Categorical perception for emotional faces. *Emotion Review*, *5*(1): 84–89. doi: 10.1177/1754073912451350.

Garrido, M. I., Kilner, J. M., Stephan, K. E., & Friston, K. J. (2009). The mismatch negativity: A review of underlying mechanisms. *Clinical Neurophysiology*. https://doi.org/10.1016/j.clinph.2008.11.029

Geiser, E., Kjelgaard, M., Christodoulou, J. A., Cyr, A., & Gabrieli, J. D. E. (2014). Auditory temporal structure processing in dyslexia: processing of prosodic phrase boundaries is not impaired in children with dyslexia. *Annals of Dyslexia*, *64*(1), 77–90. http://doi.org/10.1007/s11881-013-0087-7

Godfrey, J. J., Syrdal-Lasky, A. K., Millay, K. K., & Knox, C. M. (1981). Performance of dyslexic children on speech perception tests. *Journal of Experimental Child Psychology*, *32*, 401–424. Retrieved from https://pdfs.semanticscholar.org/8815/07804ab954e34935116469b41e3e129a4505.pdf

Gómez-Herrero, G., De Clercq, W., Anwar, H., Kara, O., Egiazarian, K., Van Huffel, S., & Van Paesschen, W. (2006). Automatic removal of ocular artifacts in the EEG without an EOG reference channel. In *Proceedings of the 7th Nordic Signal Processing Symposium* 2006. Rejkjavik, Iceland, 130-133.

Goswami, U., Fosker, T., Huss, M., Mead, N., & Szűcs, D. (2011). Rise time and formant transition duration in the discrimination of speech sounds: The Ba-Wa distinction in developmental dyslexia. *Developmental Science*, *14*(1), 34–43. http://doi.org/10.1111/j.1467-7687.2010.00955.x

Goswami, U., Thomson, J., Richardson, U., Stainthorp, R., Hughes, D., Rosen, S., & Scott, S. K. (2002). Amplitude envelope onsets and developmental dyslexia: A new hypothesis. *Proceedings of the National Academy of Sciences of the United States of America*, *99*(16), 10911–10916. doi: 10.1073/pnas.122368599

Halliday, L. F., Barry, J. G., Hardiman, M. J., & Bishop, D. V. (2014). Late, not early mismatch responses to changes in frequency are reduced or deviant in children with dyslexia: an event-related potential study. *Journal of neurodevelopmental disorders*, *6*(1), 21.

Hämäläinen, J., Landi, N., Loberg, O., Lohvansuu, K., Pugh, K., & Leppänen, P. H. T. (2018). Brain event-related potentials to phoneme contrasts and their correlation to reading skills in school-age children. *International Journal of Behavioral Development*, *42*(3), 357–372. http://doi.org/10.1177/0165025417728582

Heggie, L., & Wade-Woolley, L. (2018). Prosodic awareness and punctuation ability in adult readers. *Reading Psychology*, *39*(2), 188–215. http://doi.org/10.1080/02702711.2017.1413021

Holliman, A. J., Wood, C., & Sheehy, K. (2012). A cross-sectional study of prosodic sensitivity and reading difficulties. *Journal of Research in Reading*, *35*(1), 32–48. http://doi.org/10.1111/j.1467-9817.2010.01459.x

Holliman, A. J., Williams, G. J., Mundy, I. R., Wood, C., Hart, L., & Waldron, S. (2014). Beginning to disentangle the prosody-literacy relationship: A multi-component measure of prosodic sensitivity. *Reading and Writing*, *27*(2), 255–266. http://doi.org/10.1007/s11145-013-9443-6

Holliman, A. J., Wood, C., & Sheehy, K. (2010). Does speech rhythm sensitivity predict children's reading ability 1 year later? *Journal of Educational Psychology*, *102*(2), 356–366. http://doi.org/10.1037/a0018049

Holliman, A. J., Gutiérrez Palma, N., Critten, S., Wood, C., Cunnane, H., & Pillinger, C. (2017). Examining the independent contribution of prosodic sensitivity to word reading and spelling in early readers. *Reading and Writing*, *30*(3), 509–521. http://doi.org/10.1007/s11145-016-9687-z

Holt, L. L., & Lotto, A. J. (2010). Speech perception as categorization. *Attention, Perception, & Psychophysics, 72*(5), 1218–1227, doi: 10.3758/APP.72.5.1218.

Hommet, C., Vidal, J., Roux, S., Blanc, R., Barthez, M. A., De Becque, B., … & Gomot, M. (2009). Topography of syllable change-detection electrophysiological indices in children and adults with reading disabilities. *Neuropsychologia*, *47*(3), 761–770. https://doi.org/10.1016/j.neuropsychologia.2008.12.010

Hoonhorst, I., Medina, V., Colin, C., Markessis, E., Radeau, M., Deltenre, P., & Serniclaes, W. (2011). The development of categorical perception: Comparisons between voicing, colors and facial expressions. *Speech Communication*, *53*(3), 417-430.

Hornickel, J., Skoe, E., Nicol, T., Zecker, S., & Kraus, N. (2009). Subcortical differentiation of stop consonants relates to reading and speech-in-noise perception. *Proceedings of the National Academy of Sciences*, *106*(31), 13022–13027. http://doi.org/10.1073/pnas.0901123106

House, J. (2006). Constructing a context with intonation. *Journal of Pragmatics*, *38*(10), 1542–1558. http://doi.org/10.1016/j.pragma.2005.07.005

Huss, M., Verney, J. P., Fosker, T., Mead, N., & Goswami, U. (2011). Music, rhythm, rise time perception and developmental dyslexia: Perception of musical meter predicts reading and phonology. *Cortex*, *47*(6), 674–689. http://doi.org/10.1016/j.cortex.2010.07.010

Huttunen, T., Halonen, A., Kaartinen, J., & Lyytinen, H. (2007). Does mismatch negativity show differences in reading-disabled children compared to normal children and children with attention deficit? *Developmental Neuropsychology*, *31*(3), 453–470. http://doi.org/10.1080/87565640701229656

Jiang, A., Yang, J., & Yang, Y. (2014). MMN responses during implicit processing of changes in emotional prosody: an ERP study using Chinese pseudo-syllables. *Cognitive Neurodynamics*, *8*(6), 499–508. http://doi.org/10.1007/s11571-014-9303-3

Kasai, K., Yamada, H., Kamio, S., Nakagome, K., Iwanami, A., Fukuda, M., ... & Kato, N. (2001). Brain lateralization for mismatch response to across-and within-category change of vowels. *Neuroreport*, *12*(11), 2467-2471.

Kaufman, A. S., & Kaufman, N. L. (2004). *Kaufman Brief Intelligence Test* (2nd ed.). Circle Pines, MN: American Guidance Service.

Kawahara, H. (2006). STRAIGHT, exploitation of the other aspect of VOCODER: Perceptually isomorphic decomposition of speech sounds. *Acoustical Science and Technology*, *27*(6), 349–353. http://doi.org/10.1250/ast.27.349

Kendou, P., & O'Brien, E. J. (2014). The knowledge revision components (KReC) framework: Processes and mechanisms. In D. N. Rapp & L. G. Braasch (Eds.). *Processing inaccurate information: Theoretical and applied perspectives from cognitive science and the educational sciences.* Boston, MA: MIT Press.

Kintsch, W. (1988). The role of knowledge in discourse comprehension: A construction-integration model. *Psychological Review, 95*(2), 163-182. doi: 10.1037/0033-295X.95.2.163

Korpilahti, P., Lang, L., & Aaltonen, O. (1995). Is there a late-latency mismatch negativity (MMN) component? *Electroencephalography and Clinical Neurophysiology, 95*, 96.

Kostilainen, K., Wikström, V., Pakarinen, S., Videman, M., Karlsson, L., Keskinen, M., … & Huotilainen, M. (2018). Healthy full-term infants' brain responses to emotionally and linguistically relevant sounds using a multi-feature mismatch negativity (MMN) paradigm. *Neuroscience Letters*, *670*, 110–115. http://doi.org/10.1016/j.neulet.2018.01.039

Kuhn, M. R., & Stahl, S. A. (2003). Fluency: A review of developmental and remedial practices. *Journal of Educational Psychology*, *95*(1), 3–21. http://doi.org/10.1037/0022-0663.95.1.3

Kujala, T., Belitz, S., Tervaniemi, M., & Näätänen, R. (2003). Auditory sensory memory disorder in dyslexic adults as indexed by the mismatch negativity. *European Journal of Neuroscience*, *17*(6), 1323–1327. http://doi.org/10.1046/j.1460-9568.2003.02559.x

Kujala, T., Lovio, R., Lepistö, T., Laasonen, M., & Näätänen, R. (2006). Evaluation of multi-attribute auditory discrimination in dyslexia with the mismatch negativity. *Clinical Neurophysiology, 117*(4), 885-893. https://doi.org/10.1016/j.clinph.2006.01.002

Kujala, T., Myllyviita, K., Tervaniemi, M., Alho, K., Kallio, J., & Näätänen, R. (2000). Basic auditory dysfunction in dyslexia as demonstrated by brain activity measurements. *Psychophysiology, 37*(2), 262-266.

Kung, C. C. (2018). *Speech comprehension in a tone language: The role of lexical tone, context, and intonation in Cantonese Chinese*. Radboud University Nijmegen. Retrieved from https://repository.ubn.ru.nl/bitstream/handle/2066/197039/197039.pdf?sequence=1

LaBerge, D., & Samuels, S. J. (1974). Toward a theory of automatic information processing in reading. *Cognitive Psychology*, *6*(2), 293–323. doi: 10.1016/0010-0285(74)90015-2

Leach, J. M., Scarborough, H. S., & Rescorla, L. (2003). Late-emerging reading disabilities. *Journal of Educational Psychology*, *95*(2), 211–224. http://doi.org/10.1037/0022-0663.95.2.211

Lense, M. D., Gordon, R. L., Key, A. P. F., & Dykens, E. M. (2014). Neural correlates of cross-modal affective priming by music in Williams syndrome. *Social Cognitive and Affective Neuroscience*, *9*(4), 529–37. http://doi.org/10.1093/scan/nst017

Li, M. Y. C., Braze, D., Kukona, A., Johns, C. L., Tabor, W., Van Dyke, J. A., … & Magnuson, J. S. (2019). Individual differences in subphonemic sensitivity and phonological skills. *Journal of Memory and Language*, *107*, 195–215. https://doi.org/10.1016/j.jml.2019.03.008

Liberman, A. M., Harris, K. S., Hoffman, H. S., & Griffin, B. C. (1957). The discrimination of speech sounds within and across phoneme boundaries. *Journal of Experimental Psychology. 54*, 358–368. doi: 10.1037/h0044417

Lisker, L., & Abramson, A. S. (1964). A cross-language study of voicing in initial stops: Acoustical measurements. *WORD*, *20*(3), 384–422. http://doi.org/10.1080/00437956.1964.11659830

Liu, L., Ong, J. H., Tuninetti, A., & Escudero, P. (2018). One way or another: Evidence for perceptual asymmetry in pre-attentive learning of non-native contrasts. *Frontiers in Psychology*, *9*, 162. http://doi.org/10.3389/fpsyg.2018.00162

Lonigan, C. J., Burgess, S. R., & Anthony, J. L. (2000). Development of emergent literacy and early reading skills in preschool children: Evidence from a latent-variable longitudinal study. *Developmental Psychology*, *36*(5), 596–613. http://doi.org/10.1037//OOI2-1649.36.5.596

Lotto, A. J., & Holt, L. L. (2015). *The Frame Problem in Speech Communication: Defining the Dimensional Space for Phonetic Categorization* (NIH- R01 DC004674-09 to AJL and LLH). New York, NY: Equinox. Retrieved from https://www.cmu.edu/dietrich/psychology/holtlab/PDF/lori.%20MY%20Papers/LottoHolt_FrameProblem_HarveySussmanBook.pdf

Maassen, B., Groenen, P., Crul, T., Assman-Hulsmans, C., & Gabreels, F. (2001). Identification and discrimination of voicing and place-of-articulation in developmental dyslexia. *Clinical Linguistics & Phonetics, 15*, 319–339.

Magne C., & Brock, M. (2012). Reading acquisition and phonological awareness: Beyond the segmental level. *American Journal of Neuroscience*, *3*(1), 10–16. Retrieved from http://thescipub.com/abstract/10.3844/amjnsp.2012.10.16

Magne, C., Jordan, D. K., & Gordon, R. L. (2016). Speech rhythm sensitivity and musical aptitude: ERPs and individual differences. *Brain and Language*, *153–154*, 13–19. http://doi.org/10.1016/j.bandl.2016.01.001

Maiste, A. C., Wiens, A. S., Hunt, M. J., Scherg, M., & Picton, T. W. (1995). Event-related potentials and the categorical perception of speech sounds. *Ear and Hearing*, *16*(1), 68–89.

Manis, F. R., McBride-Chang, C., Seidenberg, M. S., Keating, P., Doi, L.M., Munson, B., & Peterson, A. (1997). Are speech perception deficits associated with developmental dyslexia? *Journal of Experimental Child Psychology, 66*, 211–235.

Männel, C., Schaadt, G., Illner, F. K., van der Meer, E., & Friederici, A. D. (2017). Phonological abilities in literacy-impaired children: Brain potentials reveal deficient phoneme discrimination, but intact prosodic processing. *Developmental Cognitive Neuroscience*, *23*, 14–25. http://doi.org/10.1016/J.DCN.2016.11.007

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177–190. http://doi.org/10.1016/j.jneumeth.2007.03.024

Masterson, J., Hazan,V. & Wijayatilake, L. (1995). Phonemic processing problems in developmental dyslexia. *Cognitive Neuropsychology, 12*, 233-259.

McBride-Chang, C. (1995). Phonological processing, speech perception, and reading disability: An integrative review. *Educational Psychologist*, *30*(3), 109–122.

McNamara, D. S., DeVega, M., & O'Reilly, T. (2007). Comprehension skill, inference making, and the role of knowledge. In Perfetti, C. A., & Schmalhofer, F. (Eds). *Higher level language processes in the brain: Inference and comprehension processes*. Mahwah, NJ: Lawrence Erlbaum Associates.

Melby-Lervåg, M., Lyster, S.-A. H., & Hulme, C. (2012). Phonological skills and their role in learning to read: A meta-analytic review. *Psychological Bulletin*, *138*(2), 322–352. http://doi.org/10.1037/a0026744

Mellard, D. F., Fall, E., & Woods, K. L. (2010). A path analysis of reading comprehension for adults with low literacy. *Journal of Learning Disabilities*, *43*(2), 154–165. http://doi.org/10.1177/0022219409359345

Messaoud-Galusi, S., Hazan, V., & Rosen, S. (2011). Investigating speech perception in children with dyslexia: Is there evidence of a consistent deficit in individuals? *Journal of Speech, Language, and Hearing Research, 54*(6), 1682–1701.

Milledge, S. V., & Blythe, H. I. (2019). The changing role of phonology in reading development. *Vision*, *3*(2), 23. https://doi.org/10.3390/vision3020023

Miller, J., & Schwanenflugel, P. J. (2006). Prosody of syntactically complex sentences in the oral reading of young children. *Journal of Educational Psychology*, *98*(4), 839–853. http://doi.org/10.1037/0022-0663.98.4.839

Miller, J., & Schwanenflugel, P. J. (2008). A longitudinal study of the development of reading prosody as a dimension of oral reading fluency in early elementary school children. *Reading Research Quarterly*, *43*(4), 336–354. http://doi.org/10.1598/RRQ.43.4.2

Moats, L. C. (2000). *Speech to print: Language essentials for teachers*. Baltimore, MD: Paul H. Brookes Publishing Co.

Mody, M., Studdert-Kennedy, M., & Brady, S. (1997). Speech perception deficits in poor readers: Auditory processing or phonological coding? *Journal of Experimental Child Psychology, 64*, 199-231.

Müller, B. W., Achenbach, C., Oades, R. D., Bender, S., & Schall, U. (2002). Modulation of mismatch negativity by stimulus deviance and modality of attention. *NeuroReport*, *13*(10), 1317–1320. https://doi.org/10.1097/00001756-200207190-00021

Mundy, I. R., & Carroll, J. M. (2012). Speech prosody and developmental dyslexia: Reduced phonological awareness in the context of intact phonological representations. *Journal of Cognitive Psychology*, *24*(5), 560–581. http://doi.org/10.1080/20445911.2012.662341

Mundy, I. R., & Carroll, J. M. (2016). Which prosodic skills are related to reading ability in adulthood? In J. M. Thomson & L. Jarmulowicz (Eds.), *Linguistic rhythm and literacy* (Vol. 17, pp. 51–76). Amsterdam: John Benjamins Publishing Company. http://doi.org/10.1075/tilar.17.03mun

Myers, E. B., Blumstein, S. E., Walsh, E, Eliassen, J., Batton, D., & Kirk, J. S. (2009). Inferior frontal regions underlie the perception of phonetic category invariance. *Psychological Science, 20*(7), 895–903. doi: 10.1111/j.1467-9280.2009.02380.x

Näätänen, R. (1992). *Attention and brain function*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Näätänen, R. (2000). Mismatch negativity (MMN): Perspectives for application. In *International Journal of Psychophysiology*, *37*, 3–10. https://doi.org/10.1016/S0167-8760(00)00091-X

Näätänen, R., Lehtokoski, A., Lennes, M., Cheour, M., Huotilainen, M., Iivonen, A., … & Alho, K. (1997). Language-specific phoneme representations revealed by electric and magnetic brain responses. *Nature*, *385*, 432–434. Retrieved from http://audition.ens.fr/P2web/Maria/Naatanen97.pdf

Näätänen, R. (2001). The perception of speech sounds by the human brain as reflected by the mismatch negativity (MMN) and its magnetic equivalent (MMNm). *Psychophysiology*, *38*(1), 1-21. http://doi.org/10.1017/S0048577201000208

National Center for Education Statistics. (2007). The Condition of Education 2007 (NCES 2007064). Washington, DC: U.S. Government Printing Office.

National Center for Education Statistics. (2018). 2017 NAEP Mathematics and Reading Assessments: Highlighted Results at Grades 4 and 8 for the Nation, States, and Districts (NCES 2018037). Washington, D.C.: National Center for Education Statistics, Institute of Education Sciences, U.S. Department of Education.

Nittrouer, S. (1999). Do temporal processing deficits cause phonological processing problems? *Journal of Speech Language and Hearing Research, 42*(4), 925–942.

Noordenbos, M. W., Segers, E., Serniclaes, W., Mitterer, H., & Verhoeven, L. (2012). Neural evidence of allophonic perception in children at risk for dyslexia. *Neuropsychologia*, *50*(8), 2010-2017. https://doi.org/10.1016/j.neuropsychologia.2012.04.026

Noordenbos, M. W., Segers, E., Serniclaes, W., & Verhoeven, L. (2013). Neural evidence of the allophonic mode of speech perception in adults with dyslexia. *Clinical Neurophysiology*, *124*(6), 1151–1162. http://doi.org/10.1016/J.CLINPH.2012.12.044

O'Brien, G., Kubota, E., & Yeatman, J. D. (2018). The relationship between reading ability and categorical perception of spectrotemporal and spectral contrasts in children. *The Journal of the Acoustical Society of America*, *143*(3), 1819–1819. http://doi.org/10.1121/1.5035970

O'Brien, G. E., McCloy, D. R., Kubota, E. C., & Yeatman, J. D. (2018). Reading ability and phoneme categorization. *Scientific Reports*, *8*(1), 16842. https://doi.org/10.1038/s41598-018-34823-8

O'Donnell, B.F., & Cohen, R.A. (1988). The N2-P3 complex of the evoked potential and human performance. In R. L. Harris, A. T. Pope, & J. R. Comstock (Eds.), *Proceedings from the First NASA Mental-State Estimation Workshop* (pp. 269 – 289). Langley, VA: NASA.

Oslund, E. L., Clemens, N. H., Simmons, D. C., Smith, S. L., & Simmons, L. E. (2016). How vocabulary knowledge of middle-school students from low socioeconomic backgrounds influences comprehension processes and outcomes. *Learning and Individual Differences*, *45*, 159-165. doi: 10.1016/j.lindif.2015.11.013

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J.-M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*, *2011*, 1–9. http://doi.org/10.1155/2011/156869

Perfetti, C. A. (2007). Reading ability: Lexical quality to comprehension. *Scientific Studies of Reading*, *11*(4), 357–383. doi: 10.1080/10888430701530730

Perfetti, C. A., & Adlof, S. M. (2012). Reading comprehension: A conceptual framework from word meaning to text meaning. In J. P. Sabatini, E. Albro & T. O'Reilly (Eds.), *Measuring up: Advances in how we assess reading ability* (pp. 3-20). Plymouth, U.K.: Rowman & Littlefield Education

Perfetti, C. A., & Hart, L. (2002). The lexical quality hypothesis. In L. Verhoeven, C. Elbro, & P. Reitsma, (Eds.), *Precursors of functional literacy* (pp. 67-86). Amsterdam, Netherlands: John Benjamins Publishing Company.

Perfetti, C., & Stafura, J. (2014). Word knowledge in a theory of reading comprehension. *Scientific Studies of Reading*, *18*(1), 22-37. doi: 10.1080/10888438.2013.827687

Phillips, C., Pellathy, T., Marantz, A., Yellin, E., Wexler, K., Poeppel, D., … & Roberts, T. (2000). Auditory cortex accesses phonological categories: An MEG mismatch study. *Journal of Cognitive Neuroscience*, *12*(6), 1038–1055. http://doi.org/10.1162/08989290051137567

Ramsøy, T., Balslev, D., & Paulson, O. (2010). Methods for observing the living brain. In B. J. Baars & N. M. Gage (Eds.), *Cognition, brain, and consciousness: Introduction to cognitive neuroscience* (Second Ed, pp. 560–562). Bulington, MA: Academic Press.

Rapp, D. N., van den Broek, P., McMaster, K. L., Kendeou, P., & Espin, C. A. (2007). Higher-order comprehension processes in struggling readers: A perspective for research and intervention. *Scientific Studies of Reading*, *11*(4), 289–312. http://doi.org/10.1080/10888430701530417

Reed, M. A. (1989). Speech perception and the discrimination of brief auditory cues in dyslexic children. *Journal of Experimental Child Psychology, 48*, 270-292.

Rodero, E. (2011). Intonation and emotion: Influence of pitch levels and contour type on creating emotions. *Journal of Voice*, *25*(1), e25–e34. http://doi.org/10.1016/J.JVOICE.2010.02.002

Sammler, D., Grosbras, M.-H., Anwander, A., Bestelmeyer, P. E. G., & Belin, P. (2015). Dorsal and Ventral Pathways for Prosody. *Current Biology*, *25*(23), 3079–3085. http://doi.org/10.1016/j.cub.2015.10.009

Sams, M., Paavilainen, P., Alho, K., & Näätänen, R. (1985). Auditory frequency discrimination and event-related potentials. *Electroencephalography and Clinical Neurophysiology / Evoked Potentials Section*, *62*(6), 437–448. https://doi.org/10.1016/0168-5597(85)90054-1

Scherer, K., Johnstone, T., & Klasmeyer, G. (2003). Vocal expression of emotion, in R. Davidson, K. Scherer & H. Goldsminth (Eds), *Handbook of affective sciences* (pp. 433–56). New York: Oxford University Press.

Shulte-Körne, G., Bartling, J., Deimel, W., & Remschmidt, H. (1999). Attenuated hemispheric lateralization in dyslexia: Evidence of a visual processing deficit. *NeuroReport, 10*(17), 3697–3701.

Schulte-Körne, G., Deimel, W., Bartling, J., & Remschmidt, H. (1998). Auditory processing and dyslexia. *NeuroReport*, *9*(2), 337–340. http://doi.org/10.1097/00001756-199801260-00029

Schulte-Körne, G. U., Deimel, W., Bartling, J., & Remschmidt, H. (2001). Speech perception deficit in dyslexic adults as measured by mismatch negativity (MMN). *International Journal of Psychophysiology*, *40*, 77–87. https://doi.org/10.1016/S0167-8760(00)00152-5

Schwanenflugel, P. J., Hamilton, A. M., Kuhn, M. R., Wisenbaker, J. M., & Stahl, S. A. (2004). Becoming a fluent reader: Reading skill and prosodic features in the oral reading of young readers. *Journal of Educational Psychology*, *96*(1), 119–129. http://doi.org/10.1037/0022-0663.96.1.119

Serniclaes, W. (2006). Allophonic perception in developmental dyslexia: Origin, reliability and implications of the categorical perception deficit. *Written Language & Literacy, 9*(1), 135–152. https://doi.org/10.1075/wll.9.1.09ser

Serniclaes, W., & Seck, M. (2018). Enhanced sensitivity to subphonemic segments in dyslexia: A new instance of allophonic perception. *Brain Sciences*, *8*(4), 54. http://doi.org/10.3390/brainsci8040054

Serniclaes, W., Sprenger-Charolles, L., Carré, R., & Démonet, J. F. (2001). Perceptual discrimination of speech sounds in dyslexics. *Journal of Speech Language and Hearing Research, 44,* 384- 399.

Serniclaes, W., Van Heghe, S., Mousty, P., Carré, R., & Sprenger-Charolles, L. (2004). Allophonic mode of speech perception in dyslexia. *Journal of Experimental Child Psychology*, *87*(4), 336–361. http://doi.org/10.1016/j.jecp.2004.02.001

Sharma, A., & Dorman, M. F. (1999). Cortical auditory evoked potential correlates of categorical perception of voice-onset time. *Journal of the Acoustical Society of America, 106*, 1078–1083. https://doi.org/10.1121/1.428048

Snowling, M. J. (2000). Language and literacy skills: Who is at risk and why? In D. V. M. Bishop & L. B. Leonard (Eds.), *Speech and language impairment in children: Causes, characteristics, intervention, and outcome* (pp. 245–260). New York, NY: Psychology Press Ltd.

Snowling, M. J. (2001). From language to reading and dyslexia. *Dyslexia*, *7*(1), 37–46. http://doi.org/10.1002/dys.185

Snowling, M. J., Lervåg, A., Nash, H. M., & Hulme, C. (2018). Longitudinal relationships between speech perception, phonological skills and reading in children at high-risk of dyslexia. *Developmental Science*, e12723. http://doi.org/10.1111/desc.12723

Stanovich, K. E. (1992). Speculations on the causes and consequences of individual differences in early reading acquisition. In P. B. Gough, L. C. Ehri, & R. Treiman (Eds.), *Reading acquisition* (pp. 307-342). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Stanovich, K. E. (1998). Refining the phonological core deficit model. *Child and Adolescent Mental Health*, *3*(1), 17–21. http://doi.org/10.1111/1475-3588.00203

Sussman, E. S., Chen, S., Sussman-Fort, J., & Dinces, E. (2014). The five myths of MMN: Redefining how to use MMN in basic and clinical research. *Brain Topography*, *27*(4), 553–564. http://doi.org/10.1007/s10548-013-0326-6

Szymanski, M. D., Yund, E. W., & Woods, D. L. (1999). Phonemes, intensity and attention: Differential effects on the mismatch negativity (MMN). *The Journal of the Acoustical Society of America*, *106*(6), 3492–3505. http://doi.org/10.1121/1.428202

’t Hart, J. (1981). Differential sensitivity to pitch distance, particularly in speech. *The Journal of the Acoustical Society of America*, *69*(3), 811–821. http://doi.org/10.1121/1.385592

Tiitinen, H., May., P., Reinikainen, K., & Näätänen, R. (1994). Attentive novelty detection in humans governed by pre-attentive sensory memory. *Nature, 3*, 90-92.

Tong, S. X., Tsui, R. K.-Y., & Fung, A. K.-K. (2018). Prosodic reading and reading comprehension in Chinese and English among Hong Kong Cantonese-English bilingual children: A longitudinal study. In *9th International Conference on Speech Prosody 2018* (pp. 858–862). Poznań, Poland: ISCA. http://doi.org/10.21437/SpeechProsody.2018-173

Vellutino, F. (1977). Alternative conceptualizations of dyslexia: Evidence in support of a verbal-deficit hypothesis. *Harvard Educational Review*, *47*(3), 334–354. http://doi.org/10.17763/haer.47.3.u117j10167686115

Vellutino, F. R., & Fletcher, J. M. (2008). Developmental dyslexia. In M. J. Snowling & C. Hulme (Eds.), *The science of reading: A handbook* (pp. 362–378). Oxford, UK: Blackwell Publishing Ltd. http://doi.org/10.1002/9780470757642.ch19

Volkmer, S., & Schulte-Körne, G. (2018). Cortical responses to tone and phoneme mismatch as a predictor of dyslexia? A systematic review. *Schizophrenia Research*, *191*, 148–160. http://doi.org/10.1016/J.SCHRES.2017.07.010

Wade-Woolley, L., & Heggie, L. (2016). The contributions of prosodic and phonological awareness to reading. In J. Thomson & L. Jarmulowicz (Eds.), *Linguistic rhythm and literacy* (Vol. 17, pp. 3–24). Amsterdam: John Benjamins Publishing Company. http://doi.org/10.1075/tilar.17.01wad

Wade-Woolley, L., & Wood, C. (2006). Editorial: Prosodic sensitivity and reading development. *Journal of Research in Reading*, *29*(3), 253–257. http://doi.org/10.1111/j.1467-9817.2006.00306.x

Wagner, R. K., Torgesen, J. K., Bradley, L., Bryant, P., Crowder, B., Mann, V., … & Wagner, A. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin*, *101*(2), 192–212. Retrieved from http://www.literacyconnects.org/img/2013/03/Phonological-Processing-WagnerTorgesen.pdf

Werker, J. F., & Tees, R.C. (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development, 7,* 49-63.

Whalley, K., & Hansen, J. (2006). The role of prosodic sensitivity in children's reading development. *Journal of Research in Reading*, *29*(3), 288–303. http://doi.org/10.1111/j.1467-9817.2006.00309.x

Wilson, D. (2013). Irony comprehension: A developmental perspective. *Journal of Pragmatics*, *59*, 40–56. http://doi.org/10.1016/J.PRAGMA.2012.09.016

Winkler, I., & Näätänen, R. (1992) Event-related potentials in auditory backward recognition masking: A new way to study the neurophysiological basis of sensory memory in humans. *Neuroscience Letters, 140*, 239-242.

Xiao, X.-Z., Wong, H. K., Wang, Y., Zhao, K., Zeng, G. Q., Yip, L.-Y., … & Tse, C.-Y. (2018). Detecting violation in abstract pitch patterns with mismatch negativity. *Psychophysiology, 55*(8), e13078. http://doi.org/10.1111/psyp.13078

Zaric, G., González, G. F., Tijms, J., van der Molen, M. W., Blomert, L., & Bonte, M. (2014). Reduced neural integration of letters and speech sounds in dyslexic children scales with individual differences in reading fluency. *PLoS ONE*, *9*(10), e110337. https://doi.org/10.1371/journal.pone.0110337

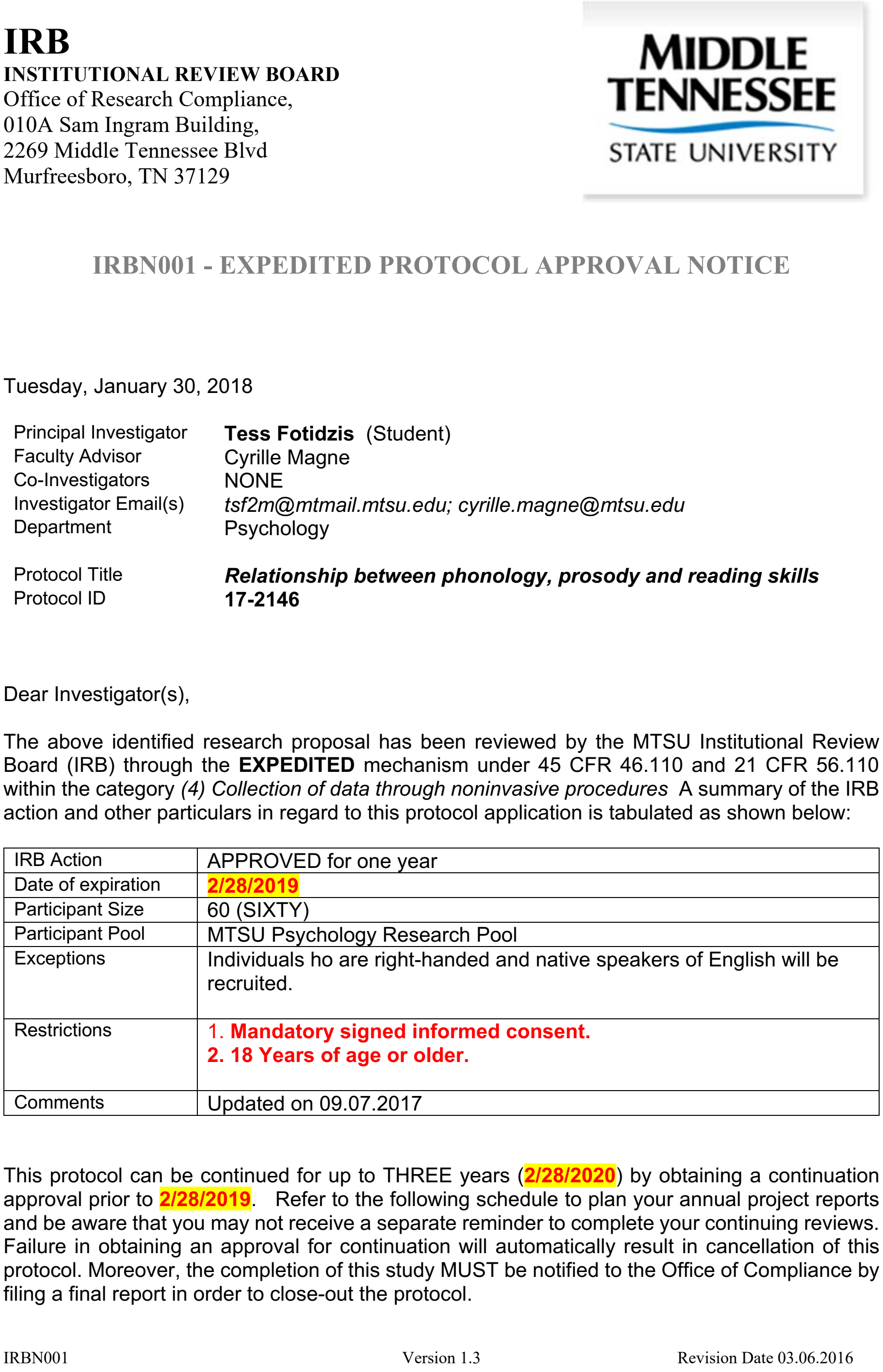
Zhang, J., Meng, Y., Tong, X., Yuan, Z., Wu, C., & Ieong, S. L. (2018). Exploring the neural correlates of lexical stress perception in English among Chinese-English bilingual children with autism spectrum disorder: An ERP study. *Neuroscience Letters*, *666*, 158–164. http://doi.org/10.1016/J.NEULET.2017.12.031

Zhang, Y., Zhang, L., Shu, H., Xi, J., Wu, H., Zhang, Y., & Li, P. (2012). Universality of categorical perception deficit in developmental dyslexia: An investigation of Mandarin Chinese tones. *Journal of Child Psychology & Psychiatry, 53*(8), 874-82. https://doi.org/10.1111/j1469-7610.2012.02528.x

Zuijen, T. L., Plakas, A., Maassen, B. A. M., Maurits, N. M., & Leij, A. (2013). Infant ERPs separate children at risk of dyslexia who become good readers from those who become poor readers. *Developmental Science, 16*(4), 554-63. https://doi.org/10.1111/desc.12049

APPENDICES

APPENDIX A: IRB APPROVAL LETTER



IRB
INSTITUTIONAL REVIEW BOARD
Office of Research Compliance,
010A Sam Ingram Building,
2269 Middle Tennessee Blvd
Murfreesboro, TN 37129

MIDDLE TENNESSEE STATE UNIVERSITY

IRBN001 - EXPEDITED PROTOCOL APPROVAL NOTICE

Tuesday, January 30, 2018

Principal Investigator	**Tess Fotidzis** (Student)
Faculty Advisor	Cyrille Magne
Co-Investigators	NONE
Investigator Email(s)	*tsf2m@mtmail.mtsu.edu; cyrille.magne@mtsu.edu*
Department	Psychology
Protocol Title	***Relationship between phonology, prosody and reading skills***
Protocol ID	**17-2146**

Dear Investigator(s),

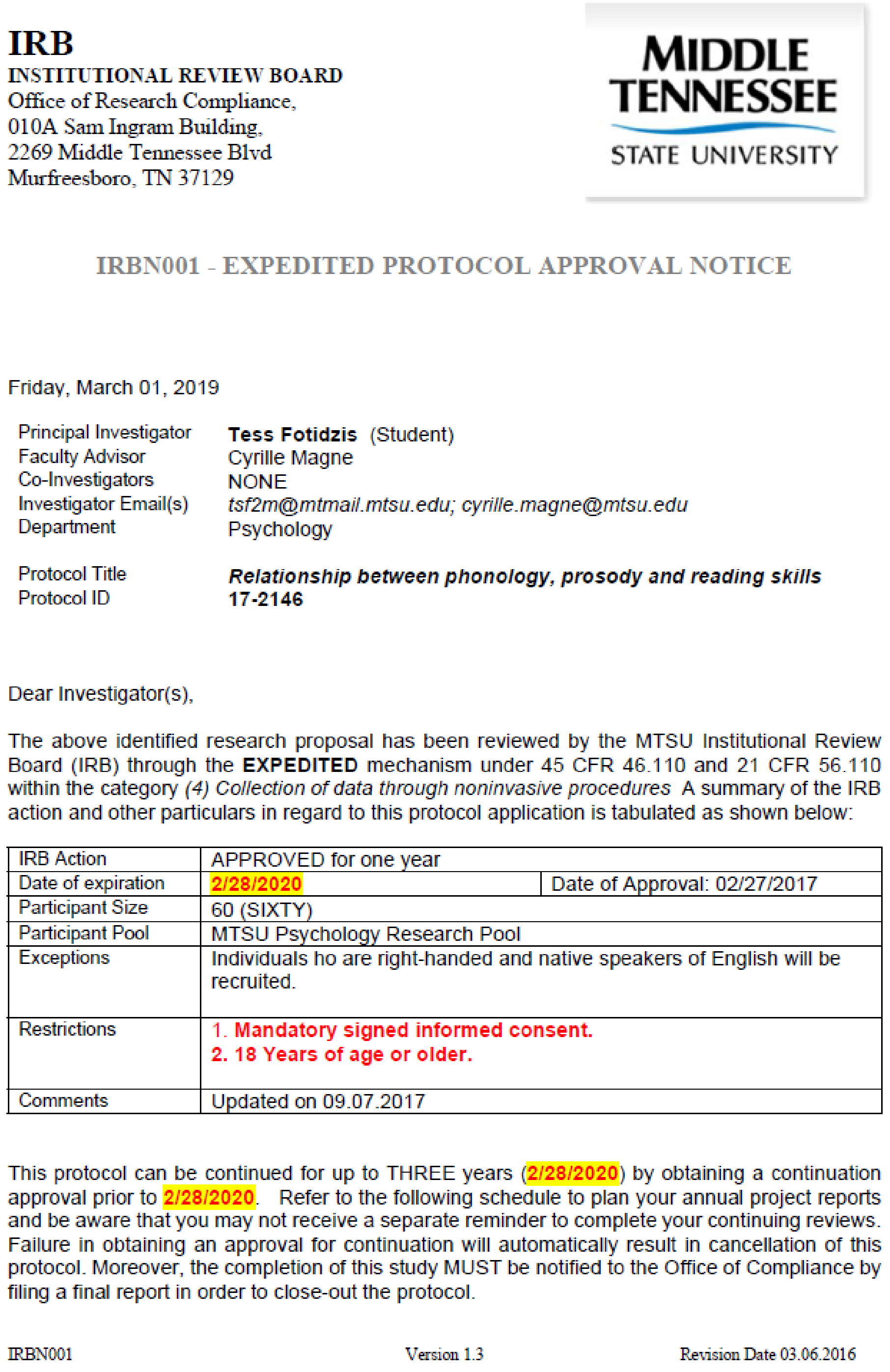
The above identified research proposal has been reviewed by the MTSU Institutional Review Board (IRB) through the **EXPEDITED** mechanism under 45 CFR 46.110 and 21 CFR 56.110 within the category *(4) Collection of data through noninvasive procedures* A summary of the IRB action and other particulars in regard to this protocol application is tabulated as shown below:

IRB Action	APPROVED for one year
Date of expiration	**2/28/2019**
Participant Size	60 (SIXTY)
Participant Pool	MTSU Psychology Research Pool
Exceptions	Individuals ho are right-handed and native speakers of English will be recruited.
Restrictions	1. **Mandatory signed informed consent.** **2. 18 Years of age or older.**
Comments	Updated on 09.07.2017

This protocol can be continued for up to THREE years (**2/28/2020**) by obtaining a continuation approval prior to **2/28/2019**. Refer to the following schedule to plan your annual project reports and be aware that you may not receive a separate reminder to complete your continuing reviews. Failure in obtaining an approval for continuation will automatically result in cancellation of this protocol. Moreover, the completion of this study MUST be notified to the Office of Compliance by filing a final report in order to close-out the protocol.

IRBN001 Version 1.3 Revision Date 03.06.2016

APPENDIX B: AMENDMENT APPROVAL LETTER



IRB
INSTITUTIONAL REVIEW BOARD
Office of Research Compliance,
010A Sam Ingram Building,
2269 Middle Tennessee Blvd
Murfreesboro, TN 37129

MIDDLE TENNESSEE
STATE UNIVERSITY

IRBN001 - EXPEDITED PROTOCOL APPROVAL NOTICE

Friday, March 01, 2019

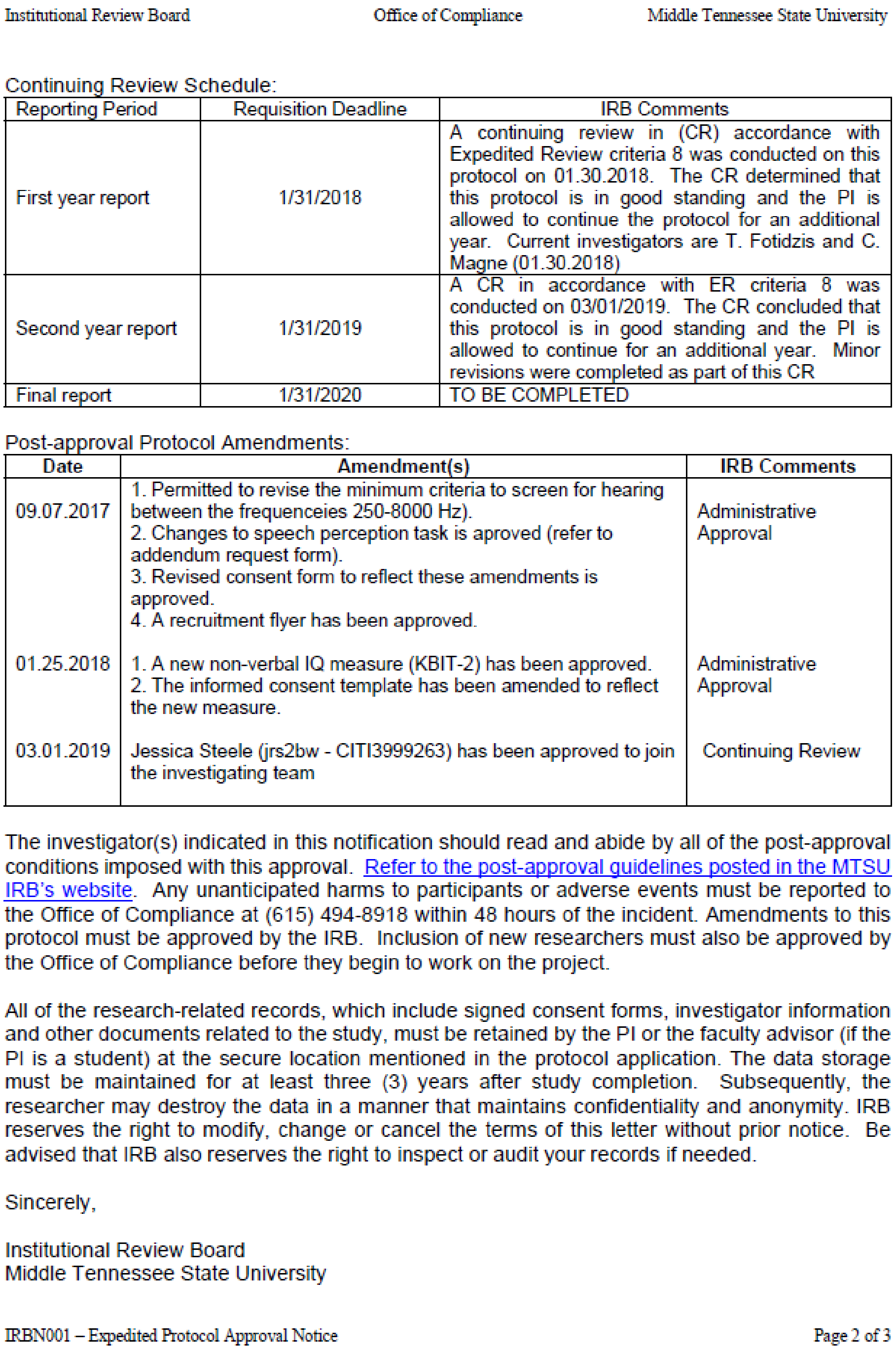
Principal Investigator	**Tess Fotidzis** (Student)
Faculty Advisor	Cyrille Magne
Co-Investigators	NONE
Investigator Email(s)	*tsf2m@mtmail.mtsu.edu; cyrille.magne@mtsu.edu*
Department	Psychology
Protocol Title	***Relationship between phonology, prosody and reading skills***
Protocol ID	**17-2146**

Dear Investigator(s),

The above identified research proposal has been reviewed by the MTSU Institutional Review Board (IRB) through the **EXPEDITED** mechanism under 45 CFR 46.110 and 21 CFR 56.110 within the category *(4) Collection of data through noninvasive procedures* A summary of the IRB action and other particulars in regard to this protocol application is tabulated as shown below:

IRB Action	APPROVED for one year	
Date of expiration	2/28/2020	Date of Approval: 02/27/2017
Participant Size	60 (SIXTY)	
Participant Pool	MTSU Psychology Research Pool	
Exceptions	Individuals ho are right-handed and native speakers of English will be recruited.	
Restrictions	1. **Mandatory signed informed consent.** **2. 18 Years of age or older.**	
Comments	Updated on 09.07.2017	

This protocol can be continued for up to THREE years (2/28/2020) by obtaining a continuation approval prior to 2/28/2020. Refer to the following schedule to plan your annual project reports and be aware that you may not receive a separate reminder to complete your continuing reviews. Failure in obtaining an approval for continuation will automatically result in cancellation of this protocol. Moreover, the completion of this study MUST be notified to the Office of Compliance by filing a final report in order to close-out the protocol.



Continuing Review Schedule:

Reporting Period	Requisition Deadline	IRB Comments
First year report	1/31/2018	A continuing review in (CR) accordance with Expedited Review criteria 8 was conducted on this protocol on 01.30.2018. The CR determined that this protocol is in good standing and the PI is allowed to continue the protocol for an additional year. Current investigators are T. Fotidzis and C. Magne (01.30.2018)
Second year report	1/31/2019	A CR in accordance with ER criteria 8 was conducted on 03/01/2019. The CR concluded that this protocol is in good standing and the PI is allowed to continue for an additional year. Minor revisions were completed as part of this CR
Final report	1/31/2020	TO BE COMPLETED

Post-approval Protocol Amendments:

Date	**Amendment(s)**	**IRB Comments**
09.07.2017	1. Permitted to revise the minimum criteria to screen for hearing between the frequenceies 250-8000 Hz). 2. Changes to speech perception task is aproved (refer to addendum request form). 3. Revised consent form to reflect these amendments is approved. 4. A recruitment flyer has been approved.	Administrative Approval
01.25.2018	1. A new non-verbal IQ measure (KBIT-2) has been approved. 2. The informed consent template has been amended to reflect the new measure.	Administrative Approval
03.01.2019	Jessica Steele (jrs2bw - CITI3999263) has been approved to join the investigating team	Continuing Review

The investigator(s) indicated in this notification should read and abide by all of the post-approval conditions imposed with this approval. Refer to the post-approval guidelines posted in the MTSU IRB's website. Any unanticipated harms to participants or adverse events must be reported to the Office of Compliance at (615) 494-8918 within 48 hours of the incident. Amendments to this protocol must be approved by the IRB. Inclusion of new researchers must also be approved by the Office of Compliance before they begin to work on the project.

All of the research-related records, which include signed consent forms, investigator information and other documents related to the study, must be retained by the PI or the faculty advisor (if the PI is a student) at the secure location mentioned in the protocol application. The data storage must be maintained for at least three (3) years after study completion. Subsequently, the researcher may destroy the data in a manner that maintains confidentiality and anonymity. IRB reserves the right to modify, change or cancel the terms of this letter without prior notice. Be advised that IRB also reserves the right to inspect or audit your records if needed.

Sincerely,

Institutional Review Board
Middle Tennessee State University

Institutional Review Board Office of Compliance Middle Tennessee State University

Quick Links:

Click here for a detailed list of the post-approval responsibilities.
More information on expedited procedures can be found here.

IRBN001 – Expedited Protocol Approval Notice Page 3 of 3