THE INFLUENCE OF IMPLICIT SPEECH RHYTHM SENSITIVITY

ON READING COMPREHENSION

by

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This work is dedicated to my parents,

Hyungsik Moon and Younghee Kwon,

who have showed an unconditional love.

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ABSTRACT

The pattern of stressed and unstressed syllables in spoken language provides rhythmic cues that are known to influence speech segmentation and language acquisition. Research using the event-related potential (ERP) method also shows that language comprehension is facilitated when spoken utterances have a highly regular stress pattern. In addition, an increasing body of evidence suggests that sensitivity to speech rhythm is linked to early literacy acquisition and that information regarding word stress patterns may be automatically retrieved during silent reading. The current ERP study was thus aimed at examining whether rhythmic regularity facilitates reading comprehension during silent reading. To this end, written sentences were created, in which the sixth word, the critical word, was either semantically expected or unexpected. The critical word was always bi-syllabic and stressed on the first syllable. In addition, the implicit rhythm generated by the stress pattern leading up to the critical word was either regular or irregular. EEG was recorded from participants while participants performed a semantic judgment task on the written sentences. ACT reading scores were also collected and used as a reading comprehension measure. Results of cluster-based permutation tests showed that Semantically Unexpected words elicited an increased centro-frontal N400 effect in both Rhythmically Irregular and Rhythmically Regular contexts. A direct comparison of the N400 effect elicited in the two rhythmic contexts revealed that it was larger and lasted longer in the Rhythmically Irregular condition than the Rhythmically Regular condition. In addition, sensitivity to implicit speech rhythm (defined as the difference between the N400 effects in the Rhythmically Regular and Rhythmically Irregular conditions) was positively correlated with reading comprehension skills. Overall, the present results support the idea that information about the stress pattern of words is automatically retrieved during silent reading, and that a regular rhythmic context may facilitates lexico-semantic integration by providing a temporal grid allowing for better predictions of upcoming linguistic units. These findings thus provide neurophysiological evidence for the Implicit Prosody Hypothesis proposing that readers build a prosodic representation of the text during silent reading. The present findings also further support the idea that speech rhythm sensitivity plays an important role in the development of reading skills.

Keywords: speech rhythm, Implicit Prosody Hypothesis, reading comprehension, ERP, N400

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CHAPTER ONE

INTRODUCTION

Over the past three decades, the important role of phonological skills (e.g., phonemic awareness, rhyme awareness, and verbal short-term memory) in literacy acquisition has been established (Melby-Lervåg, Lyster, & Hulme, 2012). Not only is phonological awareness a good predictor of reading development in children (Share, 1995), but poor phonological skills have also been consistently found in developmental reading disorders (Lyon, Shaywitz, & Shaywitz, 2003). Based on this accumulated scientific evidence, the National Reading Panel (NRP; NICHD, 2000) has identified phonemic awareness, the ability to recognize and manipulate the smallest units of sounds in speech (i.e., phonemes), as one of the five essential components of reading. Due to the complex nature of phonological representations and processes, a variety of assessments of phonological skills has been developed and used. According to Bentin (1992), these assessments can be specified along three dimensions: (1) operation required (e.g., detection or manipulation of phonological segment), (2) manner of testing awareness of phonological codes (e.g., indirect/direct or implicit/explicit), and (3) size of the relevant phonological segments (e.g., syllabic, sub-syllabic, or phonemic). Regardless of the approach, these assessments have been designed to measure primarily the segmental aspects of phonology. However, phonology also encompasses suprasegmental features, known collectively as prosody, which extends over the combination of multiple phonemes.

Prosody corresponds to the rhythmic and intonational patterns in spoken utterances, and these prosodic features are expressed through a combination of acoustic variations in pitch, durations and intensity. The present study focuses on the rhythmic aspects of prosody, and particularly sensitivity to the pattern of stressed and unstressed syllables, also known as meter (Magne, Jordan, & Gordon, 2016). Prosody plays an important role in spoken language from birth to adulthood. For instance, newborns are sensitive to the rhythmic structure of their native language (Nazzi, Bertoncini, & Mehler, 1998). Because English words more commonly start with a stressed syllable, by the age of 7 months, infants also effectively use a metrical segmentation strategy for word recognition by considering stressed syllables as word onsets (Cutler & Norris, 1988; Small, 1999). Prosodic cues may guide listeners' attention to relevant parts in the speech stream (e.g., Quené & Port, 2005), as well as contribute to lexical retrieval (e.g., Magne, Astésano, Aramaki, Ystad, Kronland-Martinet, & Besson, 2007; Moon & Magne, 2015) and syntactic processing (e.g., Pynte & Prieur, 1996). Prosody also contributes to organizing the information structure of a discourse by signaling new versus old information to the listener (Magne, Astésano, Lacheret-Dujour, Morel, Alter, & Besson, 2005). In addition, prosody helps the listener interpret the emotional state of the speaker (Besson, Magne, & Schön, 2002).

Using brain-imaging technologies, research in psycholinguistics has provided an increasing body of knowledge regarding the neural and cognitive basis of prosody perception since the late 1990s. In particular, the event-related potential (ERP) method has been frequently used in academic settings to study the different functions of prosody because of its affordable cost and reliable performance (Mensen & Khatami, 2013). ERPs are measured using electroencephalography (EEG) and correspond to changes in the brain electrical activity that are time-clocked to sensory, motor or cognitive events. There are two particular advantages using this method over behavioral tasks to study language processes: it provides a real-time and continuous measure of the processing occurring between stimulus onset and the behavioral response, and measure stimulus processing even in absence of behavioral changes. One of the most reliable ERP responses elicited by spoken and written words is the N400 component (Kutas & Hillyard, 1980). It is a negative ERP component that is maximal around 400 ms following a word onset, and it is typically distributed over centro-parietal regions of the scalp (Kutas & Federmeier, 2011). Extensive research conducted since its initial discovery in 1980 suggests that the amplitude of the N400 is an index of access to the semantic memory system (Kutas et al., 2011). Using this method, recent studies have also shed light on the neural basis of speech rhythm perception. These studies focused primarily on the electrophysiological signature of processing words with unexpected stress patterns during spoken language comprehension (e.g., Böcker, Bastiaansen, Vroomen, Brunia, & Gelder, 1999; Friedrich, Kotz, Friederici, & Alter, 2004; Magne et al., 2007; Magne, Jordan, & Gordon, 2016; Marie, Magne, & Besson, 2011; Moon et al., 2015; Rothermich, Schmidt-Kassow, & Kotz, 2012; Rothermich, Schmidt-Kassow, Schwartze, & Kotz, 2010; Schmidt-Kassow & Kotz, 2009). One of the most consistent findings across these studies is an early fronto-central negative effect that occurs somewhere between 200 and 1000 ms following the presentation of a word with an unexpected stress pattern. Since this negative component partially overlaps with the time range of the N400, the interpretation of its functional significance remains challenging. Some authors have proposed that this negative effect is indeed an increased N400 produced because an unexpected stress pattern hinders semantic processing of the word (e.g., Magne et al., 2007). Others interpreted this negative component as reflecting a general rule-based detection mechanism (e.g., Rothermich et al., 2012). However, given the variability of paradigms and languages used across these different studies, these two alternative accounts are not necessarily mutually exclusive (Magne et al., 2016). Several ERP studies have also examined how rhythm cues influence the processing of other linguistic features, such as semantics and syntax. Of particular interest for the present project, some of these studies manipulated the rhythm regularity, and found that a highly predictable regular stress pattern may facilitate semantic integration (Rothermich et al., 2012) and syntactic processing (Roncaglia-Denissen, Schmidt-Kassow & Kotz, 2013) during spoken sentence comprehension. Likewise, patients with basal ganglia lesions showed improved syntactic processing when they are primed with metrically regular musical patterns (Kotz, Gunter, & Wonneberger, 2005).

An increasing body of evidence also highlights the role of prosody sensitivity (i.e., the awareness of the suprasegmental phonological features of a given language) in the acquisition of good reading skills (Magne & Brock, 2012). Overall, research on the role of prosody sensitivity falls in three main categories: (1) analyzing the characteristics of prosody while children reading aloud (i.e., reading prosody), (2) exploring the relationship between prosody sensitivity and early reading acquisition, (3) comparing rhythm perception (both speech and non-speech) in individuals with or without dyslexia. Regarding reading prosody, a series of experiments by Schwanenflugel and collaborators found that second and third graders with good reading skills had more adult-like intonation while reading aloud (Miller & Schwanenflugel, 2006; Schwanenflugel, Hamilton, Wisenbaker, Kuhn, & Stahl, 2004). A follow-up longitudinal study revealed that the acquisition of adult-like speech intonation during first and second grades predicted later reading comprehension in third grade (Miller & Schwanenflugel, 2008). The relationship between prosodic sensitivity and reading acquisition has also been investigated in young readers, using speech rhythm perception tasks in conjunction with standardized measures of reading abilities (Holliman, Wood, & Sheehy, 2008, 2010, 2012; Whalley & Hansen, 2006; Wood, 2006). Overall, the results point to a correlation between the children's performance on the speech rhythm tasks and their reading skills. In addition, speech rhythm sensitivity is also predictive of later reading performance (Holliman et al., 2010). Regarding the third line of research, Goswami and her colleagues (Goswami, Thomson, Richardson, Stainthorp, Hughes, Rosen, & Scott, 2002) developed a temporal discrimination task using non-speech sound sequences made of square waves with varying rise times. Children and adults with dyslexia were found to perform the temporal discrimination task significantly poorer than controls matched either by age or reading level (Goswami, Wang, Cruz, Fosker, Mead, & Huss, 2011; Leong, Hämäläinen, Soltész, & Goswami, 2011; Thomson, Fryer, Maltby, & Goswami, 2006). Goswami (2011) proposed that dyslexia must therefore result from a basic auditory rhythmic processing deficit, which in turn interferes with the acquisition of appropriate phonological representations. In addition, it has been proposed that the cause of this deficit may be related to the difficulty of neural oscillations within the auditory cortex to entrain to the speech amplitude envelope, which carries rhythmic cues (Hämäläinen, Rupp, Soltész, Szücs, & Goswami, 2012). Altogether, the findings from these three different lines of research open up the possibility that poorer sensitivity to prosody, and specifically speech rhythm cues, could be an early indicator of potential reading disorders.

While the aforementioned studies have primarily focused on prosody sensitivity in spoken language, recent theoretical accounts argue that prosodic sensitivity plays a role during silent reading as well. For instance, the Implicit Prosody Hypothesis proposes that readers generate an internal representation of the prosody of the text while silently reading, as if a voice reading aloud existed in the readers' head (Fodor, 1998, 2002). In line with this hypothesis, some evidence has shown that the prosodic contour internally generated by the reader influences syntactic parsing of written sentences (e.g., Bader, 1998; Hirose, 2003; Hwang & Schafer, 2009; Hwang & Steinhauer, 2011). In addition, a series of ERP studies conducted in German (Steinhauer & Friederici, 2001; Steinhauer, 2003) and Chinese (Liu, Wang, & Zhixing, 2010) showed that when implicit intonational phrase boundaries were indicated by commas in the text, they elicited a positivity ERP component similar to the one seen in response to prosodic phrase boundaries in spoken language (Steinhauer, Alter, & Friederici, 1999). Finally, the effect of implicit prosody appears to not be restricted to intonation. Recent findings suggest that information about the stress pattern of a word is also implicitly recalled during silent reading (Ashby, 2006; Ashby & Clifton, 2005; Ashby & Martin, 2008; Magne, Gordon, & Midha, 2010). For instance, Ashby and collaborators (2005) measured eye movements while participants read sentences containing a four-syllable word, and found that four-syllable words with two stressed syllables are associated with more fixations than those with only one stressed syllable. Magne and his collaborators (2010) measured ERPs in participants while they silently read sequences of four written words. For half of the sequences, all the words had the same metrical stress pattern, while for the other half, the stress pattern of the fourth word was the opposite of the previous words in the sequence. Results revealed that fourth words with an opposite stress pattern had an increased negativity similar to the negative effect previously reported for words with unexpected stress pattern in spoken language (e.g., Magne et al., 2007).

Purpose of the Study

The purpose of the current study was two-folds. First, based on the previous evidence suggesting that the metrical stress pattern of a word affects the way it is read (e.g., Ashby, 2006; Ashby et al., 2005, 2008; Magne et al., 2010), and that a regular stress pattern may facilitate spoken language comprehension (e.g., Rothermich et al., 2012; Roncaglia-Denissen et al., 2013), the study seek to determine whether semantic integration was enhanced in written sentences with a regular stress pattern (i.e., predictable rhythmic structure). Second, given the link between speech rhythm sensitivity to reading abilities (e.g., Goswami, 2011; Holliman et al., 2010, 2012), the study examined whether sensitivity to implicit speech meter during silent reading was linked to reading comprehension skills.

Research Questions, Design, and Hypotheses

Two research questions were developed. First, is the N400 component of the ERPs associated with semantic processing (Kutas et al., 2011) modulated by the rhythmic structure of the text being read? Second, can a significant variance in reading comprehension skills be explained by individual brain differences in sensitivity to speech meter? To address these questions, participants were asked to silently read sentences and judge whether they made sense or not. Half of the sentence made sense while the other half will contain a word that was not semantically expected in the sentence context. More importantly, unbeknownst to the participants, half the sentences had a regular rhythmic structure (i.e., alternation of a stressed syllable followed by an unstressed syllable) while the other half had an irregular stress pattern. ERPs were measured in the participants using EEG recorded while they silently read the sentences. In addition, the score on the American College Testing (ACT) subtest, Reading and English, were collected. The ACT Reading test score was used as a measure of the participants' reading comprehension skills and the ACT English test score was used as a measure of general language skills. In line with the previous literature on semantic processing, the N400 component was expected to be larger in response to semantically unexpected words than semantically expected words (Kutas, Van Petten, & Kluender, 2006). More importantly, if a regular stress pattern facilitates semantic integration, as previously found for spoken sentences (e.g., Rothermich et al., 2012), the N400 effect elicited by unexpected words was expected to be smaller when preceded by a rhythmically regular context than a rhythmically irregular context. In addition, if implicit speech rhythm sensitivity was a factor contributing to reading comprehension skills, the participants' ACT reading scores were expected to correlate with individual differences in sensitivity to rhythmic regularity (as indexed by the difference in N400 effect between Rhythmically Regular and Rhythmically Irregular sentences), even when the ACT English scores were used as a control variable.

Significance of the Study

Despite converging evidence from different disciplines, and using different methodologies, that point to a role of prosody sensitivity during silent reading, the neural and cognitive mechanisms of the role of prosody during silent reading remains largely underexplored. A better understanding of the neural basis of the relationship between speech rhythm perceptions and reading processes may thus be of high interest for researchers seeking to explain the factors underlying some of the variability in reading abilities. Recent studies also highlight the potential for using rhythm-based activity for reading intervention (Flaugnacco, Lopez, Terribili, Montico, Zoia, & Schön, 2015).

CHAPTER TWO

LITERATURE REVIEW

In language, the notion of rhythm is closely related to meter, the recurring patterns of stressed and unstressed syllables in spoken language (Cummins & Port, 1998; Magne et al., 2016). Stresses correspond to the emphasis that some syllables received in a word. Stressed syllables are usually longer and louder, and may even have a higher pitch, while vowels of unstressed syllables are often reduced. Some languages are said to have a fixed stress because stresses fall at predictable locations. For instance, French has a fixed stress that usually falls on the last syllable of a word or group of words. By contrast, in languages with a variable stress, such as English or German, the location of the stresses is less predictable. In these languages, the stress is usually referred to as lexical stress because its position needs to be learned for each word. In addition, words that are longer than two syllables may receive two stresses, with one (i.e., primary stress) being stronger than the other (i.e., secondary stress). At the word level, bisyllabic nouns are mostly stressed on the first syllable while bisyllabic verbs are more often stressed on the second syllable (Kelly & Bock, 1988; Sereno & Jongman, 1995).

There is still some disagreement regarding the definition of what speech rhythm actually is, or if it even makes sense to speak about rhythm in speech. One of the main reasons stems from the fact that speech rhythm is often defined similarly to musical rhythm and is thus associated with the notion of isochronicity (i.e., units recurring at approximately equal time intervals). While every language has its own rhythmic properties, linguists have attempted to classify them into three different rhythmic categories depending on which rhythmic units are isochronous (Abercrombie, 1967, Pike, 1945). For instance, French or Italian are considered syllable-timed languages because the duration of each syllable is roughly equal, English and German are stress-timed languages because the time interval between successive stressed syllables is consistent, and Japanese is a mora-timed language because the duration of each mora (phonological unit in Japanese) is equal. Despite the popularity of this dichotomy, researchers in psycholinguistics and phonetics have failed to provide evidence for the existence of strictly isochronous units in languages. Instead, there seems to be considerable overlaps between the different rhythmic groups (Dauer, 1983; Grabe & Low, 2002), and this has led some researchers to suggest a more flexible classification. For instance, Nolan & Asu (2009) suggest that there is an orthogonal dimension between syllable- and stress-time rhythms, and the characteristics of a given language can be either, both, or neither of syllable- and stress-time categories. Miller (1984) understands a given language as a continuum of syllable- and stress-timing, and considers rhythm as a phenomenon of complex speech units, such as fluency, rather than a simple operation. Moreover, Cummins and Port (1998) argues that rhythm is based on a hierarchical organization of temporally organized prosodic elements, which listeners can use to interactively entrain with one another during a conversation (Cummins, 2009). With the lack of evidence for isochrony in speech, these alternative hypotheses have led researchers to develop appropriate assessments to capture more complex, dynamic properties of speech rhythm beyond the traditional assessments based on categorical distinctions.

Rhythm and Speech Perception

The psycholinguistic literature has accumulated a body of evidences on the important role of rhythm sensitivity for language acquisition from infant to adulthood

(Holliman et al,, 2008; Mehler, Jusczyk, Lambertz, Halsted, Bertoncini, & Amiel-Tison, 1988; Moon, Cooper, & Fifer, 1993; Nazzi et al., 1998; Wood, 2006). Nazzi and his collaborators (1998) showed that young infants, including newborns, can discriminate between utterances from their native language and those from a language of a different rhythmic category (e.g., French vs English), but not utterances from a language with a similar rhythmic structure (e.g., English vs German) or not when utterances are played backward. This finding suggests that general auditory processing mechanisms sensitive to rhythmic language cues are already in place at birth. Interestingly, cotton-top tamarins, a small monkey, primarily found in Columbia can also discriminate between Dutch (stress-timed language) and Japanese (mora-timed language), but not when these languages are played backward, suggesting that these rhythm-sensitive mechanisms observed in humans are not specific to language. In fact, infants start developing sensitivity about how the different sounds of their language combine to form words during the second half of their first year (Jusczyk, 1999). During this period, they particularly begin discriminating among speech sounds (i.e., phonemes), and acquiring the repertoire of phonemes part of their native language (Jusczyk, Luce, & Charles-Luce, 1994). In parallel, they also develop a preference for the predominant stress pattern in their language. For instance, Jusczyk and collaborators (1999) found that 7.5-month-old infants are only able to segment words starting with a stressed syllable (i.e., trochaic pattern), which compose 85-90% of words in English (Cutler & Carter, 1987). This finding has been taken as evidence for the metrical segmentation strategy, where language learners consider a stress syllable as the beginning of a word in the continuous speech stream (Cutler et al, 1988). By contrast, sensitivity to words such as “guitar” or “banana”, both starting with an unstressed syllable (i.e., iambic pattern), does not develop until 10. 5 months, likely due to the need for developing additional sets of knowledge, such as allophonic and phonotactic rules as well as articulatory cues (Jusczyk, 1999). In addition, it is worth noting that adults often talk to children, infants in particular, using infant-directed speech (IDS). It can be seen as a form of exaggerated prosody (often referred to as musical speech) and as such also includes exaggerations of the rhythmic patterns of their native language (Trainor, Austin, & Desjargins, 2000).

Rhythm cues continue to play an important role in speech perception and language comprehension in adults. Speech rhythm sensitivity still seems to guide segmentation of the continuous speech stream to isolate words through the use of information about typical stress patterns (e.g., Cutler et al., 1988; Cutler & Butterfield, 1992). The rhythmic pattern given by the alteration of stressed and unstressed syllables may also provide a temporal cue to predict the occurrence of the following stressed syllables (Large & Kolen, 1994). These expectations allow listeners to focus their attention on rhythmically salient moments in time (Large & Jones, 1999; Arantes & Barbosa, 2010). More specifically, listeners may allocate different amount of attention to stressed and unstressed syllables (e.g., Quené & Port, 2005). As a result, this may facilitate the parsing of the speech stream (Cutler & Mehler, 1993), and potentially of a second language (Morgan, 1996; Wenk, 1985). In addition, the overall rhythm generated by successive words in a spoken sentence may help generate predictions regarding upcoming words. For instance, Dilley and McAuley (2008) presented participants with 8-syllable sequences ending in 4 lexically ambiguous syllables (e.g., channel dizzy foot note book worm), which could be interpreted as having different segmentation points (e.g., foot notebook worm vs. footnote bookworm). Their findings revealed that the interpretation that the participants chose depended on the rhythmic properties of the first four syllables of the sequences.

Neural Basis of Speech Rhythm

Electroencephalography (EEG) has been popularly used to study language processing. Compared to the other neuroimaging methods, such as magnetoencephalography (MEG), positron emission tomography (PET), or functional magnetic resonance imaging (fMRI), EEG has been the most broadly employed, because of its safety and ease of recording as well as relatively low cost compared to the other methods. For instance, PET requires exposure to radiation while the use of functional magnetic resonance imaging (fMRI) is expensive as well as easily affected by head motions which may cause degradation of the measurable signal (Torkildsen, Syversen, Simonsen, Moen, & Lindgren, 2007). Although EEG recording has limited spatial resolution compared to PET and fMRI, it is preferred due to its non-invasive and harmless procedure, especially for experiments with baby and children (Teplan, 2002). In addition, the most powerful benefit of EEG is its temporal resolution at the millisecond, which is useful for the study of cognitive processing such as language (Teplan, 2002; Torkildsen et al., 2007). Event-related potentials (ERPs) are measured using the EEG method, and correspond to time-locked brain responses to certain sensory, motor or cognitive events. ERPs have been popularly used in academic settings to observe neural processes that take place from before the delivery of stimuli to after behavioral response made by a participant (Woodman, 2010). ERPs usually show a series of specific peaks and troughs (also known as ERP components) that allow us to visualize the different steps of cognitive processing during a trial (Kutas et al., 1980; Woodman, 2010).

With these advantages, researchers in psycholinguistics and cognitive neuroscience have used the ERP method to explore the brain mechanisms related to language processes and reading-related issues, such as phonological processing, decoding, vocabulary, fluency, and comprehension (Dimigen, Sommer, Hohlfeld, Jacobs, & Kliegl, 2011), as well as to find potential neural markers that can predict literacy problems. One of the most important findings of electrophysiological marker for language processing is the N400 component of the ERPS, first discovered by Kutas and Hillyard (1980), The N400 corresponds to an increased negative potential with maximal amplitude around 400ms, and was initially found in response to the visual presentation of a word that is semantically inappropriate in a sentence context (e.g., "John drinks mathematics"). Research has since shown that all words, and pronounceable letter strings, produce a N400 component, and its amplitude is proportional to semantic integration difficulty: the less expected is a word in a given context, the larger the N400 amplitude will be. In addition, it is independent of the sensory modality, having been found with spoken words and written words, as well as with sign language (Kutas et al., 2011). Because, the N400 can be seen as an overall index of language comprehension, it recently received increased attention in literacy research as an index of pre-to-post reading intervention improvement. For instance, Hasko, Groth, Bruder, Bartling, and Schulte-Körne (2014) compared the ERPs recorded in children with dyslexia and controls while they performed a phonological lexical decision task in which participants had to decide whether a visually presented stimulus sounded like a real word or not. Children with dyslexia also participated in a 6-month intervention. Results showed that children who improved after the intervention had larger post- versus pre-intervention N400 components, and that their N400 was similar to the N400 observed in the control group.

The search for electrophysiological markers of speech rhythm processing, on the other hand, is relatively new. Since 1999, several studies have investigated this issue in various languages such as Dutch (Böcker et al., 1999), French (Magne et al., 2007; Marie et al., 2011), German (Bohn, Knaus, Wiese & Domahs, 2013; Domahs, Wiese, Bornkessel-Schlesewsky, & Schlesewsky, 2008; Rothermich, et al., 2010, 2012; Schmidt-Kassow et al., 2009) and English (Magne et al., 2016; Moon & Magne, 2015). The approach taken by these studies is also variable, with some using words with incorrect stress patterns (e.g., Domahs et al., 2008; Magne et al., 2007; Marie et al., 2011; McCauley, Hestvik, & Vogel, 2013; Rothermich et al., 2012; Schmidt-Kassow et al., 2009), while others used words with correct but unexpected rhythmic/metrical patterns (Böcker et al., 1999; Bohn et al., 2013; Magne et al., 2016; Moon et al., 2015) or pseudowords with unexpected stress patterns (Rothermich et al., 2010). In addition, the task that participants were asked to performed varied across the studies, with some using distractor tasks to drive the participants' attention away from the rhythmic/metrical manipulation (e.g., Magne et al., 2016; Moon et al., 2015), some using more explicit tasks requiring participants to focus their attention directly on the pronunciation of the stimuli (e.g., Bohn et al., 2013; Domahs et al., 2008; McCauley et al., 2013), and others using both to compare the effect of attentional demand (explicit vs implicit) on rhythmic/metrical processing (e.g., Böcker et al., 1999; Magne et al., 2007; Marie et al., 2011; Rothermich et al., 2010, 2012; Schmidt-Kassow et al., 2009).

Despite the variability in term of language used, task and type of linguistic manipulation, the literature has been overall relatively consistent in showing that words with an incongruous or unexpected stress pattern elicit an early negative ERP component over the centro-frontal scalp regions. This negativity usually occurs somewhere between 300 and 600 ms after word onset (Bohn et al., 2013; Böcker et al., 1999; Magne et al., 2007, 2016; Marie et al., 2011; Moon et al., 2015; McCauley et al., 2013; Rothermich et al., 2010, 2012; Schmidt-Kassow et al., 2009), though it has also been observed as late as 1000 ms (Bohn et al., 2013; Domahs et al., 2008; McCauley et al., 2013). The scalp distribution is often bilateral (Domahs et al., 2008; Magne et al., 2007 semantic task; Marie et al., 2011; Moon et al., 2015; Rothermich et al., 2010, 2012; Schmidt-Kassow et al., 2009), but has also been found to be left-lateralized in some studies (Bohn et al., 2013; Böcker et al., 1999; McCauley et al., 2013) or right-lateralized in others (Magne et al., 2007, prosodic task). It is also worth noting that this effect is usually found regardless of whether or not the task requires the participants to focus their attention on the prosodic aspects of the stimuli (e.g., Magne et al., 2007; Marie et al., 2011; Rothermich et al., 2010; Schmidt-Kassow et al., 2009; but see Böcker et al., 1999; Rothermich et al., 2012). While the question remains open regarding which exact cognitive processes are reflected in this negativity, it has been proposed that it may represent a non-language-specific, rule-based error-detection mechanism (e.g., Magne et al., 2016; Rothermich et al., 2010), or an N400 effect reflecting increased difficulty in lexical retrieval when the stress pattern of a word is incorrect or unexpected (e.g., Bohn et al., 2013; Domahs et al., 2008; Magne et al., 2007; McCauley et al., 2013), or a contingent negative variation (CNV) elicited when a stress is missing on a syllable that was expected to be stressed (Domahs et al., 2008; McCauley et al., 2013). It is important to note, however, that given the variability among studies in term of language, type of rhythmic/metrical manipulation and task demand, these three interpretations are not mutually exclusive, and thus further research will be needed to have a full understanding of the cognitive and neural mechanisms at play during speech rhythm perception.

In addition to the aforementioned early negativity effect, several studies found a late centro-parietal positive component occurring between 500 and 900ms post-word onset in response to words with incongruous/unexpected stress patterns (Bohn et al., 2013; Domahs et al., 2008; Magne et al., 2007; Marie et al., 2011; McCauley et al., 2013; Rothermich et al., 2012; Schmidt-Kassow et al., 2009). However, in contrast to the negative effect, this positivity is mainly found when the task is explicit toward the rhythmic or metrical aspects of the stimuli. It is also important to note that a group of positive ERP components with similar latency and scalp distribution has been reported in response to syntactic incongruities (Osterhout & Holcomb, 1992), semantic anomalies (van Herten, Kolk, & Chwilla, 2005), and pitch contour manipulations (Astésano, Besson, & Alter, 2004; Paulmann, Jessen, & Kotz, 2012). Thus, the late positivity in ERPs are considered to reflect a multifactor general reanalysis process or integration mechanism (Eckstein & Friederici, 2005; Magne et al., 2005; Schmidt-Kassow et al., 2009), and is likely to be dependent on the task demand (Domahs et al., 2008; Magne et al., 2007).

Recent findings also provide evidence for an interaction between speech rhythm/meter and processing of other linguistic dimensions such as syntax, semantics and pragmatics. For instance, Schmidt-Kassow and Kotz (2009) examined the interaction between syntax and meter in German, using sentences that were correct, syntactically incongruous, metrically incongruous or both syntactically and metrically incongruous. Results showed that the three incongruous conditions (i.e., syntactically incongruous, metrically incongruous or doubly incongruous) elicited an increased P600. Interestingly, if syntactic and metrical processing were independent (i.e., computed by separate neural resources), one would expect the P600 effect produced by words that are both syntactically and metrically incongruous to be equal to the sum of the P600 effects elicited by the syntactic incongruities and metrical incongruities alone (commonly referred to as an additive model in the ERP literature). However, this was not the case. Thus, this absence of additivity of the P600 effects was taken as evidence of an interaction of meter and syntax in the P600 latency range.

The relationship between semantics and meter has been investigated in spoken French sentences (Magne et al., 2007). Magne and his colleague presented participants with spoken sentences containing words that were semantically expected or unexpected and pronounced with either a correct or an incorrect stress pattern. Words that were semantically expected but pronounced with an incorrect stress pattern elicited an increased negative ERP response that was similar to the N400 effect (Kutas et al., 2011). Moreover, metrically incongruous words were associated with the highest error rates in a semantic judgment task. The authors concluded that this increased negativity elicited by unexpected stress patterns might reflect increased difficulty of lexical access caused by an incongruous stress pattern.

Finally, a few recent studies suggest that rhythmic and metrical regularities may facilitate spoken language processing. For instance, Rothermich and collaborators (2012) investigated whether rhythm regularity facilitates semantic expectancy in German sentences. To that end, they presented sentences that were either semantically plausible or implausible. In addition, half of the sentences had a highly regular metrical structure (i.e. predictable stress pattern) while the other half was composed of metrically irregular sentences (i.e., unpredictable stress pattern). Results showed that the N400 elicited by semantically incongruous words was reduced when they were presented in a metrically regular context. These findings supported the idea that metrical regularities enhance the prediction of stress locations in a sentence context, which, in turn, facilitates lexico-semantic integration. Similarly, regular metrical structures may help processing sentences that contain syntactic errors or are syntactically ambiguous (Schmidt-Kassow et al., 2009; Roncaglia-Denissen et al., 2013).

A few neuroimaging studies have shed light about where in the brain, the processing of speech rhythm cues might occur (Aleman, Formisano, Koppenhagen, Hagoort, de Haan, & Kahn, 2005; Domahs, Klein, Huber, & Domahs, 2013; Geiser, Zaehle, Jancke, & Meyer, 2008; Klein, Domahs, Grande, & Domahs, 2011; Riecker, Wildgruber, Dogil, Grodd, Ackermann, 2002; Rothermich & Kotz, 2013). Increased brain activity in response to rhythmically or metrically unexpected linguistic stimuli have been found in a temporo-frontal cerebral network as well as various subcortical regions such as the basal ganglia and cerebellum. Based on these findings, Kotz and Schwartze (2010) proposed that rhythm processing relies on a subcortical-cortical loop that plays a critical role for timing and beat perception.

In sum, ERP studies highlight the important role of rhythmic cues in spoken language comprehension. In addition, when the language input is rendered rhythmically regular (and thus highly predictable), it seems to facilitate both semantic integration and analysis of the syntactic structure. Finally, recent neuroimaging data suggests that speech rhythm is dependent on a subcortico-cortical loop that is not specific to language nor the auditory modality. The proposed study thus seeks to examine whether the use of implicit rhythm during silent reading elicits similar brain responses as those previously reported for speech, and more specifically whether the use of texts with a regular metrical structure could facilitate reading comprehension in a similar way that a regular stress pattern has been shown to facilitate semantic processing of spoken sentences (Rothermich et al., 2012).

Speech Rhythm Sensitivity and Reading Development

A large body of research has found that the characteristics of prosody production during reading aloud (i.e., reading prosody) reflect the reading skills of the reader (Benjamin & Schwanenflugel, 2010). Despite these findings, no standard measure of prosody sensitivity is available yet. This lack likely reflects the complex nature of prosody that encompasses multiple facets that interact with several linguistic levels. As a result, in education research, various measures have been developed to study how prosody perception and production relate to reading abilities (Benjamin, 2012). Some of these measures, including the Allington (1983) scale and the National Assessment of Education Progress (NAEP) scale, have been designed to evaluate prosodic features as an aspect of oral reading fluency, in addition to accuracy and reading rate (Allington, 1983; Daane et al., 2005). Other methods include analysis of acoustic features during oral reading, such as pitch contour and pause duration (Benjamin et al., 2010; Ravid & Mashraki, 2007).

Regarding speech rhythm perception, stress-based measurements have been used to examine children's ability to intuitively acquire the rhythmic properties of each language, and how this can be used as a predictor of their reading disabilities (Benjamin, 2012). For instance, in the 'DEEdee' task, participants are presented with a prime stimulus (a picture of a familiar character/object or a spoken phrase) followed by two spoken phrases in which the syllables have all been replaced by the syllable "Dee". Only one of the two "Dee" phrases matches the prime stimulus in term of stress pattern and intonation. Whalley and Hansen (2006) found that performance on the "DEEdee" task predicted reading comprehension skills. In the mispronunciation task, participants listen to a series of bisyllabic words systematically mispronounced (i.e., stress located on the normally unstressed syllable), and must choose the corresponding object on a picture. The assumption is that, in order to perform the task successfully, participants have to mentally change the location of the stress in the word and then compare this "corrected" form to the word representations they have in their lexicon. Using different variations of this task, several studies found an association between metrical stress sensitivity and reading components, especially wording reading and phrasing component of the fluency measure, while controlling age, vocabulary, and phonological awareness (Holliman et al., 2010, 2012; Wood & Terrell, 1998; Wood, 2006). In addition, performance on the mispronunciation task was also predictive of word reading ability one year later (Holliman et al., 2010). Thus, altogether, these studies point to an important and unique contribution of speech rhythm sensitivity, independently of phonemic awareness, in the development of good reading skills at the word level. However, the contribution of speech rhythm sensitivity for reading comprehension remains largely unexplored. The proposed project seeks to address this gap.

Speech Rhythm Sensitivity and Reading Difficulty

In addition to examining the association between speech rhythm sensitivity and literacy development, researchers have also investigated the connection between rhythm sensitivity and reading disorders. Dyslexia is a developmental disorder including word recognition difficulties, as well as poor spelling and decoding abilities (Arns, Peters, Breteler, & Verhoeven, 2007). Early studies understood dyslexia as a visual processing deficit or resulting from inadequate reading instruction (Goswami, 2008). However, as evidence started accumulating, dyslexia was increasingly accepted as a cognitive deficit (Vellutino, Fletcher, Snowling, & Scanlon, 2004) that is neurobiological in nature (Arns et al., 2007). According to Tallal (2000), the main research tracks in dyslexia studies can be summarized as follows: (1) understanding dyslexia as a distinct disability, (2) the cause of phonological deficits (e.g., speech specific or basic auditory processing deficits), (3) whether dyslexia is a deficit specific to written language or rather the manifestation of a more pervasive delay in language development, and (4) the causes of dyslexia, including genetic, neurological, social, and educational factors.

The most popular hypothesis is that dyslexia results from a phonological processing deficit (Torkildsen et al., 2007). The phonological deficit hypothesis proposes that individuals with dyslexia may have an impaired phonological awareness, which is the ability to discriminate and manipulate the phonemes, and a large number of studies have indeed shown a strong relationship between phonological awareness and reading ability from early reading stage through adulthood (Torkildsen et al., 2007). This hypothesis is also supported by the findings from several studies using a variety of brain imaging methods such as EEG and fMRI. For instance, Galin and his colleagues (1992) found cognitive differences in slow brainwave activity (known as theta waves) from the temporal lobe during oral and silent reading between group with dyslexia and controls. This result was supported by Arns et al. (2007)'s coherence study that shows increasing slow activity (both delta and theta) in the frontal and right temporal area of the brain and coherence for the lower (delta and theta) and higher (alpha and beta) frequency bands. Arns et al. (2007) also found that the EEG coherence was correlated with phonological tests, such as Rapid Naming Letter, Articulation, Spelling and Phoneme Deletion. Weiss, Siedentopf, Hofer, Deisenhammer, Hoptman, Kremser, Golaszewski, Felber, Fleischhacker, & Delazer (2003) found a lower coherence in individuals with dyslexia than controls during language activity. The largest coherence difference for those with dyslexia was found between congruous and incongruous words at the end of sentences, 300 to 500 ms after the onset of the word, implying more brain activity is required for those with dyslexia in semantic integration and parsing processing (Weiss et al., 2003). Similarly, studies using the fMRI method, have consistently found that individuals with dyslexia had lower activity than matched controls in the posterior regions of the left hemisphere when performing various reading tasks (e.g., Shaywitz, Shaywitz, Pugh, Mencl, Fulbright, & Skudlarski, 2002). These regions, and more specifically the left temporo-parietal junction, have long been associated with phonological decoding skills (e.g., Pugh, Mencl, Jenner, Katz, Frost, & Lee, 2000).

Recently, several researchers have shown an increased interest in investigating whether processing of suprasegmental phonological cues was also impaired in individuals with dyslexia. To examine rhythm sensitivity, Goswami et al. (2002) developed a beat detection task using non-speech auditory sequences. A series of experiments using this task found that both adults and children with dyslexia tended to have lower rhythmic sensitivity than typical readers match for age and reading levels (Goswami, et al., 2002, 2011; Leong et al., 2011; Thomson et al., 2006). Adults with dyslexia have also been found to have difficulty processing musical rhythm (Huss, Verney, Fosker, Mead, Goswami, 2011), suggesting a more general underlying rhythmic processing deficit. Based on these findings, Goswami proposed that dyslexia is caused by a basic auditory rhythmic processing deficit that hinders the acquisition of appropriate phonological representations. Recent EEG studies suggest that this deficit may be caused by the difficulty of neural oscillations within the auditory cortex to efficiently entrain to the linguistic rhythmic cues carried by the speech signal (Goswami, 2011; Hämäläinen et al., 2012).

The Implicit Prosody Hypothesis

While the aforementioned studies strongly point to an important contribution of prosody during reading acquisition, recent evidence suggest that the inner voice may be core of ordinary reading (Breen, 2014). This assumption regarding the inner voice is not something new, and can be found in the literature throughout the 20th century (Breen, 2014). Fodor formulated the Implicit Prosody Hypothesis (IPH), proposing that the prosodic information is automatically retrieved during silent reading and contributes to comprehension (Fodor, 1998, 2002). Although the idea of the inner voice in silent reading has long been discussed, it has been supported by just a small number of scientific evidence because of the methodological limits in measuring the overarching property of suprasegmental phonology without any over language production from the participants.

Eye-tracking methodology has attracted attention with its concurrent measurement of eye movements involved with relatively natural linguistic activities, such as visual inspection of images and silent reading (Trueswell, 2008). Eye-tracking methods provide researchers with a record of an individual's moment-by-moment consideration during the on-going process of deriving meaning from various linguistic forms (Trueswell, 2008). Moreover, this method is useful for analyzing pathways of attentional distribution, which possibly provide information of how long a participant focuses on a particular item with eye-fixation, gaze duration, area of interest, and scan path (Schiessl, Duda, Thölke, & Fischer, 2003). For instance, an early study by Cooper (1974) found that the eye-movement of listeners were time-locked to the text while listening to the story, showing more than 90% of the fixations to the critical words. These benefits of eye-tracking methods allow research to explore language processing involved in silent reading and how it is supported by the reader's inner voice. Ashby and Clifton (2005) examined whether readers' eye movements are influenced by the stress pattern of the words during silent reading. Their findings revealed that participants had longer reading times and more eye fixations when reading words with two stressed syllables (*application*) than one stressed syllables (e.g., *executive*), regardless of the lexical frequency. The authors concluded that during reading, word recognition involved the recognition of lexical stress and the assembly of stress units. Further results from Ashby (2006) suggested that silent readers tended to rely more on prosodic phonological representations when processing low frequency words than they do when processing words which are encountered more frequently. Breen and Clifton (2011, 2013) conducted a series of two experiments to explore the effect of incongruous stress patterns in sentence contexts using a set of two-syllable stress homographs (e.g., nouns-verbs). Stress homographs only differ in term of stress pattern, with the noun form stressed on the first syllable (e.g., *CONduct*) and the verb form stressed on the second syllable (e.g., *conDUCT*). In both experiments, results showed increased reading times for target words whose stress pattern did not conform to the expectations set by the sentence context. Later, Breen and Clifton (2013) found that the eye movements for reanalysis were delayed until a full view of the disambiguating material, implying that an implicit prosodic representation of the target word was initially created and later revised. These findings thus support the IPH (Fodor, 1998) and Bader's (1998) Prosodic Constraint on Reanalysis theory, which suggests that the difficulties associated with revising syntactic structure are compounded when an amendment of prosodic structure is also required. In all of the experiments in this series, Breen and Clifton (2011, 2013) found that the greatest reading costs were incurred in the conditions that necessitated reanalysis of both syntax and lexical stress. Interestingly, there is also evidence that the specific prosody of the "inner voice" supplied by a reader may reflect his or her own regional accent. Filik and Barber (2011) manipulated limericks so that the rhyming potential of the final word depended upon the regional accent of the participants. For example, participants from Northern England pronounced the word "glass" with a short vowel, so that it rhymed with "mass," while participants from Southern England pronounced it with a long vowel, so that it rhymed with "sparse." Thus, the visually presented words "path" and "Garth" were expected to match the Southern England participants' expectation for rhyme, but to violate the rhyme expectations of the Northern England participants. Results indicated that disruptions in eye movements occurred when participants read the final word of a limerick that did not produce a rhyme in accordance with the participant’s regional accent, which suggests that the participants were imposing their own prosody, in terms of vowel length, onto the words while they silently read the text.

Further evidence for the IPH comes from studies using the ERP method to investigate neural signatures of the implicit retrieval of prosodic information. Magne and his colleagues (2010) explored metrical stress expectations during silent reading by measuring ERPs while participants read sequences of five bisyllabic words. The first four words of every list exhibited the same stress pattern, while the fifth word was either consistent or inconsistent with the previous pattern. Results showed an increased negative ERP component was elicited in response to final words whose stress patterns did not conform to the pattern that had been previously established by the first four words. These findings thus further support the idea that information regarding the metrical structure of a word is automatically retrieved during reading. In addition, this negative effect had similar centro-frontal scalp distribution and latency range as the negativity previously reported for rhythmically unexpected words in spoken language (e.g., Magne et al., 2007), thus suggesting that the same neural mechanisms underlying speech rhythm processing in spoken language are at play during silent reading.

Suprasegmental information that extends beyond the word level may also be implicitly activated during silent reading. Steinhauer and Friederici (2001) and Steinhauer (2003) explored the implicit processing of intonational phrase boundaries in written text through a series of ERP experiments in which participants silently read sentences containing commas. Results indicated that the Closure Positive Shift (CPS) component, which was reported by Steinhauer, Alter, and Freiderici (1999) when listeners perceive intonational phrase boundaries in spoken language, was also elicited during silent reading in response to commas that marked intonational phrase boundaries. The authors thus proposed that similar brain structures may be involved in the perception of commas in written language and the perception of prosodic boundaries in spoken language and that the particular brain response evoked (i.e., the CPS) may be related to a prosodic parsing mechanism that influences syntactic processing when listening to spoken language and reading written text. Whiles these studies do not directly examine the rhythmic aspects of prosody, they support the need for further investigation of the role of implicit speech rhythm sensitivity beyond the word level.

Summary

In sum, linguistic rhythm cues have been found to guide speech perception and language comprehension from very early on in life. In addition, sensitivity to the rhythmic cues may play an important role not only in reading acquisition, but may also continue to contribute to some of the processes involved in silent reading. Together, the aforementioned literature provides a solid theoretical background to explore the influence of speech rhythm sensitivity on reading comprehension. In particular, because speech rhythm cues have been found to generate expectancy about upcoming words in both spoken (e.g., Rothermich et al., 2012) and written language (e.g., Magne et al., 2010), the main goal of the proposed study is to determine whether a regular (and thus predictable) metrical stress pattern would facilitate comprehension of written sentence during silent reading.

CHAPTER THREE

METHODS

Participants

A total of nineteen undergraduate students (average age = 20.21 ± 1.8 year old) were recruited from a southeastern regional university. All the participants were native speakers of English with normal or corrected-to-normal vision, no hearing impairment, and no psychiatric or neurological history. Specific attention was paid to recruiting an equal number of male (n = 10) and female participants (n = 9). The study was approved by the Institutional Review Board (IRB) and written consents were obtained from the participants prior to the beginning of the experiment. Participants either received course credits or $15 for compensation.

Standardized Reading Measure

The scores on the reading and English sections of the American College Testing (ACT) were collected to examine the relationship between reading comprehension and speech rhythm sensitivity. The ACT test is a standardized college readiness test for college admissions in the U.S. The reading section is a 35-minute test that comprises short passages from four categories (prose fiction, social science, humanities, and natural science) and forty multiple-choice questions that test the reader’s comprehension of the passages. The ACT English scores were used as a general language skill measure to examine the unique variance of reading comprehension measured with the ACT reading. The English section lasts 45 minutes and includes five passages each accompanied by fifteen multiple-choice questions. The questions cover usage and mechanics of English (e.g., punctuation, grammar, sentence structure) as well as rhetorical skills (e.g., organization, style). Both reading and English scores range between 1 and 36.

EEG Speech Rhythm Sensitivity Task

A total of 256 sentences were created for the purpose of the experiment. Each sentence was composed of nine words, and the critical word (the sixth word in the sentence) consisted of a bisyllabic noun and was always preceded by 10 syllables. Among the 256 sentences, 128 were semantically expected and 128 were Semantically Unexpected (See Table 1). Semantically Unexpected sentences were created by replacing the critical word by one that did not fit within the sentence context. In addition, the rhythmic structure (i.e., stress pattern) of the sentences was manipulated so that for half of the sentences (N = 128) the ten syllables leading-up to the critical word either formed a regular alternation of a stressed syllable followed by an unstressed syllable (i.e., regular rhythm), while for the other half (N = 128), they formed an irregular stress pattern (i.e., irregular rhythm). Thus, to summarize, the experimental design will be 2 (Semantically Expected vs. Semantically Unexpected) x 2 (Rhythmically Regular vs. Irregular) repeated measures.

Table 1

Examples of stimuli in each condition

Rhythmic Regularity	Semantic Expectancy	Example
Regular	Expected	R**i**chard strongly challenged Billy's written **statement** about the accident Ss Ss Ss Ss Ss Ss
Regular	Unexpected	R**i**chard strongly challenged Billy's written **doughnut** about the accident Ss Ss Ss Ss Ss Ss
Irregular	Expected	Bob angrily challenged Nathaniel's fierce **statement** about the accident S Sss Ss sSs S Ss
Irregular	Unexpected	Bob angrily challenged Nathaniel's fierce **doughnut** about the accident S Sss Ss sSs S Ss

Note: Stressed syllables are underlined and target words are in bold.

The amplitude of the N400 component is known to be inversely proportional to the degree of semantic expectancy: the less expected is a word, the larger is the N400 (Kutas et al., 2011). To avoid the possible confound that the semantic context of sentences in the rhythmically irregular conditions was weaker than for sentences in the rhythmically regular conditions, several pilots studies were conducted on previous iterations of the linguistic stimuli. As a result, the linguistic stimuli were adjusted until semantically expected sentences were judged as being similarly plausible in both rhythm conditions, and that, likewise, semantically unexpected sentences were judged as being similarly implausible in both rhythm conditions. In addition, because the amplitude of the N400 was previously found to be influenced by lexical frequency (Kutas et al., 2011), the log HAL frequency (Lund & Burgess, 1996) was used to control the frequency of the adjectives preceding the critical words in the rhythmically regular (Mean = 9.3, SD = 1.9) and irregular conditions (Mean = 9.0, SD = 1.6). A paired t-test did not reveal any significant difference between the two rhythm conditions (p = .24).

Each participant was presented with 32 sentences in each experimental conditions (Semantically Expected and Rhythmically Regular, Semantically Expected and Rhythmically Irregular, Semantically Unexpected and Rhythmically Regular, Semantically Unexpected and Rhythmically Irregular). Finally, note that two difference lists of 128 sentences were built from the pool of 256 available sentences in order to present each critical word in both semantically expected and semantically unexpected conditions across participants, but with no within-subject repetition.

Procedure

During the experiment, participants were seated in a soundproof room and were instructed to avoid moving their eyes, head, or other body parts except when a series of X's appears on a computer screen between each trial. To minimize eye movements, each written sentence was presented word-by-word on a computer screen using the software E-prime (PST, Inc., Pittsburgh, PA). Participants were instructed to silently read each sentence carefully and then to judge whether it was semantically correct or not. Sentences were presented in black on white background. Each trial began with the presentation of a fixation cross for 1000 ms. Then, each word was successively presented for 300 ms followed by a blank screen of 400 ms. This presentation rate resulted in a stimulus onset asynchrony of 700 ms, which was within the typical range for reading experiments (Dambacher, Dimigen, Braun, Wille, Javobs, & Kliegl, 2012). Following the last word of the sentence, the screen remained blank until the participant gave an answer using a response box. Before the beginning of the next trial, a series of X’s were displayed on the computer screen for 2000 ms to indicate that the participants could blink or move their eyes. Sentences were grouped in separate blocks of Rhythmically Regular and Rhythmically Irregular conditions (4 blocks of 32 sentences total). Within each block, semantically expected and semantically unexpected sentences were be presented in a pseudo-randomized order (no more than two successive sentences from the same experimental condition). Response key–finger association and the order of the blocks were counter-balanced across participants.

EEG Data Acquisition

EEG were recorded continuously from 128 Ag/AgCl electrodes embedded in sponges in a Hydrocel Geodesic Sensor Net (EGI, Eugene, OR, USA) placed on the scalp with Cz at the vertex (See electrode layout in Appendix A), connected to a NetAmps 300 high-impedance amplifier, using a MacBook Pro computer. (See Appendix C for the electrode layout on the scalp.) The sampling rate of the EEG acquisition was 500Hz, and impedances were kept below 50 kOhm. Data were referenced online to Cz, but later re-referenced offline to the average of the left and right mastoid electrodes. The vertical and horizontal electrooculograms (EOG) were also recorded in order to detect the blinks and eye movements. EEG preprocessing was carried out with NetStation Viewer and Waveform tools (EGI, Eugene, OR, USA). The EEG was filtered offline with a bandpass of 0.1 to 20 Hz. Epochs lasting 100 ms before and up to 1000 ms after the onset of the target word was extracted from the continuous EEG data. Trials contaminated by artifacts (e.g., eye movements, blinks, amplifier saturation, electrode drifting or muscle activity) or incorrect answers were excluded from further analysis. The ERPs were computed by averaging the remaining epochs for each participant, condition, and electrode site, relative to a 100 ms pre-stimulus baseline.

EEG Data Analysis

Statistical analyses were performed on the ERPs using Matlab (The Mathworks, Natick, MA) and the cluster-based permutation method implemented in the open-source Fieldtrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011). The cluster-based permutation method proposes a data-driven approach to temporal and spatial localization of the effects without having to specify latency ranges or regions of interest a priori (Maris & Oostenveld, 2007), while offering a solution to increased family-wise error rate resulting from the problem of multiple comparisons. Monte Carlo significance probability, as a *p-value*, was calculated to examine the significance using an overall alpha of .05. Planned comparisons were conducted between Semantically Expected and Semantically Unexpected conditions, separately for Rhythmically Regular and Rhythmically Irregular sentences (i.e., Rhythmically Regular and Semantically Expected *vs* Rhythmically Regular and Semantically Unexpected; Rhythmically Irregular and Semantically Expected *vs* Rhythmically Irregular and Semantically Unexpected).

To compare the effect of Semantic Expectancy between Rhythmically Regular and Rhythmically Irregular sentences, difference waves were computed separately for both Rhythmically Regular and Rhythmically Irregular contexts by subtracting ERPs in the semantically unexpected condition from the ERPs in the semantically expected condition (i.e., Rhythmically Regular and Semantically Unexpected *minus* Rhythmically Regular and Semantically Expected; Rhythmically Irregular and Semantically Unexpected *minus* Rhythmically Irregular and Semantically Expected). The two resulting difference waves, respectively representing the Semantic Expectancy effect in the Rhythmically Regular condition and the Rhythmically Irregular condition, were then compared using the same cluster-based permutation procedure as described above.

Relationship between Rhythm Sensitivity and Reading Skills

To investigate the relationship between implicit speech rhythm sensitivity and reading comprehension, correlations were computed between the individual ACT reading scores and the size of the difference between the Semantic Expectancy effects in the Rhythmically Regular and Rhythmically Irregular conditions. To this end, an index of implicit speech rhythm sensitivity was calculated from the ERP using the following two steps: 1) for each significant cluster found the comparison between the difference waves in the Rhythmically Regular and Rhythmically Irregular conditions, the ERP amplitude at each electrode and at each time point of the significant cluster was averaged together (These calculations will be done separately for the Rhythmically Regular and Irregular conditions); 2) then, the averaged cluster value obtained for the Rhythmically Irregular condition was subtracted from the averaged value obtained for the Rhythmically Regular condition, resulting in a single value reflecting the sensitivity to the implicit rhythm structure of the sentences. To account for potential effect of individual difference in English skills as general language skills, a partial correlation was also computed between the speech rhythm sensitivity index and ACT reading score after excluding the effect of English ACT scores.

CHAPTER FOUR

RESULTS

Behavioral Data

The means and standard deviations of accurate rates for each experimental condition are presented in Table 3. Overall, the accurate rates were consistently above 90% across the four conditions, indicating that participants performed well in the semantic task. Results of a two-way repeated ANOVA indicated no significant main effect of either Semantic Expectancy or Rhythmic Regularity, as well as no significant interaction between these two factors.

Table 2

The means and standard deviations of accuracy rates in the semantic task

Accurate Rate (%)	Semantically expected		Semantically unexpected	
	Rhythmically Regular (*n*=18)	Rhythmically Irregular (*n*=18)	Rhythmically Regular (*n*=18)	Rhythmically Irregular (*n*=18)
Mean	93.8	91.4	91.3	90.5
SD	5	11	8	9

ERP Data

The grand-average ERPs in the four experimental conditions are presented on Figure 1. In all four conditions, following the onset of the critical word, the ERPs showed a typical pattern of waveforms including the N1 and P2 components, The N1/P2 complex is commonly interpreted as reflecting sensory and perception processes from multiple generators located in the occipito-parietal, occipito-temporal, and frontal regions of the cortex in response to a visual stimulus (e.g., Clark, Fan, & Hillyard, 1995; Woodman, 2010). From around 300ms, the ERPs started to show a different pattern of waveform across conditions. The semantically unexpected conditions (Figure 1, blue and green traces) are associated with larger negative ERPs than the semantically expected conditions (Figure 1, red and cyan traces). However, the latency range of this negative ERP difference appears to start later and ends earlier in the Rhythmically Regular condition (350-500 ms) than in the Rhythmically Irregular Condition (300-800 ms). Several planned cluster-based permutation tests were conducted to identify the exact temporal and spatial localization of these differences between semantically expected and semantically unexpected conditions, separately for rhythmically regular and rhythmically irregular sentences (i.e., Rhythmically Regular and Semantically Expected *vs* Rhythmically Regular and Semantically Unexpected; Rhythmically Irregular and Semantically Expected *vs* Rhythmically Irregular and Semantically Unexpected).

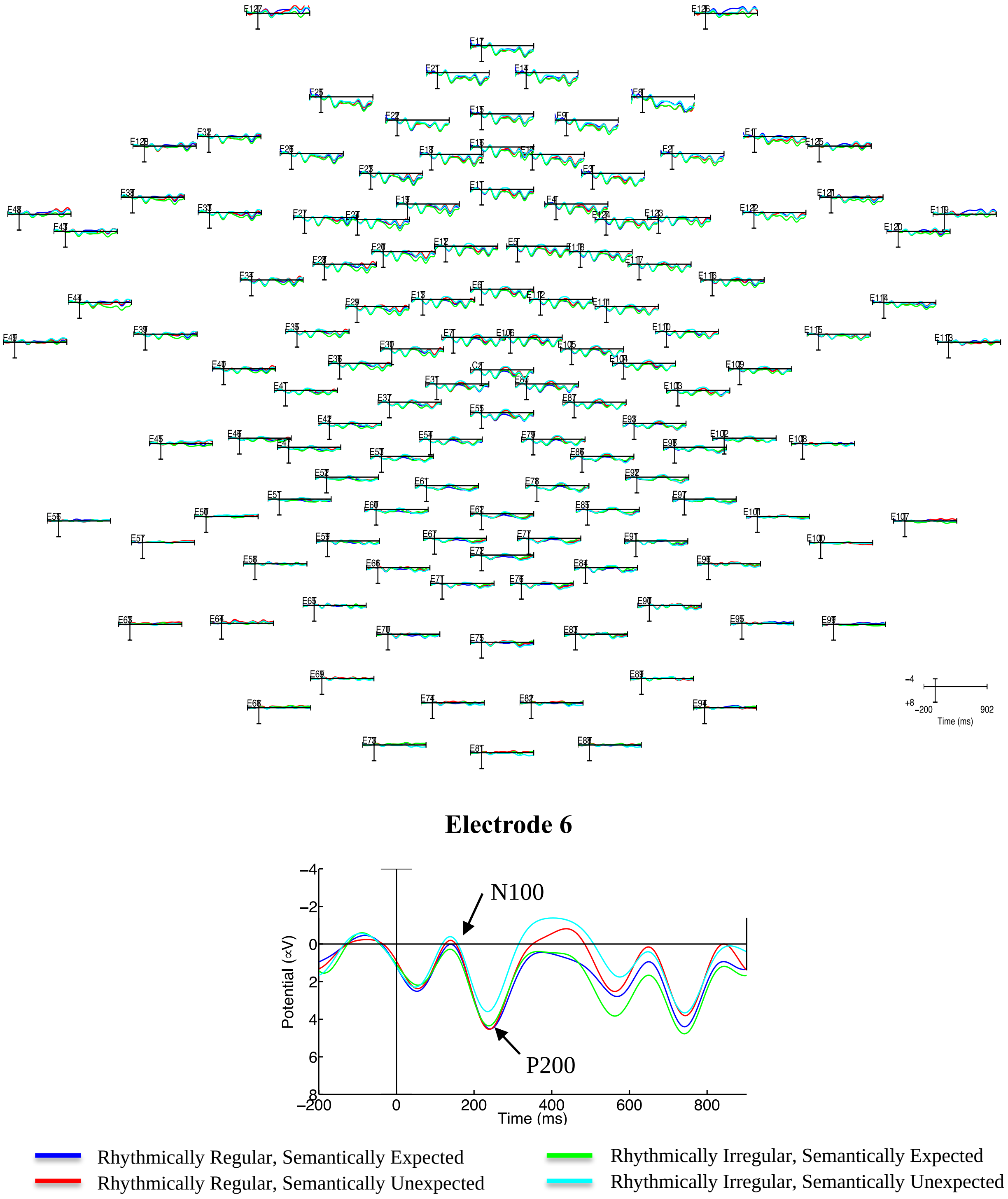
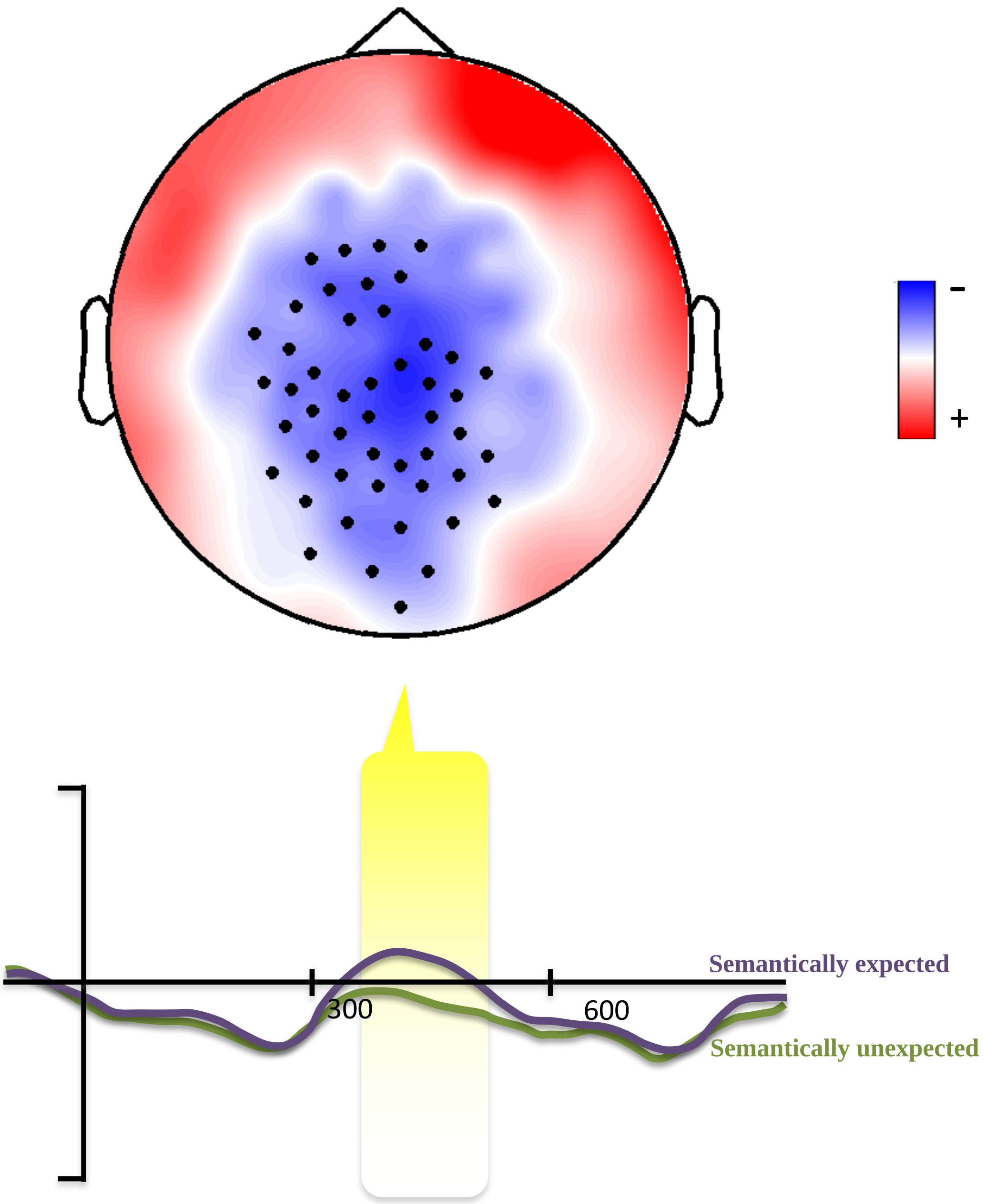


Figure 1. Grand-average ERP elicited by a critical word in the four experimental conditions. The top panel shows the ERP waveform for all electrodes and the bottom panel presents a large view of representative electrode on the centro-frontal region of the scalp. The bottom panel shows one of the electrodes (Electro 6) for the four conditions. The negative amplitude is indicated upward on this and the following figures.

Effect of Rhythmic Regularity

For critical words following a Rhythmically Regular context, the results of a cluster-based permutation analysis between Semantically Expected and Semantically Unexpected Conditions indicated that semantically unexpected words were associated with an increased negativity between 358 and 518 ms post word onset ($p = 0.018$). As can been seen on Figure 2, this negative ERP difference was significant over the centro-frontal regions of the scalp.

When critical words followed a Rhythmically Irregular context, they also elicited an increased negative ERP component when semantically unexpected between 306 and 830ms post critical-word onset ($p = 0.001$). Similar to the results for the rhythmically regular context, the difference was significant over the centro-frontal regions of the scalp (See Figure 3).



358 - 518 ms (p = 0.018)

Figure 2. N400 effect elicited by the critical word following a Rhythmically Regular context (Bottom panel). Mean waveforms for Semantically Expected and Unexpected averaged over the electrodes included in the significant negative cluster. The latency range of the significant clusters is indicated by a yellow rectangle. Topographic maps represent mean differences in scalp amplitudes in the latency range of the significant clusters (Top panel). Electrodes belonging to the cluster are shown with a black dot over the scalp (**•**).

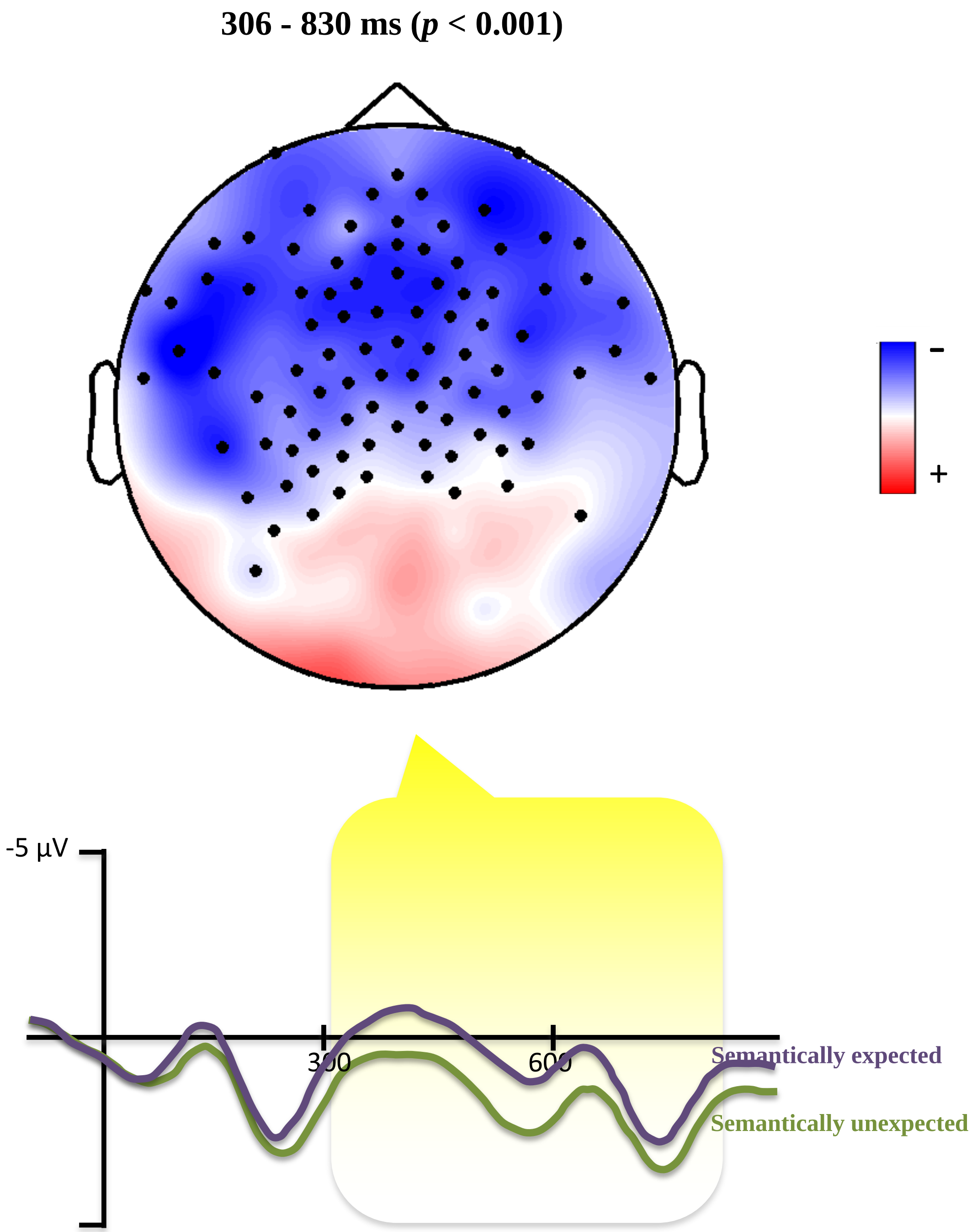


Figure 3. N400 effect elicited by the critical word following a Rhythmically Irregular context before a critical word (Bottom panel). Mean waveforms for Semantically Expected and Unexpected averaged over the electrodes included in the significant negative cluster. The latency range of the significant clusters is indicated by a yellow rectangle. Topographic maps represent mean differences in scalp amplitudes in the latency range of the significant clusters (Top panel). Electrodes belonging to the cluster are shown with a black dot over the scalp (**•**).

The previous results suggest that the latency and duration of the negative ERP effect elicited by semantically unexpected words depend on the rhythmic regularity of the context leading up to the critical word. Indeed, the negative effect elicited by semantically unexpected critical words started earlier and lasted longer when it was preceded by a rhythmically irregular context (308 and 830 ms) than a rhythmically regular context (358-518 ms). To further investigate the potential effect of rhythm regularity, ERP difference waves were computed by subtracting the ERPs in the Semantically Expected Condition from those in the Semantically Unexpected condition, separately for the Rhythmically Regular and Rhythmically Irregular conditions. A cluster-based permutation test was then conducted between the two difference waves. Results indicated that the difference wave for the Rhythmically Irregular condition was more negative than the difference wave for the Rhythmically Regular condition from 488 ms to 598 ms post critical-word onset ($p = 0.008$), and that this effect was significant over centro-frontal regions of the scalp (See Figure 4).

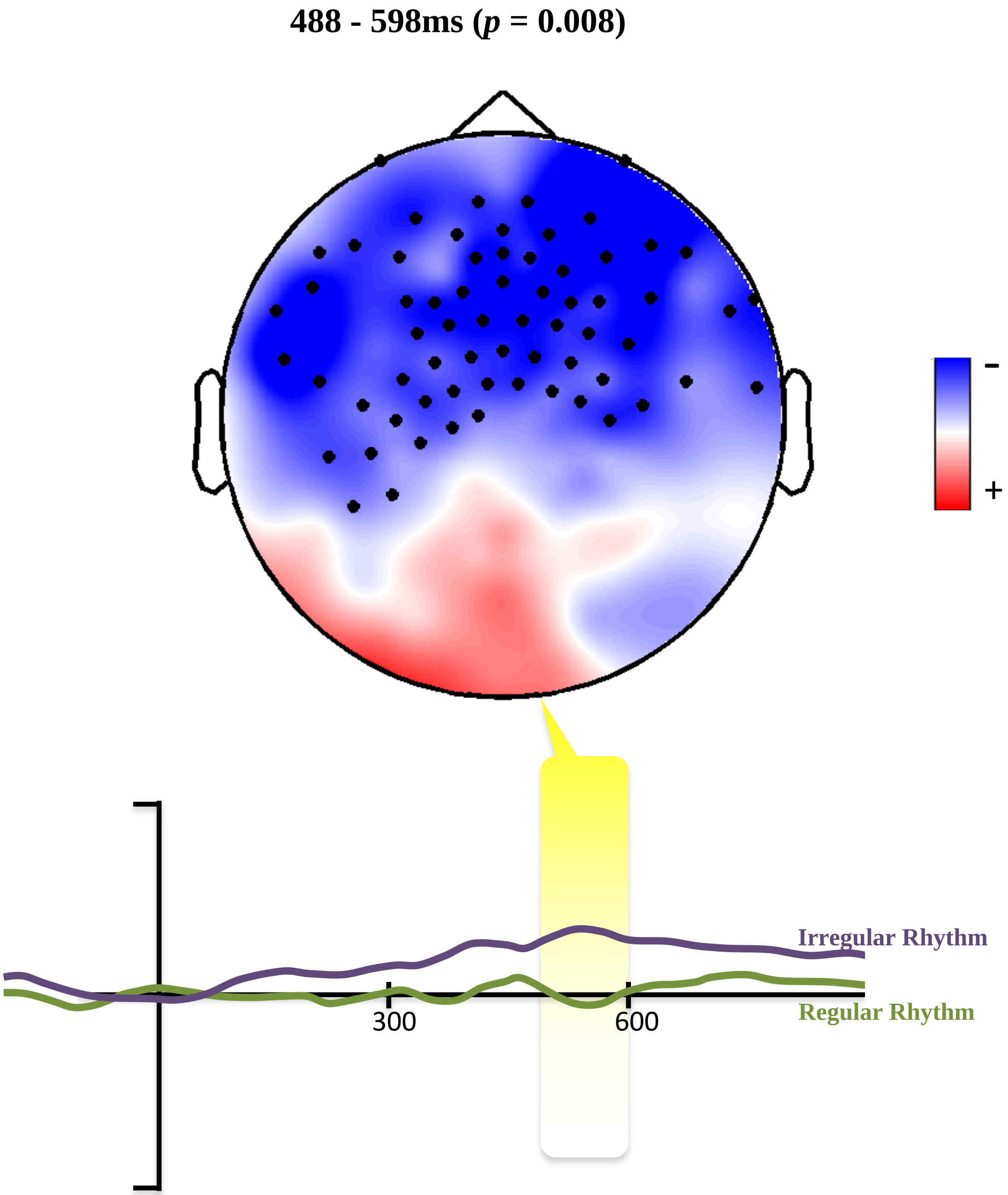


Figure 4. Difference in semantic effects between Rhythmically Regular and Irregular context (Bottom panel). Mean waveforms for Rhythmically Regular and Irregular averaged over the electrodes are included in the significant negative cluster. . The latency range of the significant clusters is indicated by a yellow rectangle. Topographic maps represent mean differences in scalp amplitudes in the latency range of the significant clusters (Top panel). Electrodes belonging to the cluster are shown with a black dot over the scalp (•).

Correlation between ERPs and Reading Measures

The average score of participants was 24.79 (*SD* = 5.04) on the ACT reading score and 24.84 (SD = 5.1) on the ACT English score. The correlation between ACT reading scores and ACT English scores was high ($r = .81$, $p < .001$). In order to further investigate the link between speech rhythm sensitivity and reading comprehension ability, an ERP index of speech rhythm sensitivity was calculated using the procedure outlined in the Methods section. The results of the correlation analysis indicated a significant strong positive relationship between sensitivity to speech rhythm and reading comprehension (ACT reading scores), implying that a student with more sensitivity to rhythmic change is likely to have a higher reading comprehension score ($r = .56$, $p = 0.006$). There was also a moderate correlation between speech rhythm sensitivity and ACT English scores, but it was not significant ($r = .39$, $p = .095$), Finally, a partial correlation result between sensitivity to speech rhythm and ACT reading score while controlling for ACT English score approached significance ($r = .45$, $p = 0.063$).

CHAPTER FIVE

DISCUSSION

In the current study, meter, the pattern of stressed and unstressed syllables in spoken language in English was used to investigate the role of implicit speech rhythm in reading comprehension. The results of the study can be summarized as follow. First, this negative ERP effect was larger and lasted longer for critical words following a Rhythmically Irregular context than a Rhythmically Regular context. Second, sensitivity to speech meter was associated with reading comprehension (ACT reading scores), even after accounting for basic English skills (ACT English scores). The results will be further discussed in light of the previous literature, and then the limitation of the current study will be addressed. Afterwards, potential direction for future research will be suggested.

Effect of Rhythmic Regularity

Based on previous findings, it was predicted that semantically unexpected words would elicit an increased negativity compared to semantically expected words, an effect referred to as the N400 (e.g., Kutas et al., 1980; see Kutas et al., 2011, for a review). In line with this prediction, critical words that were semantically unexpected in the sentence context elicited an increased negative ERP component, both for Rhythmically Regular and Irregular conditions. In addition, this negative effect shared a similar latency range (i.e., 358-518 ms for the Rhythmically Regular condition and 306-830 ms for the Rhythmically Irregular condition) and scalp distribution (i.e., central regions of the scalp) as the N400 component found in the visual modality (Kutas et al., 2011). The N400 is usually larger for words that do not fit in the semantic context of a word, sentence or discourse, its amplitude has been interpreted as reflecting the difficulty in either integrating semantic information and/or generating semantic expectancies (Kutas et al., 2011).

The first research question of this study addressed whether the N400 component of the ERPs associated with semantic processing was modulated by the rhythmic structure of the written context. The current findings revealed the N400 effect associated with semantically unexpected words started earlier and lasted longer in the Rhythmically Irregular condition (306-830ms) than the Rhythmically Regular condition (358-518ms). In addition, the N400 effect was more broadly distributed over the scalp in the Rhythmically irregular than the Rhythmically regular condition, as evidenced by the difference in numbers of electrodes that were part of the significant negative cluster in each condition (See black dots on top panels of Figures 2 and 3, respectively).

This result is in line with previous ERP studies using spoken language (e.g., Rothermich et al., 2012). Using a similar design as in the present study but with spoken German sentences, Rothermich and her colleagues found that semantically unexpected words elicited larger N400 effects when they were embedded in sentences spoken with a regular stress pattern (i.e., regular rhythm) than when they were presented in sentences with unpredictable stress. The authors proposed that a regular pattern of stressed and unstressed syllables might facilitate lexico-semantic integration by generating a form of metrical priming that helps make predictions about upcoming words in the sentence. Semantic processing would thus necessitate the recruitment of less cognitive and neural resources, resulting in a smaller N400 effect in response to semantic incongruities when rhythm is regular (and thus highly predictable). Similarly, Dilley and McAuley (2008) demonstrated that distal (i.e., distant or nonlocal) prosody influences the lexical expectancy of upcoming spoken words in a sequence. The authors proposed a perceptual grouping hypothesis that distal prosodic cues in on-going utterances provides a form of periodic expectations about the prosodic properties of upcoming syllables, which may facilitate word segmentation and lexical recognition (Brown, Salverda, Dilley, & Tanenhaus, 2011; Dilley et al, 2008). Interestingly, the effect of rhythmic expectancies is not confined to lexico-semantic processing. A regular rhythm has also been shown to help processing sentences that contain syntactic errors or are syntactically ambiguous (Schmidt-Kassow et al., 2009; Roncaglia-Denissen et al., 2013). It would thus be interesting to determine in future studies whether such an influence of rhythm on syntax exists in reading as well.

The fact that rhythm regularity affects semantic processing even in written sentences is also in line with recent studies using ERPs (Luo & Zhou, 2010; Magne et al., 2010) or eye-tracking methodology (Breen et al., 2011; Kentner, 2012), showing that information about the stress pattern of words is automatically retrieved during silent reading and may affect word recognition. More generally, the present findings also support the Implicit Prosody Hypothesis (IPH), which proposes that readers project a default prosodic contour onto the written text during silent reading by automatically retrieving prosodic information (Fodor, 1998). While the IPH remains largely underexplored due to methodological limitation for measuring implicit retrieval of prosodic information, the increasing body of evidence in its favor (e.g., Steinhauer et al., 1999, 2001; Liu et al., 2010) suggests that sensitivity to prosodic (and thus rhythmic) information merits further consideration in cognitive models of reading.

Finally, the results of the permutation analysis showed that the N400 effect in the

Rhythmically Irregular condition was more frontally distributed than in the Rhythmically Regular condition. While linking EEG activity observed on the scalp to brain regions should be done with caution, this observation is in line with the findings of several recent neuroimaging studies (Aleman et al., 2005; Domahs et al., 2013; Geiser et al., 2008; Klein et al., 2011; Riecker et al., 2002; Rothermich et al., 2013). Overall, increased brain activity in response to rhythmically unexpected linguistic stimuli have been found in a temporo-frontal cerebral network as well as various subcortical regions such as the basal ganglia and cerebellum. Kotz and Schwartze (2010) proposed that rhythm processing relies on a subcortical-cortical loop that plays a critical role for timing and beat perception. Interestingly, this model is not restricted to the auditory model, nor to language functions. It is thus possible that a similar network could be at play for implicit speech rhythm processing during reading.

Relationship between Implicit Rhythm Sensitivity and Reading Comprehension

The second research question of the present study addressed whether there was a significant correlation between implicit rhythm sensitivity and reading comprehension skill. The reading section of the American College Testing (ACT) was used as a measure of reading comprehension skill. In addition, the English section of the ACT, which is designed to assess the ability to understand the conventions of English (e.g., punctuation, grammar, sentence structure) and rhetorical skills (e.g., organization, style), was collected to control for potential confounds of individual differences in English abilities in the correlation between implicit speech rhythm sensitivity and reading comprehension skills. Despite the high correlation between reading skills and English skills ($r = .81$, $p < .001$), the implicit speech rhythm sensitivity derived from the ERP data was only significantly correlated with reading skills (*r* = .56, *p* = 0.006). Interestingly, this relationship was still approaching significance even after controlling for English skills (*r* = .45, *p* = 0.063). Thus the link between reading skills and speech rhythm sensitivity is unlikely to results from individual differences in general language abilities. However, since the ACT reading subset only focuses on reading comprehension (and to some extent on vocabulary), it should be noted that future studies should seek to determine which components of the reading process (e.g., phonological processing, decoding, fluency, language comprehension) are the most likely affected by speech rhythm sensitivity.

An association between rhythm sensitivity and reading skills is supported by previous studies showing that sensitivity to stress cues in spoken language is relate to early reading acquisition (See Magne & Brock, 2012, for a review). In particular, sensitivity to word stress patterns has been found to be associated with word reading and phonological awareness as well as fluency at the phrase level (e.g., Holliman et al., 2010; Whalley et al., 2006). Likewise, in studies comparing rhythm perception between individuals with dyslexia and a control group, both children and adults with dyslexia showed poorer performances on rhythm perception tasks (Goswami et al., 2002, 2011; Leong et al., 2011; Thomson et al., 2006). Evidence from several studies have suggested that listeners do not pay equal attention to every syllable in spoken utterances, and that stressed syllables may particularly act as attentional attractors in the speech stream (e.g., Pitt & Samuel, 1990). Consequently, a deficit in basic auditory rhythm processing may interfere with attentional processes involved in the proper acquisition of phoneme representations (Goswami, 2011; Hämäläinen et al., 2012).

Together, with the results of the current study, these findings strongly suggest that speech rhythmic sensitivity could provide an early indicator of future reading development and potential reading difficulties. In addition, the fact that such relationship was found in the present study with an adult population suggests that the knowledge about one’s native language rhythm (i.e., implicit speech rhythm) may still play an important role in the reading process in skilled readers.

Limitations and Future Directions

Several limitations regarding the implementation of this study should be considered. The first limitation relates directly to the high sensitivity of the ERP methods to movement artefacts. In particular, eye movements produce electrical currents that are particularly challenging to dissociate from brain electrical activity in the EEG data. As a result, it is common practice in reading experiments using ERPs to present sentences word by word in the middle of a screen, in order to minimize eye movements from the participants. This is the approach that was also adopted in the present study. However, it is important to acknowledge that a word-by-word presentation rate is different than a natural reading situation. Not only reading involves a series of rapid eye movement (i.e., saccades) and fixation from one place to another in the text, but it is also well documented that readers make regressions back to previously read words in approximately 14% of the time, likely when encountering difficulties within the text (Starr & Rayner, 2001). Reading thus involves a dynamics of eye movements that is much more complex than having words being read in succession one after the other. The use of a word-by-word presentation also results in another methodological limitation regarding the inter-stimulus interval (ISI) used between successive words. The present study used a fixed ISI of 500ms, which is much slower than the averaged 200-to-250 ms word fixation time observed in natural reading (Dambacher et al., 2012). In addition, readers do not move their eyes between words with the same time and does not look at each word in a sentence with a regular eye-fixation time, but rather move with a different eye-fixation time. The use of a slower ISI in ERP studies is however necessary to minimize the potential overlap of the ERP components elicited by each word in the sentence. Finally, the use of a regular ISI may generate a temporal regularity, thus creating its own rhythmic pattern that may interplay with the implicit rhythm generated from the stress patterns within the sentences. In order to control for this potential confound, the present study is currently being replicated using a random inter-stimulus interval (ISI), to examine whether the observed facilitating effect of a regular stress pattern on semantic processing still holds even when word presentation is not temporally predictable. Recent developments in the use of simultaneous eye-tracking and EEG methodologies to account for eye movement artifacts in ERP data brings the possibility to address the aforementioned limitations closer to reality.

The second limitation of the study relates to the use of ACT reading scores as reading a comprehension measures. This was skill due to the popularity as a standardized test for measuring reading comprehension skills for college admission. However, it is important to note that the ACT reading test is not designed to evaluate potential deficits in the core elements of reading skills, such as phonemic awareness, phonics, reading fluency, vocabulary, and reading comprehension (NICHD, 2000) nor is it used for diagnosis purposes. Instead, the ACT is administered primarily to measure college readiness of high-school students and its scores are used for admission decision at many U.S. institutions. In addition, it is possible that scores on the ACT could reflect individual differences in general cognitive abilities, such as processing speed, attention and working memory. Working memory, in particular, is a cognitive process that allows to temporarily store and manipulate a limited amount of information during active processing of information (Kane & Engle, 2002), and has been shown to a key factor in reading ability (Daneman & Carpenter, 1980; Brady, 1991). It has also been seen as a key causal factor of developmental dyslexia as well as deficits in many cognitive processes (Jefrries & Everatt, 2004; Loosli, Buschkuehl, Perrig, & Jaeggi, 2012). Future studies using a more comprehension assessment battery of language, reading and cognitive skills would thus help refined which component(s) of reading are more closely linked to implicit rhythm sensitivity.

General Conclusion

Previous studies found a link between sensitivity to speech rhythm in spoken language and reading skills. The findings of the present study expand this literature by providing evidence for such a link even when speech rhythm is not overtly expressed (i.e., implicit). In addition, while the majority of the literature has focused primarily on the role of prosody in the acquisition of accurate phonological representation, the present results are in line with recent studies suggesting that prosody, especially speech rhythm, also plays a critical role during the reading process. The present findings also provide neurophysiological evidence for the Implicit Prosody Hypothesis stating that prosodic information is automatically retrieved during silent reading and may contribute to reading comprehension (Fodor, 1998).

These findings can benefit educational researchers by clarifying the factors that contribute to the development of good reading skills. The results may be of particular interest for researchers seeking to design new assessments and intervention programs, by using EEG as a progress-monitoring tool (e.g., Lemons, Key, Fuchs, Yoder, Fuchs, Compton, Williams, & Bouton, 2010). The cognitive neuroscience techniques, including ERPs, are expected to contribute to measuring the complex nature of implicit prosody that encompasses multiple facets that interact with several linguistic levels, as well as to provide a key information in an individual's reading profile in educational settings. Moreover, the findings of the present study may lead to new insights regarding potential neural markers that would be quite useful in the study of disorders of reading acquisition as well as provide a scientific background for future intervention study. Of particular interested for the latter, a growing literature has demonstrated the link between sensitivity to speech rhythm and musical rhythm ability (e.g., Anvari, Trainor, Woodside, & Levy, 2002; Magne et al., 2016; Marie et al., 2011), as well as between reading difficulty and deficits in processing musical rhythm from childhood to adulthood (e.g., Huss et al., 2011). Kotz and Schwartze (2010) argued that such an overlap between musical rhythm and speech rhythm skills might be possible due to the existence of a shared subcortico-cortical network that functions for timing and beat perception, in both music and language. It is thus not surprising that a few recent longitudinal studies with poor readers randomly assigned to music instruction have outlined the possible benefit of music instruction for the development of reading-related skills (See Gordon, Fehd, & McCandliss, 2015; Fujioka, Ross, Kakigi, Pantev, & Trainor, 2006, for a review).

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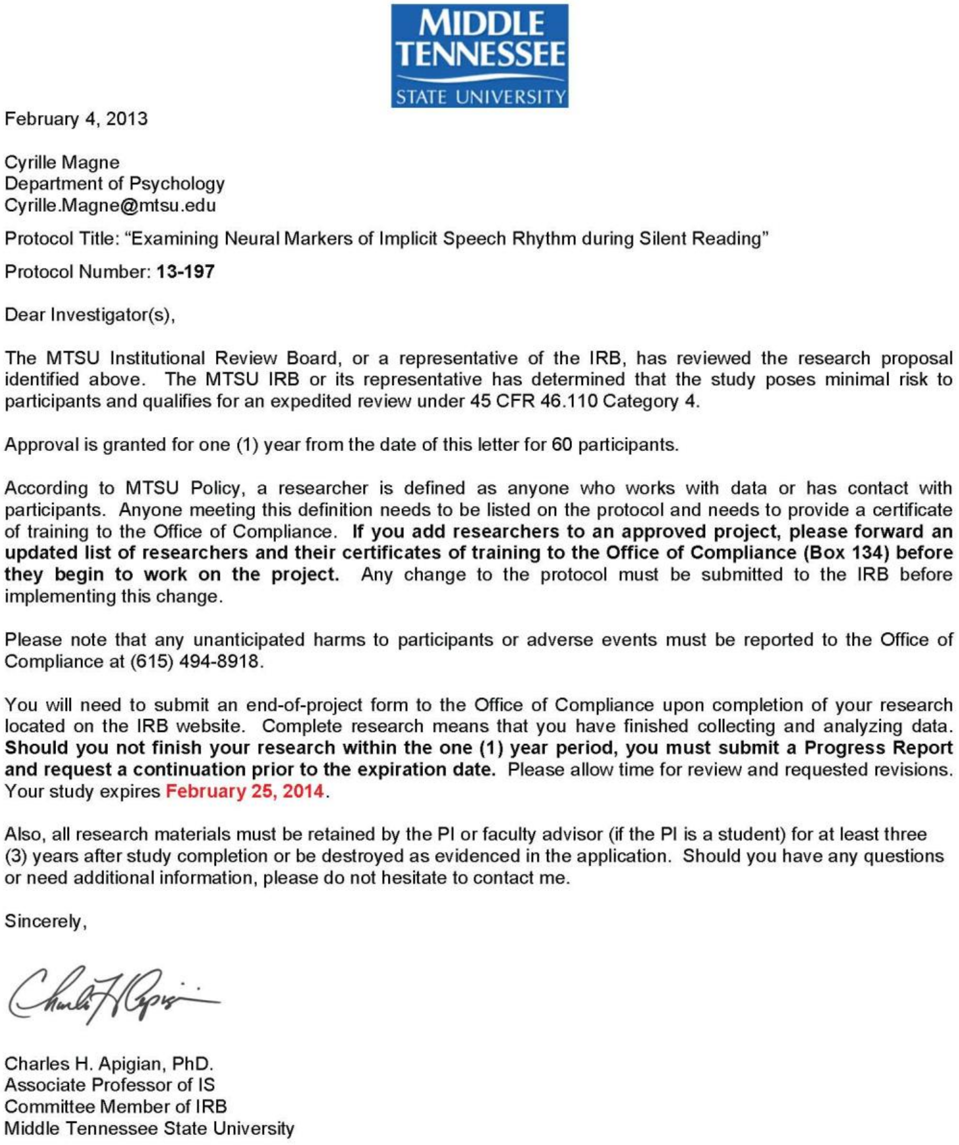
APPENDICES

APPENDIX A

IRB Approval Letter and Consent Form



MIDDLE
TENNESSEE
STATE UNIVERSITY

February 4, 2013

Cyrille Magne
Department of Psychology
Cyrille.Magne@mtsu.edu

Protocol Title: "Examining Neural Markers of Implicit Speech Rhythm during Silent Reading"

Protocol Number: **13-197**

Dear Investigator(s),

The MTSU Institutional Review Board, or a representative of the IRB, has reviewed the research proposal identified above. The MTSU IRB or its representative has determined that the study poses minimal risk to participants and qualifies for an expedited review under 45 CFR 46.110 Category 4.

Approval is granted for one (1) year from the date of this letter for 60 participants.

According to MTSU Policy, a researcher is defined as anyone who works with data or has contact with participants. Anyone meeting this definition needs to be listed on the protocol and needs to provide a certificate of training to the Office of Compliance. **If you add researchers to an approved project, please forward an updated list of researchers and their certificates of training to the Office of Compliance (Box 134) before they begin to work on the project.** Any change to the protocol must be submitted to the IRB before implementing this change.

Please note that any unanticipated harms to participants or adverse events must be reported to the Office of Compliance at (615) 494-8918.

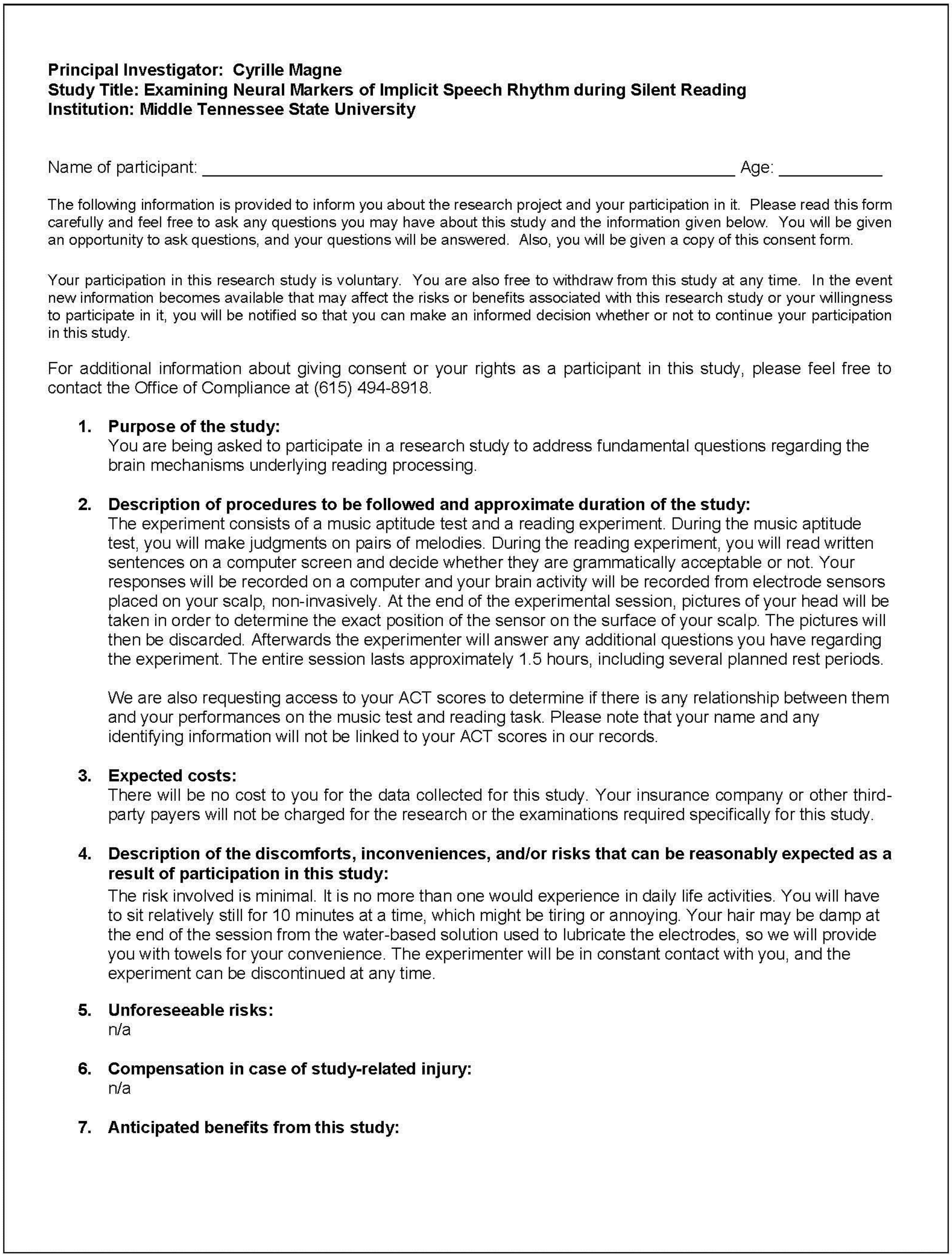
You will need to submit an end-of-project form to the Office of Compliance upon completion of your research located on the IRB website. Complete research means that you have finished collecting and analyzing data. **Should you not finish your research within the one (1) year period, you must submit a Progress Report and request a continuation prior to the expiration date.** Please allow time for review and requested revisions. Your study expires **February 25, 2014**.

Also, all research materials must be retained by the PI or faculty advisor (if the PI is a student) for at least three (3) years after study completion or be destroyed as evidenced in the application. Should you have any questions or need additional information, please do not hesitate to contact me.

Sincerely,

Charles H. Apigian, PhD.
Associate Professor of IS
Committee Member of IRB
Middle Tennessee State University

Informed Consent Form



Principal Investigator: Cyrille Magne
Study Title: Examining Neural Markers of Implicit Speech Rhythm during Silent Reading
Institution: Middle Tennessee State University

Name of participant: ____ Age: _________

The following information is provided to inform you about the research project and your participation in it. Please read this form carefully and feel free to ask any questions you may have about this study and the information given below. You will be given an opportunity to ask questions, and your questions will be answered. Also, you will be given a copy of this consent form.

Your participation in this research study is voluntary. You are also free to withdraw from this study at any time. In the event new information becomes available that may affect the risks or benefits associated with this research study or your willingness to participate in it, you will be notified so that you can make an informed decision whether or not to continue your participation in this study.

For additional information about giving consent or your rights as a participant in this study, please feel free to contact the Office of Compliance at (615) 494-8918.

1. **Purpose of the study:**
   You are being asked to participate in a research study to address fundamental questions regarding the brain mechanisms underlying reading processing.

2. **Description of procedures to be followed and approximate duration of the study:**
   The experiment consists of a music aptitude test and a reading experiment. During the music aptitude test, you will make judgments on pairs of melodies. During the reading experiment, you will read written sentences on a computer screen and decide whether they are grammatically acceptable or not. Your responses will be recorded on a computer and your brain activity will be recorded from electrode sensors placed on your scalp, non-invasively. At the end of the experimental session, pictures of your head will be taken in order to determine the exact position of the sensor on the surface of your scalp. The pictures will then be discarded. Afterwards the experimenter will answer any additional questions you have regarding the experiment. The entire session lasts approximately 1.5 hours, including several planned rest periods.

   We are also requesting access to your ACT scores to determine if there is any relationship between them and your performances on the music test and reading task. Please note that your name and any identifying information will not be linked to your ACT scores in our records.

3. **Expected costs:**
   There will be no cost to you for the data collected for this study. Your insurance company or other third-party payers will not be charged for the research or the examinations required specifically for this study.

4. **Description of the discomforts, inconveniences, and/or risks that can be reasonably expected as a result of participation in this study:**
   The risk involved is minimal. It is no more than one would experience in daily life activities. You will have to sit relatively still for 10 minutes at a time, which might be tiring or annoying. Your hair may be damp at the end of the session from the water-based solution used to lubricate the electrodes, so we will provide you with towels for your convenience. The experimenter will be in constant contact with you, and the experiment can be discontinued at any time.

5. **Unforeseeable risks:**
   n/a

6. **Compensation in case of study-related injury:**
   n/a

7. **Anticipated benefits from this study:**

Middle Tennessee State University Institutional Review Board
Informed Consent Document for Research

This study does not provide you with any health care. The study is strictly for research purposes and will have no direct health or medical benefit to you as an individual. The proposed experiments will enable us to address fundamental questions regarding the brain mechanisms underlying reading processes.

8. **Alternative treatments available:**
n/a

9. **Compensation for participation:**
Your will receive 4 credits for your participation in this study.

10. **Circumstances under which the Principal Investigator may withdraw you from study participation:**
If you are visually impaired, have had psychology or neurological disorders, or are not native speaker of English, you may be withdrawn from participating in the study.

11. **What happens if you choose to withdraw from study participation:**
You may decline to join this study or withdraw from this study at any time without negative consequences; that withdrawal would not in any way affect your standing with the University.

12. **Contact Information.** If you should have any questions about this research study or possibly injury, please feel free to contact Dr. Cyrille Magne at 615-898-5599.

13. **Confidentiality.** All efforts, within reason, will be made to keep the personal information in your research record private but total privacy cannot be promised. Your identity will remain confidential. You will be assigned an ID code, and completed forms will be stored in locked files to which only the Principal Investigator will have access. All computer data files pertaining to you will be accessible by subject ID code only. Your information may be shared with MTSU or the government, such as the Middle Tennessee State University Institutional Review Board, Federal Government Office for Human Research Protections, if you or someone else is in danger or if we are required to do so by law. De-identified version of your behavioral and EEG data will be made publicly available or shared with other researchers for research purpose only.

14. **STATEMENT BY PERSON AGREEING TO PARTICIPATE IN THIS STUDY**
I have read this informed consent document and the material contained in it has been explained to me verbally. I understand each part of the document, all my questions have been answered, and I freely and voluntarily choose to participate in this study.

____________________ ____
Date Signature of patient/volunteer

Consent obtained by:

____________________ ____
Date Signature

____
Printed Name and Title

APPENDIX B

Speech Rhythm Sensitivity Task Sample Sentences

1. Rhythmically Regular & Semantically Expected Sentences
   - Richard strongly challenged Billy′s written **statement** about the accident.
   - Hannah simply bandaged Colin's wounded **shoulder** after his fall.

2. Rhythmically Regular & Semantically Unexpected Sentences
   - Richard strongly challenged Billy′s written **doughnut** about the accident.
   - Hannah simply bandaged Colin's wounded **dinner** after his fall.

3. Rhythmically Irregular & Semantically Expected Sentences
   - Bob angrily challenged Nathaniel′s fierce **statement** about the accident.
   - Don securely bandaged Benjamin's bruised **shoulder** after the collision.

4. Rhythmically Irregular & Semantically Unexpected Sentences
   - Bob angrily challenged Nathaniel′s fierce **doughnut** about the accident.
   - Don securely bandaged Benjamin's bruised **dinner** after the collision.

Note: Stressed syllables are underlined and target words are in **bold**.

APPENDIX C

Electrode Layout on the Scalp