INVESTIGATING SKILLED READING IN SCHOOL-AGED CHILDREN: AN EEG STUDY

by

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ABSTRACT

There exist conceptual gaps between the behavioural and electrophysiological accounts of skilled reading development that limit the ability to interpret them cohesively. The goal of this study was to bridge these gaps and determine how behavioural measures of ortho-semantic learning – skills thought to be involved in the transition to skilled reading – relate to N170 print and lexical tuning, established neurophysiological markers of visual word expertise. Thirty-six grade 3 children completed assessments of ortho-semantic learning. Electroencephalography (EEG) was then used to record their neural activity during a lexical decision task. Group-level EEG data revealed significant bilateral N170 print and lexical tuning effects. The print tuning effect was significantly modulated by orthographic learning, but not by fluency or semantic learning. Lexical tuning was not modulated by any of the behavioural measures of reading. Future research should further investigate these relationships using contrasts of additional conditions and more robust measures of reading skills.

LIST OF ABBREVIATIONS USED

Ortho-semantic	orthographic and semantic
DRC	dual route cascaded model of reading
EEG	electroencephalography
ERP	event-related potential
PMN	phonological mapping negativity
RE	rhyming effect
VWFA	visual word form area
fMRI	functional magnetic resonance imaging
HRM	Halifax regional municipality
HRB	Halifax regional school board
REB	research ethics board
TOWRE-2	Test of Word Reading Efficiency, second edition
CTOPP-2	Comprehensive Test of Phonological Processing, second edition
M-PPVT-3	Modified Peabody Picture Vocabulary Test, third edition
WASI	Wechsler Abbreviated Scale of Intelligence
WISC-4	Wechsler Abbreviated Scale of Intelligence, fourth edition
LDT	lexical decision task
ICA	independent components analysis
GAM	generalized additive mixed-effects

AIC	Akaike information criterion
ROI	region of interest
AMA	adaptive mean amplitude
CI	confidence interval

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CHAPTER 1: INTRODUCTION

Reading is a complex skill that requires the development, recruitment, and synthesis of several cognitive and linguistic processes. Children begin the process of learning to read with no preexisting knowledge of the printed representations of their language. After some basic training and exposure to print, they begin to master basic reading abilities and are able to convert strings of printed letters to words that they have previously learned through spoken language — a stage in reading development called novice reading (Chall, 1996; Fitzgerald & Shanahan, 2000). Arguably the most complex aspect of reading development, however, is the transition from novice to skilled reading, at which time children begin to efficiently and seemingly automatically map printed words to their stored sound and meaning representations in the brain. The transition to skilled reading is considered to be a critical developmental achievement in reading, as it allows children to focus not on the act of reading itself, but instead on the use of reading as a learning tool for fostering new knowledge and gaining new skills (Share, 2004; Pikulski & Chard, 2005; Chall, 1996).

Unfortunately, however, not all children achieve skilled reading. There is well documented individual variability in the speed and extent to which skilled reading is achieved, and this variability is thought to have a range of substantial real-world implications, from academic and vocational success to social integration (Lloyd, 1978; Hernandez, 2011; Cohen et al., 2018). Because skilled reading has such important consequences, many research efforts have been devoted to clarifying its underpinnings and understanding the nature of its development.

Behavioural-psychological research on skilled reading development focuses primarily on the relative contributions of component skills in orthography, phonology, and semantics. Findings in this body of literature suggest that children in the early stages of reading rely on the process of phonemic decoding, which is the process of mapping printed letters to sounds. Children use this strategy to access spoken word forms and ultimately, word meaning. As they continue to develop reading skills, however, the literature suggests that phonemic decoding becomes more automatic, and consequently, children rely less on this process in order to read printed words (Dyer et al., 2003). It is thought that in later reading development, skills in orthographic and semantic learning, or the capacity to learn new written forms and their corresponding meanings, respectively, are more predictive of reading ability than other underlying skills (Share, 2008; Nation & Castles, 2017; Mimeau et al., 2018).

The electrophysiological literature also provides an account of reading development; however, the investigations in this body of literature focus on the underlying neural activity involved in reading, which is indexed by a series event-related potentials (ERPs) — neural signals recorded using electroencephalography (EEG) that correspond to the presentation of a stimulus. The N170 ERP component has been the primary focus of electrophysiological studies of reading development. The N170 shows two different effects in response to printed stimuli: the print tuning effect (i.e., greater neural response to printed words compared to symbols; Bentin et al., 1999) and the lexical tuning effect (i.e., greater neural response to printed consonant strings compared to printed words; Compton et al., 1991; McCandliss et al., 1997). The magnitude and lateralization of these two effects show characteristic changes throughout reading development, and these changes are thought to reflect the development of visual expertise for printed words.

It is clear that although both bodies of literature provide accounts of reading development, these accounts are relatively independent of each other — measuring different skills and reporting different constructs. In order to develop a more in-depth understanding of skilled reading development, the current study aimed to bridge the conceptual gaps between the behavioural and electrophysiological accounts of reading development. Specifically, the goal of this study was to determine how behavioural measures of orthographic and semantic learning — skills thought to be directly involved in the transition to skilled reading — relate to N170 print and lexical tuning, established neurophysiological markers of visual word expertise. In order to do this, thirty-six children in grade 3 completed assessments of the behavioural skills involved in reading, including an adaptation of a well-studied ortho-semantic learning paradigm. Next, EEG was used to record participants' neural activity while they read letter-based and non-letter stimuli on a screen during a lexical decision task. The EEG data was then analyzed in a time window characteristic of the N170, and the mean amplitude and lateralization of the N170 print tuning and lexical tuning effects were examined both at the group level and in relation to individual differences in scores of reading fluency, orthographic learning, and semantic learning. These investigations were conducted in order to answer the following research questions:

1) Are characteristic group-level and fluency-modulated N170 print and lexical tuning effects present in this sample of grade 3 readers?

2) Are the amplitude and lateralization of the N170 print and lexical tuning effects modulated by skills involved in intermediate stages of reading development — specifically orthographic and semantic learning?

In relation to research question 1, I hypothesized that a group-level bilateral print tuning effect would be present in this sample of grade 3 readers. The presence of a group-level lexical tuning effect was exploratory, given reports suggesting that it is later to emerge than print tuning (Maurer, Brandeis, et al., 2005; Posner & McCandliss, 2000). Furthermore, I expected that (1) readers with higher scores of fluency would show larger amplitude, left-lateralized print tuning effects compared to less fluent readers, and (2) readers with higher scores of fluency would show left-lateralized lexical tuning effects, whereas this effect would be absent in less fluent readers.

In relation to research question 2, I predicted readers with higher scores of orthographic learning would show similar patterns of N170 print and lexical tuning amplitude and lateralization to that of readers with higher scores of fluency, reflecting connections between subsystems involved in visual and linguistic processing of orthographic structure. The relationship between semantic learning and N170 effects was exploratory in this study, as learning the meaning of novel orthographic forms requires associations between different cues (e.g., contextual, pragmatic, environmental) and previously stored semantic knowledge — unlike the word-level, visual orthographic and lexical processing indexed by the N170 print and lexical tuning effects, respectively.

Group-level results indicated significant bilateral N170 print tuning and lexical tuning effects. These effects were not significantly modulated by fluency in either hemisphere. Analysis of individual differences in N170 effects and ortho-semantic learning revealed a bilateral orthographic learning-modulated print tuning effect, where children with higher scores of orthographic learning showed larger amplitude print tuning effects than children with lower orthographic learning skills. Orthographic learning did not modulate the lexical tuning effect in either hemisphere. Semantic learning did not modulate the print or lexical tuning effects in the current study.

The findings in this study provide preliminary evidence for novel group-level N170 effects in grade 3 readers (i.e., a bilateral lexical tuning effect), as well for a functional relationship between orthographic learning and the N170 print tuning effect. These preliminary findings serve as a foundation for future studies investigating the relationships between ortho-semantic learning and N170 effects. The body of literature examining these relationships will ultimately help us to maximize our understanding of skilled reading development. This will in turn allow us to work toward the long-term goal of using brain correlates of reading as a tool to identify areas of difficulty in reading for each child so that they can be specifically targeted by intervention or educational techniques, thereby maximizing individual reading abilities and improving academic outcomes.

CHAPTER 2: LITERATURE REVIEW

2.1 READING CHANGES BRAIN ACTIVITY

The ability to read is considered to be a substantial milestone in typical development; however, unlike other developmental milestones, reading is neither automatic nor innate. It is a complex process that requires explicit teaching, repeated exposure, and the recruitment, synthesis, and refinement of many cognitive and linguistic skills. These are reflected by changes in brain activity that can be noted throughout reading development, as the neural pathways involved in reading are re-organized and refined (Maurer, Brem, et al., 2005). Understanding the nature of these changes is important for understanding the corresponding perceptual and cognitive processes that are occurring as reading skills develop.

2.2 UNDERLYING SKILLS INVOLVED IN READING

In order to effectively understand these neurocognitive developmental changes, it is first important to understand the underlying skills that are implicated in the literature. In general, theories of reading development emphasize the importance of three component skills: orthography, phonology, and semantics.

2.2.1 Orthography

Orthography refers to the conventions for writing in a language. It describes and defines the symbols used to translate the individual sounds in a word (phonemes) into written forms (graphemes). Orthography also provides rules for using the written symbols, including the ways in which they can be combined to form acceptable written words, based on the relationships between phonemes and graphemes (spelling; Seidenberg,1992; Donohue, 2007). Furthermore, it addresses the appropriate use of other components of written language such as hyphenation, capitalization, and punctuation — all of which are important for sentence-level orthography (Venezky, 1999). Although the term orthography is typically used to refer to a standardized, prescriptive set of conventions, newer alternative definitions are recognizing orthography as any form of writing in a given language without determination of correct or incorrect, while also acknowledging that the application of orthographic rules has a range of standardization (Sebba, 2007).

2.2.2 Phonology

Phonology refers to the system of speech sounds (phonemes) in a language and the relationships between them. A critical phonological skill that serves as a precursor for reading is *phonological awareness*, which is a child's awareness of the internal sound structures of words and the ability to manipulate this structure, as indicated by the ability to identify syllable onsets and rimes, identify individual phonemes, identify/generate rhyming words, match spoken initial consonants, move/delete/add phonemes within a spoken word, and count the number of phonemes in a spoken word (Stahl & Murray, 1994). Phonological awareness can be measured independently of reading because it neither relies on nor addresses orthographic representations (Dyer et al., 2003).

The ability of relating orthographic to phonological forms is a more complex phonological skill called *phonemic decoding* (also known as phonological decoding) — a process through which speech sounds are mapped onto the orthographic symbols that they represent, and vice versa (Dyer et al., 2003). Unlike phonological awareness, phonemic decoding abilities are thought to emerge with reading acquisition and early reading development; however, these two skills are not completely independent, as phonological decoding clearly relies to some extent on the awareness of phonemes and the ability to identify and manipulate them (Tunmer & Nesdale, 1982). These skills are often reflected in the literature as one factor representing phonological abilities (Dyer et al., 2003; Compton, DeFries, & Olson, 2001; for a detailed review of phonology and reading, see Goswami & Bryant, 2016).

2.2.3 Semantics

Semantics refers to meaning, which is the relationship between words, phrases, sentences, or passages and what they represent. At the word level, orthographic and phonological representations are associated with specific meanings and contexts, which are stored as representations in the *mental lexicon* — a theoretical construct referring to the mental store of an individual's vocabulary and associated semantic information (Thomason, 2012). Semantics is directly associated with reading comprehension, as word meaning is clearly needed in order to both map orthographic and phonological information to a concrete representation of an object, action, concept, etc., and use this fundamental, word-level semantic information to comprehend larger-scale printed messages (i.e., phrases, sentences, discourse).

2.2.4 Additional Factors Contributing to Reading Ability

It should be noted that there are additional cognitive, linguistic, and environmental factors that are known to contribute to reading abilities, such as morphology (word structure; Bryant & Nunes, 2004; Pacton & Deacon, 2008; Nation & Castles, 2007), reading exposure (Cepeda et al., 2006), explicit instruction (Bus & Van Ijzendoorn, 1999; Chall, 1987), writing (Fitzgerald & Shanahan, 2000; Zhang et al., 2011; Kim et al., 2004), and sentence-level syntax and discourse (Nystrand, 2006; Landi et al., 2006); however, these skills are outside the scope of this study, and were not addressed in the experimental design.

2.3 STAGE MODELS OF READING DEVELOPMENT

In an effort to understand the relative contributions of orthography, phonology, and semantics throughout reading development, many experts have characterized the related patterns of change as developmental stages (Frith, 1985; Chall, 1996; Wolf, 2008; Ehri, 1991; Gunning, 2010), which allows for a more structured conceptualization of this complex, dynamic process. The term "stages" is used with a caveat in the reading literature, however, as the development of reading-related skills is thought to be continuous and overlapping (Chall, 1996) with individual variability in the timing and extent to which different skills are achieved (Oulette & van Daal, 2017) — qualities that do not fit the typical implications of the term (i.e., patterns that are discrete and sequential).

Although this inherent variability is reflected in the different stage models of reading (e.g., specific verbiage, number of stages, approximate ages of skill acquisition), the overarching patterns of change are consistent across models and can be subsumed under the following classifications: pre-reading; early and novice reading; and skilled reading.

2.3.1. Pre-Reading

The term *pre-reading* encompasses the stages of reading development that typically occur from birth to six years (Chall, 1996; Wolf, 2008), during which time children with no preexisting literacy skills begin to develop oral vocabulary (i.e., stored phonological and semantic representations of spoken words in the mental lexicon), as well as phonological awareness and emergent literacy (i.e., a basic awareness and knowledge of print). It should be acknowledged that although the label “pre-reading” is commonly used in the reading literature, this terminology does not take into consideration individuals of any age who do not develop literacy skills, given that reading is not an innate developmental process. These individuals are sometimes differentiated in the literature as *non-readers.*

2.3.1.1 The Importance of Spoken Language

Pre-reading children form early whole-word phonological and semantic representations for hundreds of words through exposure to spoken language. They learn to apply this knowledge in order to interact with their environments (e.g., labeling, requesting, commenting; Roth et al., 2006), thereby developing a basic understanding of the fundamental importance and purpose of language. Spoken word knowledge and the development of early oral vocabulary are thought to play important roles in the early stages of learning to read (Frost, 1998).

Spoken language also facilitates the development of phonological awareness in pre-reading children. They begin to understand that individual sounds (e.g., learning and reciting the alphabet) comprise the internal structure of the whole-word phonological units previously stored in the mental lexicon (Hu, 2003; Studdert-Kennedy & Goodell, 1995; Walley, 1993). They learn to manipulate these phonemes through a number of different activities involving spoken language, such as generating rhyming word pairs (e.g., *dog – frog)*, experimenting with alliteration (e.g., *little lizards leaping*), and isolating sounds in spoken words (e.g., recognizing that *mommy* starts with */m/*; Roth et al., 2006; Bryant et al. 1990). The development of phonological awareness is pivotal, as this skill is considered to be the foundation for later-developing grapheme-phoneme associations (Chall, 1996; Ziegler & Goswami, 2005), which ultimately facilitates early spelling and word reading (Fitzgerald & Shanahan, 2000).

2.3.1.2 Emergent Literacy

In addition to spoken language, children also rely on early exposure to print in order to develop emergent literacy skills. Emergent literacy constitutes a basic awareness and knowledge of print without any true knowledge of individual orthographic forms (Children's Literacy Initiative, 2017). Through continuous print exposure, children begin to recognize, very rudimentarily, that these written forms represent spoken language. As such, they begin to show an interest in books, reading, and listening to others read — an emergent literacy skill referred to as print motivation (Neumann et al., 2013). Through observation, instruction, and experimentation, children begin to strengthen their print concepts. They begin to hold and manipulate books correctly and understand that written language is organized in a specific direction (e.g., left to right in English and many other languages). They may pretend to read while observing the pages of a familiar book, or even retell familiar stories from memory while turning and scanning the pages. These emergent literacy skills have all been recognized as important contributors to later reading success (Nichols et al., 2004; Campbell, 1998).

2.3.2 Early and Novice Reading

Early and novice reading capture the stages of development that are thought to occur between six and eight (Chall, 1996) or nine (Wolf, 2008) years of age. They signify the initial acquisition and development of basic, low-level reading abilities. The transition from emergent literacy to early reading (also referred to as conventional reading; Sulzby, 1992; Riley, 1995) is achieved as children begin to encode printed letters as a very specific class of visual input and convert this input into conceptual linguistic representations (Perfetti & Liu, 2005). In other words, early readers begin to recognize orthographic forms as representations of the words learned through spoken language, and proceed to map these representations to their stored phonological and semantic information. In the early stages of reading, it is thought that children learn novel orthographic forms via two different modalities: *sight word reading* and *phonemic decoding*.

2.3.2.1 Sight Word Reading

Sight word reading describes the process through which children learn the orthographic representation of a word as whole unit, either by forming associations between the visual features of the word and its meaning (e.g., associating the tail of the letter *g* in the word *dog* as a visual cue representing a dog's tail; Gough & Hillinger, 1980; Rieben & Perfetti, 2013), or simply by committing the whole-word orthographic form to memory through repeated pairing of its visual and auditory representations (Huo & Wang, 2017). Sight word reading is considered to be an effective strategy in the early stages of learning to read because children are typically only exposed to a small number of written words — the majority of which are regular and high frequency (e.g., animal names, common objects; Kear & Gladhart, 1983). Sight word reading allows children to rapidly access the meanings of a small subset of written words through unique associations between print and phonology/semantics without needing to apply grapheme-phoneme correspondences.

Sight word reading is also important for learning the orthographic representations of irregular words, or words that do not have typical orthographic-to-phonological mappings (e.g., *pint*, *yacht*). Irregular words require the reader to have some form of exposure to and/or instruction of its spoken form in order to map the whole-word orthographic code directly to its phonological and semantic codes. Because the typical relationship between orthography and phonology is compromised in the case of irregular words (Wang et al., 2013), sight word reading continues to be a necessary strategy for learning novel irregular orthographic forms throughout reading development, even with the development of additional reading-related skills (Ehri, 2005).

With the exception of irregular words, the use of sight word reading as a primary strategy for learning novel orthographic forms becomes increasingly insufficient throughout reading development, as the number of novel printed words to which children are exposed increases rapidly (e.g., estimates of 10,000 new words per year for an average fifth grader; Nagy & Herman, 1987), and the visual features of these written forms become increasingly less distinct. Furthermore, children also begin to encounter words in text that they have never heard before: novel letter strings for which they have no preexisting phonological or semantic representations. As such, children must adopt a more systematic, generalizable strategy in order to learn both the meanings and spelling patterns of new words (Ricketts et al., 2011).

2.3.2.2 Phonemic Decoding

A more systematic strategy for reading that early readers are thought to develop is phonemic decoding: a child's ability to use grapheme-phoneme correspondences to decode unfamiliar orthographic forms into spoken forms, and then apply their knowledge of the spoken word form to access its meaning – ultimately giving them access to the hundreds or even thousands of words stored in their mental lexicons (Share, 1995). Phonemic decoding also allows children to learn novel orthographic forms for which they have no existing phonological or semantic representations; however, in this case, the word's meaning must be derived from context (e.g., pictures, surrounding written words and sentences, environmental cues, pragmatic cues) or explicit instruction. Although it is more generalizable than sight word reading, phonemic decoding is thought to be cognitively laborious, and consequently, the early use of this strategy as a primary reading mechanism is generally slow and inefficient (Oulette & van Daal, 2017).

2.3.2.3 Novice Readers

As children continue to gain experience with written and spoken language, they begin to read more fluently and efficiently by consolidating the skills that they have developed throughout early reading (i.e., sight word vocabulary, grapheme-phoneme correspondences, phonemic decoding, use of context). At this stage, children are considered to be novice readers: readers that have mastered basic low-level reading skills, and that possess different strategies for reading that can be integrated as needed. In the literature, novice readers are described as becoming 'unglued from print' (Chall, 1996), as their decoding skills become stronger and the process of decoding a novel orthographic form and accessing its meaning is less overt and effortful. Ungluing from print allows readers to focus less on decoding the letters and more on meaning and context (Fitzgerald & Shanahan, 2000).

2.3.3 Skilled Reading

At approximately eight or nine years of age (Chall, 1996), children begin to develop more skilled reading, which is characterized by a reader's fluency (speed and accuracy of reading) and comprehension (the ability to understand the meaning of what is read; Pikulski & Chard, 2005). Skilled reading can be described as the effortless, accurate recognition of an orthographic representation (Share, 2004), and the efficient, rapid mapping of this representation to its meaning and phonology (Pikulski & Chard, 2005; Nation & Snowling, 1998; Deacon, 2015).

Skilled readers are able to efficiently and seemingly automatically recognize visual word forms and access their meanings without the need for conscious grapheme-phoneme correspondence — reflecting a more robust form of sight word reading. The comparatively effortless nature of skilled reading allows the reader to focus not on the act of reading itself, but instead on the use of reading as a learning tool for fostering new knowledge and new skills. Skilled reading continues to mature into adolescence and adulthood, as the complexity and breadth of the texts that are read increases (e.g., expository and narrative texts, texts with multiple viewpoints), and the purpose of reading becomes highly individualized and integrated into daily life (Chall, 1996).

2.4 THE DUAL ROUTE MODEL OF READING

It is clear that within the stage models of reading, each stage is characterized by changes in the mechanisms recruited for written word processing. Another prominent model of reading called the dual route model (Coltheart, 2001), offers an alternative yet complementary conceptualization of these mechanisms — one that is more continuous and word-specific.

According to the dual route model, there are two separate yet interactive routes that develop over time and facilitate the process of reading. One route is called the *direct route* (also described as the lexical route), through which words are read via direct access to their orthographic (spelling), phonological (pronunciation), and semantic (meaning) representations already stored in the mental lexicon. The second route is referred to as the *indirect route* (also described as the non-lexical route) — a less efficient system that requires grapheme-phoneme conversion with no initial reference to the mental lexicon (Coltheart et al., 2001; Dien, 2009).

Reading via the direct route requires activation of word-specific representations (orthographic, phonological, and semantic) stored in memory. As such, all familiar words, both regular and irregular, can be processed through this route, as they are all stored in the mental lexicon. On the other hand, unfamiliar written words are unable to be processed through this route because they do not have stored lexical representations (Rapcsak et al., 2007). These unfamiliar words must be processed through the indirect route, which does not require whole-word representations, but instead processes written words via grapheme-phoneme correspondence rules. The indirect route is able to process any letter strings that follow these correspondence rules (e.g., unfamiliar regular words, or even non-words such as *frod*); however, it is unable to process irregular words, as they are in violation of these rules and would be read via this route with regularization errors (e.g., *yacht* read as a rhyming word for *matched*; Sheriston, 2016).

So, within the context of this framework, children in the early stages of reading development who have limited exposure to a small subset of written words, rely primarily on the indirect route for written word processing. They must use written-to-spoken language conversion rules to establish knowledge of new orthographic forms and their corresponding representations, which allows them to expand their mental lexicons and store this information for future access. Children with more experience and exposure to written word forms are thought to rely less on decoding, as they have established representations for many more words in their mental lexicons and are able to process written words via the direct route — the mechanism that constitutes skilled reading (Sheriston, 2016).

2.5 REAL WORLD IMPLICATIONS OF SKILLED READING

It is well-acknowledged that skilled reading is important for academic achievement, professional success, and social integration (Lloyd, 1978; Hernandez, 2011; Cohen et al., 2018). Unfortunately, however, there is a substantial amount of documented individual variability in the ease and speed with which skilled reading is achieved (Cohen et al., 2018), and critically, some children never achieve skilled reading (Juel, 1988). This spectrum of reading abilities has substantial real-world implications.

One longitudinal study (N = 4000) reported that students who did not read skillfully by the third grade were four times more likely to leave school without a diploma than skilled readers (Hernandez, 2011). An additional longitudinal study concluded that children who did not achieve skilled reading by grade 3 showed decreased levels of college enrolment and vocational achievement (Lesnick et al., 2010). Studies have also shown that children who are slower to develop reading skills lag behind academically even when other cognitive abilities are comparable to same-aged peers (Gabrieli et al., 2011; Chall et al., 1990), and demographic characteristics are included as controls (Lesnick et al., 2010).

2.6 THE TRANSITION TO SKILLED READING

This variability in skilled reading acquisition certainly reiterates the need to understand the nature of its development. Although the stage and dual route models of reading offer useful accounts of larger-scale developmental changes (i.e., the transition from a reading mechanism that is primarily reliant on alphabet decoding, to one that recognizes words rapidly and holistically; Rack et al., 1994; Nation & Castles, 2017), they fall short in describing the skills that drive these changes (Quinn et al., 2017; Rack et al., 1994; Nation & Snowling, 1998; Deacon, 2015). As such, the central question that remains is *how* novice readers transition to a more efficient, seemingly automatic system of word recognition and comprehension. In other words, which underlying skills facilitate the transition to skilled reading?

Although relatively unaccounted for in the general models of reading, the ambiguity of this transition is certainly not for lack of investigation. The nature of these neurocognitive changes has been a topic of debate among reading researchers for several decades. As a result, a substantial body of research has developed that is specifically committed to investigating the skills that contribute to the development of skilled reading.

2.7 THEORIES OF SKILLED READING DEVELOPMENT

2.7.1 The Self-Teaching Hypothesis

The self-teaching hypothesis (Share, 1995) is a prominent theory of reading development that emphasizes the importance of phonemic decoding in successful word reading through its role in forming new orthographic representations; a process called *orthographic learning* (Share, 2008). This theory proposes that by engaging in phonological decoding, children consequently teach themselves unique orthographic representations via print-to-sound translation (Conners et al., 2011), while simultaneously accumulating knowledge about the rule-based orthography of the language (e.g., regularities, exceptions, and conventions; Nation & Castles, 2017).

For each successfully decoded orthographic representation, there is an opportunity for direct connections to be formed between the orthographic and spoken representations of the word (Nation & Castles, 2017; Nation et al., 2007), and it is through these connections that the orthographic lexicon is formed. The stored representations then become accessible for when these same orthographic forms are encountered in the future, which results in a more direct route to word reading (Oulette & van Daal, 2017), consistent with the dual-route model of reading. Through continued exposure to and experience with printed language, and as readers continue to decode and store new orthographic forms, they are thought to be able to store longer, more detailed orthographic representations, reducing the need for explicit phoneme-grapheme conversions (Share, 2004; Oulette & van Daal, 2017) — a concept that is been supported by other theories of reading (Ehri 2005; Ehri 2014; Perfetti & Hart, 2002; Rack et al., 1994).

2.7.1.1 The Role of Context and Meaning

Context is also thought to be important when an unfamiliar orthographic form is encountered, according to Share’s hypothesis (Share, 1995; Nation & Castles, 2017). When a novel orthographic form — one for which the reader has no preexisting phonological or semantic associations — is encountered in a particular context, the word’s semantic information can often be determined using the surrounding semantic, syntactic, or pragmatic information (Cain et al., 2003; Ricketts et al., 2011). This process is called *semantic learning*. Studies have shown that scores on assessments of reading comprehension (Swanborn & de Glopper, 2002) and existing vocabulary (Cain et al., 2004; Ewers & Brownson, 1999) significantly predict a child's semantic learning, or their ability to determine the meaning of new words from context based on their ability to accurately read, understand, and make use of the information to learn the new words.

The effects of context on orthographic learning have been variable in the literature, however — with some studies concluding that it supports word reading (Archer & Bryant, 2001; Nation & Snowling, 1998), others reporting no effect of context (Cunningham, 2006; Ricketts et al., 2008), and some even finding reduced orthographic learning for words learned in context (Landi et al., 2006; Stuart et al., 2000). This variability is thought to be related to reading ability. Landi and colleagues (2006) reported that children with lower levels of reading ability (measured by oral reading accuracy) showed poorer word retention for novel orthographic forms learned in context compared to those learned in isolation. They attributed this finding to the idea that lower-level readers need to devote more cognitive resources to the orthographic and phonological mappings of a word as they decode it, and context acts as a form of distraction for these resources, resulting in less skilled readers failing to encode the appropriate information about the novel word.

2.7.1.2 Modeling the Self-Teaching Hypothesis

The self-teaching hypothesis has also been investigated using computational models of reading. Computational models add a greater level of precision to data analyses and are useful for manipulating very particular variables to simulate different levels of skill or development (e.g., simulating specific reading disabilities; Nation & Castles, 2017).

One model that has been used to study the self-teaching hypothesis is the Dual-Route Cascaded model (DRC; see Coltheart et al., 2001) — a computational version of the dual-route model based on the information processing system involved in visual word reading (for a detailed review of the neural regions implicated in the DRC, see Dien, 2009; for an additional review of computational models of visual word reading, see Barber & Kutas, 2007). Pritchard and colleagues (2014) modeled the self-teaching mechanism by starting with a functional indirect route and an existing oral vocabulary, then introducing novel written words to be processed by the indirect route. One important finding was that the introduction of context was most beneficial when the attempt to decode phonologically was only partially successful (e.g., for irregular novel words or exceptions to typical orthographic and phonological rules), which supports both the phonological decoding and context components of the self-teaching hypothesis.

2.7.2 The Lexical Quality Hypothesis

Another important theory of reading is called the lexical quality hypothesis (Perfetti & Hart, 2002). Unlike the self-teaching hypothesis, which addresses the acquisition of novel representations, the lexical quality hypothesis focuses on the role of acquired lexical representations in the development of skilled reading — particularly comprehension skills. In the literature (Perfetti & Hart, 2002; Perfetti, 2007), lexical quality refers to the extent to which readers' phonological, orthographic, and semantic representations are precise (e.g., the ability to differentiate *four* vs. *flour*), flexible (e.g., the ability to recognize the synonymy between *late fees* and *fees incurred by failing to* *return the item by the required date*), and efficiently integrated (i.e., easily retrieved from memory stores; for detailed examples, see Perfetti & Hart, 2001; Perfetti & Hart, 2002). Precise, flexible and efficiently integrated representations are described as having high lexical quality.

The lexical quality hypothesis posits that comprehension of a written word is greatly impacted by the lexical quality of its mental representations, whereby individual differences in the quantity and quality of these representations corresponds to individual differences in reading comprehension (Perfetti, 2007). High quality representations minimize confusion about a word's orthographic form, and consequently, its meaning, which leads to faster more automatic processing (i.e., efficient retrieval of the phonological and semantic information corresponding to the orthographic form) and leaves more cognitive resources for comprehension processes (Perfetti, 2007). Low quality representations, on the other hand, result in effortful retrieval, which can jeopardize comprehension through inefficient processing and the simultaneous activation/retrieval of more than one word (Perfetti & Hart, 2002; Mimeau et al., 2018).

The consequences of lexical quality can be well-observed, even in skilled readers, by considering different conditions in which the orthographic, phonological, and/or semantic representations of a word are not precise and well-defined, but instead are ambiguous, irregular, or lack one-to-one mapping (Perfetti & Hart, 2002). For example, reduced lexical quality can occur when one orthographic form represents one phonological form, but has more than one meaning (e.g., *crane*); when one orthographic form represents different phonological forms and consequently different meanings (e.g., *live*); and when two orthographic forms represent a single phonological form, but have two meanings (e.g., *seed* and *cede*; Parfetti & Hart, 2002). These ambiguities can reduce efficiency and speed of processing, which can confound the comprehension of these words.

Given that this phenomenon is present in skilled readers, for novice readers or less skilled readers with fewer high quality representations (e.g., some orthographic/phonological representation of a word, but an inaccurate or absent semantic representation; Perfetti & Hart, 2002), one might assume that this effect would be stronger and more frequent. Indeed, this assumption has been supported by findings in the literature. For example, Perfetti and Hart (2002) presented participants with written stimulus pairs: one real word and one non-word that posed a threat to lexical quality (e.g., *wails*, which has the same phonological representation as *whales* but does not share the same orthographic or semantic information). They asked participants to determine whether the words were related in meaning, and found that less skilled readers took longer to process these pairs and were more likely to confuse the threat with its real-word counterpart (for a review of additional supporting evidence, see Perfetti, 2007).

2.8 STUDIES ON ORTHOGRAPHIC AND SEMANTIC LEARNING

It is evident that a common theme throughout the theories of reading development seems to be the implication of orthographic and semantic learning (commonly referred to as ortho-semantic learning) in the transition to skilled reading (i.e., fluent word reading and comprehension; Oulette & van Daal, 2017; Cunningham, 2006; Ricketts et al., 2011; Bowey & Miller, 2007; Share, 2004; Perfetti & Hart, 2002). As such, it is unsurprising that studies investigating these hypotheses have directed much of their attention to understanding ortho-semantic learning abilities.

2.8.1 Ortho-Semantic Learning Paradigm

Many studies in the literature have implemented different adaptations of a paradigm originally developed and implemented by Share (1999) in order to investigate orthographic learning (Cunningham, 2006; Bowey & Miller, 2007; Ricketts et al., 2011; Tucker et al., 2016; Wang et al., 2011; Mimeau et al., 2018) and semantic learning (Cain et al., 2003; Ricketts et al., 2008; Ricketts et al., 2011) throughout reading development. In this paradigm, children typically read short, four- to five-sentence stories that introduce a novel word (i.e., a string of letters that satisfy typical grapheme-phoneme rules, but for which children have no preexisting orthographic, phonological, or semantic representations; e.g., *kleb*), and then provide some context for the word, such that children can infer its meaning (e.g., *The kleb is used to get juice from oranges*). After reading the stories, children are asked to choose the correct spelling and meaning of these words from four different written-word and picture choices, respectively, serving as a measure of their ability to learn these new orthographic forms and their corresponding meanings.

2.8.2 Ortho-Semantic Learning and Reading Ability

Many studies using adaptations of this paradigm have reported significant correlations between ortho-semantic learning and reading ability. Bowey & Miller (2007) found that orthographic learning scores, as measured by the orthographic choice task described above, were associated with scores of both word reading accuracy and comprehension — a finding that has been supported by several other studies (Cunningham, 2006; Ricketts et al., 2011). Similar conclusions have been drawn with regard to semantic learning, with reports of significant correlations between semantic learning and both reading fluency and comprehension in 8-year-old children (Ricketts et al., 2011), as well as reports of impaired semantic learning for 8- and 9-year-old children with reading comprehension difficulties (Cain et al., 2003; Ricketts et al., 2008).

2.8.3 A Novel Approach

Although these findings provide evidence for a relationship between ortho-semantic learning and reading ability (i.e., word-reading and comprehension), the primary approach of the previous studies was to investigate the *predictors* of ortho-semantic learning, with the thought that if a particular variable accounts for unique variance in orthographic or semantic learning ability, then that variable must be involved in its development (Nation & Castles, 2017). As such, these associations were all reported as zero-order correlations signifying word reading and comprehension as predictors of ortho-semantic learning, but were not addressed in the main findings, as orthographic learning was found to be best predicted by phonemic decoding and orthographic knowledge (Bowey & Miller, 2007; Cunningham, 2006; Ricketts et al., 2011), and semantic learning was most strongly predicted by semantic knowledge (Ricketts et al., 2011).

A recent subset of the literature has further examined the relationship between ortho-semantic learning and reading ability by turning the investigations to the skills that are predicted *by* ortho-semantic learning, which is a novel contribution to the body of literature on skilled reading development. Mimeau and colleagues (2018) used an adaptation of the ortho-semantic learning paradigm to investigate whether individual differences in orthographic and semantic learning predicted differences in word reading (as measured by fluency and accuracy) and comprehension in grade 3 children, while controlling for ortho-semantic knowledge among other reading-related skills. They found that orthographic learning had a direct effect on word reading (congruent with the self-teaching hypothesis) and an indirect effect on comprehension via word reading. Furthermore, they found that semantic learning had a direct effect on reading comprehension (in line with the lexical quality hypothesis), but no direct effect on word reading, contrary to what they had hypothesized.

2.9 LIMITATIONS OF BEHAVIOURAL RESEARCH

Although these findings provide some indication as to the skills that best predict reading outcomes, they are based solely on behavioural assessments and analyses, and do not provide concrete predictions at the neural level (Mechelli et al., 2003). Understanding the neural processes underlying behavioural findings is of particular importance in the case of skilled reading development, as the current body of behavioural literature is clearly still relatively inconclusive in terms of the relative contributions of underlying skills (Deacon et al., 2012; Conrad & Deacon, 2016; Vellutino et al., 1994).

One prominent method of investigating neural processes related to reading is a neurophysiological recording technique called electroencephalography (EEG).

2.10 NEUROPHYSIOLOGICAL MEASUREMENTS OF READING

2.10.1 Electroencephalography

Neuroimaging techniques such as EEG have proven to be effective tools for developing a more precise and detailed understanding of language processing and language development. EEG is sensitive to changes in the electrical current that is generated by the flow of charged particles across the neuronal membrane; specifically, currents from the synaptic excitation of pyramidal dendrites in the cerebral cortex

(Teplan, 2002; Luck, 2005). These weak voltage fluctuations are directly measured in real time using scalp electrodes, and then amplified, offering an electrophysiological measure of neural activity on a millisecond timescale (Maurer & McCandliss, 2007). In raw form, however, EEG signals are difficult to interpret relative to any specific neurocognitive processes, as the signals measured at the scalp are actually the summation of hundreds of individual sources, changing rapidly over time (Luck, 2005). The spatial resolution of EEG data is also limited because the scalp and surrounding tissues directly interfere with the electrical signal, distributing or "smearing" it across the surface of the scalp (Kutas & Federmeier, 2011).

2.10.2 Event-Related Potentials

In order to extract information about EEG responses that are specific to sensory, motor, or cognitive events, it is possible to time- and phase-lock the EEG signals to the event. These waveforms, representing stimulus-specific brain activity, are called event-related potentials (ERPs). ERPs are useful tools in studying neural activity associated with language and reading because they provide excellent temporal resolution, allowing for a quantitative, real-time account of the activity on a millisecond timescale, making it a more precise measure of cognitive processes.

2.10.3 ERP Components

The peaks and troughs of the ERP waveforms at each electrode can be characterized in terms of components: features of the waveform that have consistent timing, scalp distribution, and polarity, and are associated with a particular cognitive process (Maurer & McCandliss, 2007; Luck, 2005). Conventionally, ERP components are named in terms of their polarity at peak electrodes (i.e., either 'N' denoting negative polarity or ‘P’ denoting positive polarity), as well as a number, which specifies the typical latency of the peak amplitude of the waveform in milliseconds (e.g., ‘400’ denoting a consistent peak around 400 ms; Dien, 2009). An additional label is also included in many cases, denoting the general electrode site where the ERP component amplitude is largest (e.g., fronto-temporal; Teplan, 2002; Maurer & McCandliss, 2007).

2.11 ERP INDICES OF WORD READING

ERPs can provide useful insights into the rapid visual word processing involved in reading, in order to better investigate the neural mechanisms involved at different stages of reading development (Sánchez-Vincitore et al., 2017). There are several ERP components associated with reading that all typically occur within the first second after a word is read (Dien, 2009).

2.11.1 The P1

One of the earliest components is called the P1; a positive voltage deflection, greatest over lateral occipital regions, occurring around 100 to 150 ms after a word is read. The P1 is thought to index low-level visual-perceptual processing that occurs prior to the parsing of letters to form complete words (Dien, 2009), and indeed the P1 is not specific to words but is elicited by the onset of any visual stimulus (Luck, 2005). Studies have found that the P1 is sensitive to word length (larger amplitude P1 for longer words; Hauk & Pulvermuller, 2004), and orthographic regularities such as bigram and trigram frequencies (i.e., how often two or three letters occur together) — with larger positive amplitudes found for less frequent letter sequences (Hauk et al., 2006).

2.11.2 The P150

Shortly after the P1, at about 150 ms, is another positive peak called the P150, which is maximal over the vertex — the electrode site over the top of the head. In the neurocognitive literature on reading, the P150 appears to reflect an early, low-level perceptual sensitivity to whole words compared to other non-lexical stimuli, such as object pictures (Schendan et al., 1998) and strings of written symbols (Maurer et al., 2010). It was also found to be sensitive to word frequency (Proverbio et al., 2004). Because of its close temporal proximity to other ERP components indexing reading, the P150 is sometimes considered to be a later portion (later peak latency) of the P1 component (Sereno, 1998), as well as the positive pole of the next closest reading-related component: the N170 (Joyce & Rossion, 2005).

2.11.3 The N170

The N170 is a negative-going deflection, peaking between 150 and 200 (Maurer, Brandeis, et al., 2005) or 250 ms (Brem, 2013) after visual stimulus presentation. It is sometimes referred to in the literature as a subcomponent of the robust visual N1 component, which is typically thought to reflect an early response to visual stimulation and is linked to visual selective attention, visual discrimination processes, and matching new visual stimuli to those previously experienced (Haider et al., 1964; Mangun & Hillyard, 1991; Sur & Sinha, 2009).

Although the N170 is sometimes referred to as N1 in the literature, this component has been found to have its own discrete sensitivities related to different classes of visual stimuli (Maurer, Brandeis, et al., 2005). In the reading literature, there is a substantial body of evidence reporting a left-lateralized (Schendan et al., 1998; Bentin et al., 1999; Brem et al., 2005; Rossion et al., 2003; Maurer, Brandeis, et al., 2005) occipito-temporal negativity that is typically elicited by two different categories of printed stimuli: letter-based and non-letter stimuli. Letter-based stimuli maintain the orthographic characteristics of printed letters. Stimuli in this category include real words (lexically and orthographically valid), non-words (pronounceable letter strings that violate typical orthographic rules and are not lexically valid), pseudo-words (pronounceable letter strings that follow typical orthographic rules but are not lexically valid), and consonant strings (unpronounceable letters strings that violate orthographic rules and are not lexically valid). Non-letter stimuli are typically presented in the form of symbols or symbol strings and are visually and perceptually similar to printed letters in terms of their size and composition, but are easily distinguished from real letters. These are sometimes referred to as false fonts. Contrasting neural responses to these stimuli allows for a more in-depth understanding of the ways in which the visual brain areas support the process of reading (Maurer et al., 2010). Studies using such contrasts in the literature have generally reported two different N170 effects in adult readers: print tuning and lexical tuning.

2.11.3.1 Print Tuning

The term *print tuning* reflects the finding in neurophysiological research that the N170 is sensitive to printed, letter-based stimuli. This tuning is indicated by a larger amplitude N170 for letter strings than for non-letter symbols such as false fonts (Bentin et al., 1999); a finding which has been replicated many times (Brem et al., 2005; Eulitz et al., 2000; Maurer, Brandeis, et al., 2005; Maurer, Brem, et al., 2005; Schendan, et al., 1998; Tarkiainenet al., 1999; Zhang et al., 1997). Some studies also report a larger N170 for all letter-based stimulus types (consonant strings, words, and pseudo-words) compared to non-letter stimuli (shapes, symbols, pseudo-letters or false fonts; Bentin et al., 1999; Simon et al., 2004), expanding the concept of print tuning to a sensitivity to all forms of letter-based stimuli. Print tuning is thought to reflect an efficient, visual-perceptual identification mechanism that is specialized for letter-based printed forms compared to symbols and other stimuli that control for visual features (Maurer, Brandeis, et al., 2005; Maurer, Brem, et al., 2005; Bentin et al., 1999). This perceptual expertise is so automatic in adult skilled readers that it can even be found during tasks involving written words that do not require active reading (Bentin et al., 1999; Eulitz et al., 2000; Maurer et al., 2010).

2.11.3.2 Lexical Tuning

Some studies have also found differential sensitivities of the N170 to orthographic patterns within the different letter-based stimuli. One of the primary findings from such studies is a left-lateralized, larger amplitude N170 for consonant strings than words, with the amplitude in response to pseudo-words falling in between (Compton et al., 1991; McCandliss et al., 1997). This finding is referred to in the literature as lexical tuning — a smaller, less robust effect than print tuning indexing higher-level linguistic processing and specialization (e.g., sensitivity to orthographic regularities; Maurer, Brem, et al., 2005). The lexical tuning effect for pseudo-words is less consistent in the literature, with other studies reporting no significant amplitude difference between words and pseudo-words (Bentin et al., 1999; Wydell et al., 2003; Maurer, Brem, et al., 2005; Hauk et al., 2006) and even the opposite effect, with a larger amplitude for words over pseudo-words (Maurer et al., 2006). There are currently no concrete explanations in the literature as to why this variability exists and what mediates it, other than the suggestion that variability in task requirements across studies might lead to differential results (see Maurer & McCandliss, 2007).

2.11.3.3 Additional Sensitivities of the N170

It should be noted that the N170 is also considered to be an index of perceptual expertise related to other classes of visual stimuli such as faces and objects (Rossion et al., 2000; Hinojosa et al., 2015; Eimer, 2000). The face sensitivity of the N170 is well-researched, primarily through manipulations of facial angles (see the face inversion effect; Jacques et al., 2007), facial race (Vizioli et al., 2010), and emotion (Righart et al., 2008; Blau et al., 2007). Although the N170 elicited in response to faces and objects is also strongest over occipto-temporal areas (for a detailed account of implicated neural regions see McCarthy et al., 1999), it is generally right-lateralized (Rossion & Jacques, 2008), further distinguishing it from the left-lateralized sensitivity to print that is likely related to the left hemisphere dominance for language processing more generally (Dehaene & Cohen, 2011).

2.11.4 The PMN and RE

The N170 is followed by several other components, all of which reflect different aspects of reading and lexical processing. The phonological mapping negativity (PMN), alternatively described as the phonological mismatch negativity, is a negative-going deflection that occurs between 250 ms and 300 ms post stimulus and is typically greatest over fronto-central regions (Desroches et al., 2008; Robson et al., 2017). Connolly and Phillips (1994) concluded that the PMN seems to reflect a process through which perceived words are compared to a phonological template that is developed by preceding context (e.g., sentential context, preceding phonemic context). The PMN is typically investigated by contrasting containing phonemes that are either in violation of phonological expectations (i.e., incongruent with the phonemic and contextual template) or are congruent with phonological expectations (i.e., congruent with phonemic and contextual template) — either in words (Desroches et al., 2008; Newman et al., 2003) or sentences (Connolly et al. 1990). The amplitude of the PMN is found to be larger when the perceived stimulus violates phonological expectations.

Although research investigating the PMN has primarily addressed stimuli presented in the auditory modality, there are several reports of a PMN elicited by visual stimuli (i.e., written words and sentences; Rugg, 1984; Connolly et al., 1995), which also reflects phonological processing and shows a stronger response to written stimuli that violate phonological expectations.

Another ERP component that indexes a different form of phonological processing is the rhyming effect (RE). The RE component is typically elicited when a pair of written words are presented, and a phonemic judgement of rhyme is required (Rugg & Barrett, 1987; Sanquist et al., 1980). It has an onset similar to the PMN, around 250-300 ms after the onset of a target; however, it peaks much later at around 400-450 ms, and is maximally distributed across midline and right tempero-parietal sites. The RE is shown to have a substantially larger amplitude in response to non-rhyming compared to rhyming stimuli (Coch et al., 2005).

2.11.5 The N400

The N400 is arguably the best-studied language- and reading-related ERP component. It is a negative-going deflection peaking around 400 ms after stimulus onset, and is thought to index aspects of lexical semantic processing, or processing involving word meaning (Kutas and Hillyard, 1983). The amplitude of the N400 is larger in response to stimuli that are low frequency (Van Petten & Kutas, 1990), less predictable (Kutas & Hillyard, 1983), and/or semantically anomalous (Kutas and Federmeier, 2011; Lau et al., 2008), suggesting that this component may be modulated by the amount of effort required to access the appropriate lexical representations in long-term memory (Lau et al., 2008) and to integrate this lexical information into the current context held in working memory (for a detailed review, see Kutas & Federmeier, 2011).

2.12 THE N170 AS A BIOMARKER OF READING DEVELOPMENT

Although all of the aforementioned ERP components have their own robust findings in adult studies of reading, the N170 has been the primary component of interest in ERP studies of reading involving children, as its amplitude and lateralization show characteristic patterns of change with age and reading ability, thus offering unique neurobiological insights into the processes involved in reading development.

2.12.1 Print Tuning Evidence

Developmental changes in the N170 amplitude and latency have been documented in a number of studies investigating typical reading development in children. Maurer and colleagues examined the development of N170 print tuning through a series of longitudinal studies. They first assessed pre-reading children in kindergarten (Maurer, Brem, et al., 2005), and then reassessed the same children in second grade (Maurer et al., 2006) and fifth grade (Maurer et al., 2011) — comparing each dataset to adult skilled readers. Among the sample of children at the pre-reading age, the researchers compared those with higher and lower letter knowledge. N170 print tuning was effectively absent (i.e., no difference between responses to words and symbols) in pre-reading kindergarten children with little-to-no letter knowledge, and marginally larger but right-lateralized for those with higher letter knowledge (unlike the strong left-lateralized sensitivity in adult readers). It was noted that the right lateralization seen in the later pre-reading stages may be more reflective of visual familiarity than language processing (i.e., recognition of printed letters as familiar visual stimuli through frequent exposure, rather than direct representations of language which would engage left hemisphere language areas; Maurer, Brem, et al., 2005; Sánchez-Vincitore et al., 2017).

A bilateral print tuning effect emerged in the same children in grade 2, after they had mastered basic reading skills, supporting the idea that the specialization of this effect occurs after the beginning of reading training. It also provides evidence that the effect cannot be explained by general maturation, as this would affect both the sensitivity to words and symbol strings (Maurer et al., 2006). The amplitude of the N170 print tuning effect for children in grade 2 was significantly larger than the amplitude of the effect in the adult population. Furthermore, the amplitude of the N170 distinguished among children within this group of grade 2 readers, wherein the N170 print tuning was stronger (larger amplitude) for fluent readers than less fluent readers, based on behavioural assessments of fluency tested in grade 2 (Maurer et al., 2006).

In grade 5 readers they found a significant N170 print tuning effect for words compared to symbols; however, the print tuning effect in this group was more reflective of the adult effect, as it was found to be left-lateralized and with reduced amplitude compared to grade 2 readers. These results collectively suggest an early developmental peak in the N170 sensitivity to print that becomes reduced and more left-lateralized with increasing age and/or reading development. Further evidence suggests that the print tuning effect is greatest before adolescence (~ 16 years of age), as no difference was found between the amplitudes of adolescent and adult groups (Brem et al., 2006).

These findings suggest that the development of N170 print tuning does not follow the previously hypothesized developmental trajectory (i.e., linear increase in strength throughout development; McCandliss & Noble, 2003; Cohen & Dehaene, 2004), but instead its development is non-linear (an inverted U-shape; Maurer et al., 2006), reflecting an early sensitivity to print that emerges concurrently with early reading development and then decreases with continued learning and experience. These findings have been attributed to the extensive, widespread plasticity within the neural networks recruited during the initial tuning to words, followed by the corresponding fine tuning of this specialization over time as patterns of neural activity are established (Sánchez-Vincitore et al., 2017; Maurer et al., 2007).

2.12.2 Lexical Tuning Evidence

Although the body of literature on the lexical tuning of the N170 is less robust than that of print tuning, there are several reports indicating that it also shows patterns of change throughout reading development — although as previously mentioned, these reports have been variable (McCandliss, 1997) with little explanation provided.

One developmental study (Posner & McCandliss, 2000) investigated N170 lexical tuning in a cross-sectional study of children ages four, seven, and ten (i.e., preschool, first grade, and fourth grade, respectively). They found no N170 lexical tuning effect in children who were initially learning to read (which they considered to be the four- and seven-year-old groups), but reported that the effect began to emerge over posterior left hemisphere regions in 10-year-old children only for words compared to consonant strings (i.e., no effect for pseudo-words and consonant strings), suggesting that the lexical tuning of the N170 in 10-year-old children was emerging but not fully developed. Overall, they concluded that lexical tuning effects emerge gradually with the fine-tuning of visual word processing through reading experience and fluent visual word recognition. This finding is congruent with other studies reporting the emergence of a lexical tuning effect only after the first five years of reading instruction (Maurer, Brem, et al., 2005; Maurer, Brandeis, et al., 2005; Posner & McCandliss, 2000; McCandliss & Noble, 2003).

Zhao and colleagues (2014), found an earlier left hemisphere N170 lexical tuning effect (i.e., larger amplitude for words compared to consonant strings) in seven-year-old German children, but only in those children with high reading ability, as measured by pseudo-word naming — an index of phonemic decoding skill (i.e., the speed and accuracy of phonemic decoding), which they acknowledged was crucial in the early stages of reading acquisition based on Share's (1995) self-teaching hypothesis. They noted that these lexical effects in younger but more skilled readers suggest a stronger influence of reading ability on developmental changes indexed by the N170 than of age on its own.

2.13 THE N170 AND BEHAVIOURAL MEASURES OF READING SKILLS

It is evident, based on the electrophysiological findings discussed above, that changes in N170 amplitude and lateralization throughout reading development index patterns of neural change associated with learning to read; however, these findings are generally reported to reflect a form of experience-driven visual specialization (i.e., expertise) specific to print, with only a few studies investigating the relationships between N170 modulation and reading ability (fluency and comprehension) or — critically — the underlying skills and processes related to reading (i.e., orthography, phonology, and semantics).

Recent electrophysiological work has begun to consider these potential relationships. The most prominent hypothesis arising from this work is the phonological mapping hypothesis (Maurer & McCandliss, 2007), which focuses on progressive left lateralization of N170 print tuning throughout the early and novice stages of reading development and how this relates to the reading ability.

2.13.1 N170 Lateralization: The Phonological Mapping Hypothesis

The phonological mapping hypothesis posits that the shift of the N170 print tuning effect from the right hemisphere to the left occurs when orthographic and phonological subsystems are connected. In other words, the shift is caused by a strengthening of connections between the left hemisphere areas involved in phonological and visual processing through constant pairing during reading acquisition and development (Maurer & McCandliss, 2007; Sánchez-Vincitore et al., 2017).

This hypothesis is in line with findings from previously described studies in both the behavioural and electrophysiological research. For example, within the framework of this hypothesis, the early right lateralization of N170 print tuning found in pre-reading children with some awareness of and exposure to print (Maurer, Brem, et al., 2005) reflects general visual familiarity and expertise, which is processed similarly to other visual stimuli (e.g., faces and objects) in right hemisphere areas. The N170 print tuning then transitions to a bilateral effect as phonological and visual areas are initially paired due to the early dependence on phonemic decoding that is reported in the behavioural literature (i.e., the initial reliance on the indirect route in the dual route model of reading). The gradual shift in children with higher levels of reading to the left-lateralized N170 print tuning seen and in adults represents automatic connections between these areas (i.e., grapheme-to-phoneme automaticity), suggesting less reliance on phonemic decoding and more automatic, efficient mapping between orthography and stored representations (i.e., the direct route of the dual route model).

The phonological mapping hypothesis has implications for N170 lexical tuning as well. It is supported by studies reporting that the left-lateralized lexical tuning to print is absent in early readers and novice readers, and emerges in more skilled readers (as measured by pseudo-word reading speed and accuracy), which suggests again that this left-lateralized effect reflects phoneme-to-grapheme automaticity, fluent visual word processing (Posner & McCandliss, 2000), and corresponding higher-level linguistic processes associated with skilled reading (Zhao et al., 2014) carried out in left hemispheric temporal and frontal brain areas associated with language processing (Petersen and Fiez, 1993; Brem et al., 2006).

2.13.1.1 The Visual Word Form Area

One specific brain area that is considered to be the neural generator of this lateralized effect is the left midfusiform gyrus, which is located in the occipito-temporal cortex and is commonly referred to as the Visual Word Form Area (VWFA; Cohen & Dehaene, 2004). The VWFA was first labeled by Cohen and colleagues (2000), who posited that this area was specifically devoted to the processing of letter strings and could be observed in any literate individual. Polk and Farah (2002) further specified the nature of VWFA activation to printed words, suggesting that the sensitivity of the VWFA to print is not simply one of perceptual familiarity, but is instead reflective of abstract linguistic properties such as orthographic regularity.

The specialization of the VWFA to printed words has been supported by data from both neuroimaging and neuropsychological research. Studies using functional magnetic resonance imaging (fMRI) have reported greater activation for printed words compared to non-linguistic stimuli such as checkerboards (Cohen et al., 2002) and printed digits (Polk et al., 2002), as well as non-lexical stimuli (e.g., consonant stings; Cohen et al., 2002) and spoken words (Dehaene et al., 2002). Reports from neuropsychological studies of individuals with damage to the VWFA offer conclusions congruent with neuroimaging data, in that lesions in the VWFA result in impairments of reading that do not affect writing or auditory word comprehension, and only modestly affect printed numbers (pure alexia; Beversdorf et al., 1997; Leff et al., 2001; Starrfelt & Behrmann, 2011).

In recent years, the specificity of the VWFA has been challenged (Price & Devlin, 2003; 2011; Vogel et al., 2014); however, there is a corresponding body of literature suggesting that the hypothesis still holds — arguing primarily that findings implicating the VWFA in the processing of other non-word stimuli can be explained by its proximity to multimodal processing regions (Cohen & Dehaene, 2004), and does not detract from its critical contribution to visual word recognition (for additional arguments see Dehaene & Cohen, 2011). Despite opposing views on the terminology and concept of VWFA's specialization to print, it is widely acknowledged — even by VWFA supporters — that the process of reading is ultimately not limited to one neural region, but instead involves the recruitment of and connection between a much larger network (for a review see Fiez

& Petersen, 1998; Posner & McCandliss, 2000). This is consistent with the literature reviewed above, noting that there are a series of ERP components associated with different stages of word recognition in reading.

2.14 SUMMARY

The complex process of learning to read skillfully has been addressed in both the behavioural-psychological and neurophysiological fields of research. While both fields continue to refine their accounts of the factors contributing to this process, they do so largely independently of each other — focusing on different constructs, processes, measures, and theories.

In the behavioural literature, reading development is characterized in terms of the relative contributions of orthography, phonology, and semantics. Phonological skills are thought to play an important role in both the initial acquisition of reading and the development of early orthographic representations (Tunmer & Nesdale, 1982; Conrad & Deacon, 2016; Share, 1995; Bowey & Miller, 2007; Cunningham, 2006; Ricketts et al., 2011). As such, many findings in the behavioural research identify phonemic decoding skills and existing orthographic knowledge as the strongest predictors of reading ability in the early stages of reading development (Bowey & Miller, 2007; Ricketts et al., 2011). These findings are congruent with models of reading suggesting an early reliance on grapheme-phoneme correspondences to map visual words to their spoken forms in an effort to access word meaning — a process which is effortful and inefficient, as it employs an indirect route from visual word form recognition to semantics (Coltheart, 2001; Sheriston et al., 2016; Chall, 1996). Skilled reading, on the other hand, is thought to rely more on skills of ortho-semantic learning (Share, 1995) — a child's ability to learn novel orthographic forms and their meanings, which facilitates the encoding of more robust, high-quality lexical representations that can be rapidly and directly accessed during future encounters (Perfetti & Hart, 2002; Coltheart, 2001).

The electrophysiological literature also reports developmental changes corresponding to experience with and exposure to print; however, these changes are primarily characterized as a gradual fine-tuning of neural processes involved in visual expertise and specialization for print. Electrophysiological markers of reading development have been indexed by the amplitude and lateralization of the N170 print tuning (i.e., the contrast of neural activity in response to visual real word and false font stimuli) and lexical tuning (i.e., visual real word and consonant string stimuli) effects.

The print tuning effect is reported to follow a U-shaped developmental trajectory: absent in pre-reading children with no letter knowledge, peaking in novice readers, and gradually decreasing into adolescence and adulthood (Maurer, Brem et al., 2005; Maurer et al., 2006; Maurer et al., 2011) — a trajectory which has been attributed to the initial widespread neural recruitment of basic object recognition processes, followed by the consequent fine-tuning of these pathways as the print recognition mechanism becomes more efficient and specialized (Maurer et al., 2011). The N170 print tuning effect is also thought to shift from right, to bilateral, to left hemisphere lateralization throughout reading development, which according to the phonological mapping hypothesis, reflects the strengthening of connections between left hemisphere regions devoted to visual and phonological processing (i.e., the development of grapheme-phoneme automaticity; Maurer & McCandliss, 2007). The lexical tuning effect, on the other hand, is thought to emerge concurrently with skilled reading over left hemisphere posterior regions, reflecting the fine-tuning of both visual and lexical characteristics of printed words (e.g., orthographic regularities, or common patterns of printed letters).

Evidently, there are conceptual gaps between the accounts of reading development from these two fields that limit the ability to interpret them cohesively. While skilled reading undoubtedly requires some form of visual expertise and specialization to print, the electrophysiological construct of *tuning* is not found in behavioural studies of reading, making it difficult to determine the extent of the relationship between the developmental patterns in N170 print/lexical tuning and the patterns found in the relative contributions of underlying skills noted in the behavioural literature. Similarly, while basic functional relationships have been documented between reading ability and N170 print/lexical tuning amplitude and lateralization in the electrophysiological literature, little is offered by way of investigating the underlying skills that drive these reading-related changes. Even the most prominent hypothesis in the ERP literature linking behavioural measures to changes in N170 characteristics (i.e., the phonological mapping hypothesis) is limited to a description of reading acquisition and early reading development, and does not directly address skilled reading development, nor the corresponding shift in the relative contributions of underlying skills that is evident in the behavioural literature (i.e., the later predictive value of ortho-semantic learning compared to phonemic decoding).

2.15 THE CURRENT STUDY

The goal of the current study was to bridge the conceptual gap between these two bodies of literature by investigating the relationship between behavioural and electrophysiological markers of reading development, in order to develop a more in depth understanding of skilled reading in school-aged children. Specifically, this study aimed to determine how behavioural measures of orthographic and semantic learning — skills thought to be directly involved in the transition to skilled reading — relate to N170 print and lexical tuning, established neurophysiological markers of visual word expertise and higher-level lexical processing of print.

In order to do this, grade 3 participants (aged 8–9 years) first completed a series of behavioural assessments of reading-related skills, including an adaptation of a well-documented ortho-semantic learning paradigm based on the self-teaching hypothesis of skilled reading development (Mimeau et al., 2018). Next, EEG was used to record participants' neural activity while they read letter-based and non-letter stimuli on a screen during a lexical decision task. The ERP data was then analyzed in a time window characteristic of the N170, and the mean amplitude and lateralization of the N170 print tuning (real words versus false font) and lexical tuning (real words versus consonant strings) were examined both at the group level and in relation to individual differences in scores of fluency, orthographic learning, and semantic learning. These investigations were conducted in order to answer the following research questions:

1) Are characteristic group-level and fluency-modulated N170 print and lexical tuning effects present in this sample of grade 3 readers?
2) Are the amplitude and lateralization of the N170 print and lexical tuning effects modulated by skills involved in intermediate stages of reading development — specifically orthographic and semantic learning?

2.16 HYPOTHESES

2.16.1 Research Question 1: Group-Level and Fluency-Modulated Print and Lexical Tuning

Previous ERP research has reported characteristic changes in the group-level N170 print and lexical tuning effects throughout reading development. This research has also provided evidence of individual differences in the N170 effects that are modulated by individual differences in reading fluency. These investigations, however, have included only individuals in kindergarten (Maurer, Brem, et al., 2005), grade 2 (Maurer et al., 2006; Zhao et al., 2014), grade 5 (Maurer et al., 2011), grade 12 (Brem et al., 2006), and into adulthood (Maurer et al., 2011; Brem et al., 2006), with no reports of potential changes unique to the ages and grade levels in between. Understanding differences in reading development in grade 3 readers should be of particular importance, given that grade 3 is considered to be a transitional stage in reading with high variability in reading skills — yet to date, there have been no ERP investigations specific to grade 3 readers. As such, this research serves as a replication-extension of previous group-level and individual difference findings that will offer novel insights into reading development as evidenced by ERP measures.

2.16.1.1 Group-Level N170 Effects

Based on previous group-level findings in the literature, I predicted that there would be a significant difference between the neural activity in response to real words and false font stimuli with a larger mean amplitude in response to real words, reflecting the presence of a group-level N170 print tuning effect in this sample of grade 3 readers. Furthermore, I expected that the group-level print tuning effect would be bilaterally distributed, based on findings by Maurer and colleagues (2006; 2011), who reported a bilateral N170 print tuning effect in grade 2 readers, with group-level left lateralization emerging after additional years of reading experience in grade 5 readers.

The presence of a lexical tuning effect at the group level (i.e., a significant difference between the neural activity in response to real words and consonant strings, with a larger mean amplitude for consonant strings) was more exploratory in the context of this study, as this effect has been known to emerge later than print tuning, with some reports indicating that it is absent until approximately 10 years of age (Maurer, Brem, et al., 2005; Maurer, Brandeis, et al., 2005; Posner & McCandliss, 2000; McCandliss & Noble, 2003).

2.16.1.2 Fluency-Modulated Print and Lexical Tuning

Based on previous findings, I hypothesized that individual differences in reading fluency would modulate individual differences in the print and lexical tuning effects, as reported in the literature throughout reading development. First, I predicted that more fluent readers would show a left-lateralized, reduced amplitude print tuning effect compared to less skilled readers, who would show a larger amplitude print tuning effect that was bilateral (i.e., no significant difference between hemispheres). Although the previous investigation of grade 2 readers revealed that fluency distinguished among this group wherein more fluent readers showed *larger* amplitude N170 print tuning effects, the reports of larger-scale developmental changes in print tuning (i.e., grade 2 readers compared to grade 5 readers; Maurer et al., 2011) suggest that more fluent readers (i.e., grade 5 readers) begin to show more left-lateralized, reduced amplitude print tuning effects compared to less skilled readers (grade 2 readers), reflecting fine-tuning of neural processes involved in visual specialization for print. Given the high variability in reading skills among grade 3 readers and the corresponding range of fluency scores noted in the current study (range of age equivalent scores = 7;6 – 14;0), my hypothesis pertaining to fluency and print tuning was based on these larger-scale changes, suggesting that the variability within the grade 3 sample reflected broader developmental differences in reading ability than the within-group differences noted in grade 2 readers.

Second, I hypothesized that a left-lateralized lexical tuning effect would be present only for readers with higher scores of fluency, and that the lexical tuning effect in readers with lower scores of fluency would be absent. This hypothesis was based on previous reports suggesting that lexical tuning may be more dependent on reading ability than on age alone, as it was found in younger (seven-year-old) readers with higher scores of word reading (Zhao et al., 2014).

2.16.2 Research Question 2: Individual Differences in Ortho-semantic Learning and N170 Effects

This study is the first to relate measures obtained from the well-studied ortho-semantic learning paradigm used in behavioural research to ERP measures of reading development, such as the N170 print and lexical tuning effects. As such, findings related to this research will provide foundational evidence for a relationship (or lack thereof) between the ortho-semantic learning — behavioural measures implicated in the transition to skilled reading development — and N170 ERP effects related to the visual processing of orthographic forms.

2.16.2.1 Orthographic Learning and N170 Effects

I hypothesized that similar to fluency, orthographic learning would also modulate the N170 print and lexical tuning effects.

In terms of print tuning modulation, I expected that readers with higher scores of orthographic learning would show smaller amplitude, left-lateralized print tuning effects than those with lower scores of orthographic learning, who would show a larger amplitude, bilateral print tuning effects — similar to the fluency-modulated findings. This hypothesis was based on the fact that both orthographic learning and N170 print tuning reflect a form of sensitivity to orthographic structure, and so it is likely that a child's ability to recognize and learn novel orthographic structures relies not only on visual expertise for print or the linguistic knowledge of printed orthographic forms, but on the connection between these two complimentary subsystems, and synthesis of the underlying neural processes involved. A smaller, left-lateralized N170 print tuning effect for readers with stronger orthographic learning skills would reflect the neural fine-tuning and strengthening of connections between visual and linguistic subsystems involved in processing orthographic structure, and consequently, novel orthographic forms. Evidently, this finding would serve as an extension of the phonological mapping hypothesis (Maurer & McCandliss, 2007), which emphasizes connections between left-hemisphere visual and linguistic areas involved in printed word decoding.

I also expected that orthographic learning would modulate the N170 lexical tuning effect, whereby this effect would be left-lateralized in readers with higher scores of orthographic learning and absent in readers with lower scores of orthographic learning. This hypothesis was based on the idea that higher-level lexical processing of orthographic forms (i.e., effortless recognition of regularities and exceptions) also requires both visual and linguistic expertise, requiring stronger connections between left-hemisphere language and visual processes.

2.16.2.2 Semantic Learning and N170 Effects

The relationship between semantic learning and N170 print and lexical tuning was exploratory in the current study. I hypothesized that semantic learning might reflect a more advanced development of the direct route, where the meaning of a novel orthographic form is learned via associations between different cues (e.g., contextual, pragmatic, environmental) and previously stored semantic knowledge — unlike the word-level, visual orthographic and lexical processing indexed by the N170 print and lexical tuning effects, respectively.

CHAPTER 3: METHODS

3.1 PARTICIPANTS

Thirty-six native English-speaking children enrolled in grade 3 programs within the Halifax Regional Municipality (HRM) were recruited. Grade 3 was selected because it is the stage of a child's education in which there is a shift from 'learning to read' to 'reading to learn' (Hernandez, 2011). Consequently, it is also the point in a child's reading development where substantial variability is noted in reading fluency/comprehension, as well as phonological, orthographic, and semantic skills. Participants were recruited in the HRM via participant database through Dalhousie's Early Social Development Lab, direct recruitment through public schools within the Halifax Regional School Board (HRSB), and public advertisement. The participant sample consisted of 19 boys and 17 girls (chronological age range = 7;6 – 9;5, mean = 8;9, SD = 0;5, 34 right handed). Although English was the native and dominant language for all children, 10 were enrolled in French immersion programs and five of the children had some exposure to other languages (German, Arabic, Mandarin, or Cantonese). All participants had normal hearing and normal or corrected-to-normal vision, with no reported developmental, neurological, or psychiatric disorders — including reading or other language disorders. Participants and their parents/guardians provided informed assent and consent, respectively, before participating in the study. They were compensated monetarily ($30 + an additional $10 for travel costs), as well as with a certificate of completion. The research protocol was approved by the Dalhousie University Social Sciences and Humanities Research Ethics Board (REB).

3.2 BEHAVIOURAL PROCEDURE AND MEASURES

The study was conducted at the NeuroCognitive Imaging Laboratory in the Life Sciences Centre at Dalhousie University. At the beginning of each session, participants and their parents/guardians were given a written consent form and informed of the study's purpose and procedures, as well as potential risks and benefits. They were given the opportunity to ask any questions that they had about the study. Written informed consent was obtained from participants' parents/guardians, and oral assent was obtained from participants. The study was only conducted if both parent/guardians and children gave consent/assent.

Participants then completed a series of nine behavioural assessments addressing both reading ability directly, and other skills that are thought to contribute to reading ability. This protocol was based on the behavioural testing conducted by Mimeau and colleagues (2018) and lasted approximately 1 hour, 10 minutes. All behavioural assessments were administered manually and are described below in order of the skills that they address. They were administered in the following order for all participants: Test of Word Reading Efficiency, Second Edition (TOWRE-2; Sight Word Efficiency and Phonemic Decoding subtests); Woodcock Reading Mastery Test-Revised (Passage Comprehension subtest); orthographic knowledge task (Mimeau et al., 2018); semantic knowledge task (Mimeau et al., 2018); Wechsler Abbreviated Scale of Intelligence (WASI; Matrix Reasoning subtest); Woodcock Reading Mastery Test-Revised (Word Identification subtest); a modified version of the Peabody Picture Vocabulary Test, Third Edition (M-PPVT-3); Comprehensive Test of Phonological Processing, Second Edition

(C-TOPP-2; Elision subtest); and the Wechsler Abbreviated Scale of Intelligence, Fourth Edition (WISC-4; Digit Span subtest).

3.2.1 Reading Skills

Three standardized tasks were used to assess reading skills. The Sight Word Efficiency subtest of the TOWRE-2 (Torgesen et al. 1999) was administered to assess reading fluency (speed and accuracy). In this task, participants read aloud as many words as they could during a 45-second time interval from a list of words that gradually increased in length and difficulty.

The Word Identification subtest from the Woodcock Reading Mastery Test-Revised (Woodcock, 1998) was used to assess word reading accuracy. This subtest required children to read aloud words of increasing difficulty.

The Passage Comprehension subtest, also from the Woodcock Reading Mastery Test-Revised (Woodcock, 1998), was used as a measure of comprehension of written text. During this task, participants had to silently read sentences or short passages of increasing length and complexity, all of which contained a missing word. Participants were asked to provide an appropriate word to fill the missing blank.

3.2.2 Phonological Skills

The Phonemic Decoding subtest of the TOWRE-2 (Torgesen et al. 1999) and the Elision subtest of the CTOPP-2 (Wagner et al., 1999) were used to assess phonemic skills. The Phonemic Decoding test required participants to read aloud as many non-words as they could in 45 seconds from a list of non-words that contained phonemes seen in the English language. The Elision subtest, a measure of phonological awareness, assessed participants' ability to remove phonological segments from spoken words to form different words. The participants were verbally instructed repeat the original word, and then to remove particular phonemes from that word and generate the new word aloud.

3.2.3 Orthographic Knowledge

A homophone judgment task was used to characterize the participants' existing orthographic knowledge. In this task, participants chose the correct of two alternative spellings for a known word (e.g., *The boy liked to read stories with mysterey/mystery.*), which assessed their whole-word orthographic knowledge. This task was used by Mimeau and colleagues (2018), which they adapted from Olson, Kliegl, Davidson, and Foltz (1985).

3.2.4 Semantic Knowledge

Two tasks were administered to assess semantic knowledge. The first task was a homophone judgment task, in which participants selected the more appropriate of two real words given the context of the sentence (e.g., *The father read a story to his youngest son/sun.*). This task was also used by Mimeau and colleagues (2018) and adapted from Olson, Kliegl, Davidson, and Foltz (1985).

The second task was a modified version of the PPVT-3 (Dunn & Dunn, 2007). Participants were shown four black and white images at a time, and were asked to point to the image that represented a spoken word provided verbally by the experimenter. This modified, 51-item version (1/4 of the original number of stimuli) was validated for children in Grades 1 to 3 by Sparks and Deacon (2015), and similar abbreviated versions have been used in additional previous research (Wang et al. 2009; Pasquarella et al., 2011). The items for the modified version were selected in such a way that the progression of difficulty found in the original test was maintained (see Sparks & Deacon, 2015).

3.2.5 Nonverbal Intelligence

The Matrix Reasoning subtest of the WASI (Wechsler, 1999) was used in order to tap into fluid intelligence and broad visual intelligence, which has been found to correlate with word reading in Grade 3 children (Deacon, Benere, & Castles, 2012). In this task, participants were shown pictures containing incomplete patterns of increasing difficulty. Participants were asked to select the correct piece out of five choices that finished each pattern.

3.2.6 Working Memory

The Digit Span subtest of the WISC-4 was used to assess working memory, as research suggests it is correlated with word reading and reading comprehension in 9-year-old children (Cain, 2007). This subtest required participants to repeat lists of digits, increasing in length, in either the same order as dictated, or in the reverse order.

3.2.7 Measures Excluded in Current Study

It should be noted that the following data was not included in the analysis of the current study: Scores on the WASI, WISC-4, orthographic knowledge task (Mimeau et al., 2018), semantic knowledge task (Mimeau et al., 2018), M-PPVT-3, and Woodcock Word Identification and Passage Comprehension subtests, as well as demographic information such as age, sex, and socio-economic status (SES) and school program (English or French Immersion). The focus of the current study was primarily to investigate the relationship between reading ability, ortho-semantic learning skills, and

N170 ERP characteristics. As such, a more exhaustive analysis should be conducted in the future, including these additional items as predictor variables.

3.3 EEG PROCEDURE AND MEASURES

After completing the behavioural assessments, participants were fitted with the EEG cap (~10-15 minutes) and seated in an electrically shielded, sound attenuating booth. During EEG recording, participants completed a Lexical Decision Task (LDT; described below) containing three blocks, presented on a computer screen in the booth. Before each of the three blocks, participants completed an ortho-semantic learning task (described below), which took approximately 8–10 minutes. During these periods, impedance checks and adjustment of electrodes was also conducted as needed. The EEG session lasted approximately 1 hour and 20 minutes for each participant.

3.3.1 Lexical Decision Task

The LDT was performed by participants during EEG recording, so that ERPs could be derived for each condition presented during the LDT. Following application of the EEG net and the first block of the ortho-semantic learning task, participants completed a short practice block of 10 trials so that they became acquainted with the types of stimuli and methods of response they would be exposed to during the task. The practice trials were supervised by an experimenter to ensure that participants understood the task fully. Following the practice block, the first of three LDT blocks began. Each trial began with a blank grey screen for 2.5 s, followed by a fixation cross in the centre of the screen for 0.5 s. The experimental stimulus (see below) was then presented in white for 1 s and was followed again by a blank screen. Participants then decided whether the stimulus was a word or not by entering *yes* or *no* on a USB numeric mini keypad

(Nexxtech; Barrie, ON). The blank screen was displayed until participants made a yes/no selection to ensure that all trials were matched with a behavioural response. Participants were instructed to consider novel words learned during ortho-semantic learning task as words in the context of the LDT.

3.3.2 LDT Stimuli

The LDT consisted of 5 experimental conditions: real words, non-words, novel words (words presented as target items in the ortho-semantic learning task), consonant strings, and false font (all described below). The experiment contained a total of 198 stimuli (100 real words, 50 novel non-words, 48 novel words, 50 consonant strings, and 50 false font). These stimuli were pseudo-randomly distributed into the 3 experimental blocks, such that equal numbers of items from each condition appeared in each block, and the novel words learned prior to that block were shown in the corresponding LDT block.

3.3.2.1 Real Words

A real word list of single-syllable words was generated using the Children's Printed Word Database (Masterson et al., 2010). This database, generated in the United Kingdom, contains a comprehensive list of vocabulary in reading materials used by 5- to 9-year-old children, along with information regarding critical characteristics of these words for their use as experimental stimuli (for a description of database generation and calculations of word characteristics, see Masterson et al., 2010). Using the information from this database, all real words were controlled for word frequency (frequency per million; range = 103 to 1,880, average = 323.97), word length (range = 3 to 5, average = 3.99, number of phonological neighbours (range = 0-29, average = 12.69) and orthographic neighbours (range = 0 to 17, average = 6.49). Only content words (specific verbs and nouns) were selected.

3.3.2.2 Non-words

The non-words were generated using the same list of 50 real words from the Children's Printed Word Database as discussed above, but replacing either one or two phonemes in the word, such that the modified stimuli were not real words, but were still pronounceable. These non-word stimuli were not learned in previous tasks or assessments, including the ortho-semantic learning task or any of the standardized language assessments.

It should be noted that while typical non-word stimuli are pronounceable letter strings that *violate* orthographic rules and are not lexically valid, the non-words created in this paradigm were more reflective of typical pseudo-words, as they followed typical orthographic rules.

3.3.2.3 Novel Words

The novel words used in the LDT were the novel words used by Mimeau and colleagues (2018) that were learned during the orthographic and semantic learning tasks (described below).

3.3.2.4 Consonant Strings

Consonant strings were generated using a random consonant generator (Reed, n.d.), with strings ranging from 3 to 5 (average = 3.99) — consistent with the qualities of the real word stimuli.

3.3.2.5 False Fonts

False fonts were created based on a protocol developed and implemented by Grossi and Coch (2005). Using Adobe Photoshop Software, the letters from real word stimuli were individually rotated by either 90 or 180 degrees. Additionally, letters that had either vertical or horizontal symmetry (e.g., *u*), were vertically altered (i.e., expanded or diminished) on one side. Overall spatial characteristics of the original letters (i.e., height, width, and inter-letter distance) were maintained for all false font stimuli.

3.3.2.6 Conditions Excluded in Current Study

It should be noted that the non-word and novel word conditions were administered, but were not included in the primary analysis of the current study; however, they were included in a preliminary visualization of between condition differences. The focus of the current study was on the N170 print and lexical tuning effects, which are characterized primarily by contrasts between real words and false font (print tuning), and real words and consonant strings (lexical tuning). An N170 lexical tuning effect has also been elicited in previous studies using contrasts between real words and pseudo-words, and pseudo-words and consonant strings; however, as previously noted, these findings are less consistent and the reasons for this are at present unclear (Bentin et al., 1999; Wydell et al., 2003; Maurer, Brem, et al., 2005; Hauk et al., 2006; Maurer et al., 2006). Furthermore, one of the novel contributions of this study was to add a semantic learning component, through which participants came to associate meaning with one set of pseudo-words. This created the potential that even the pseudo-words in this study for which no new meanings were learned, would be processed differently than in a typical study in which all pseudo-words were meaningless.

3.3.3 Ortho-Semantic Learning Task

3.3.3.1 Adaptations to the Ortho-Semantic Learning Paradigm

The ortho-semantic learning task used in this study (described in detail below) was based on Mimeau and colleagues' (2018) adaptation of the previously described ortho-semantic learning paradigm. A number of additional adaptations were made to their protocol for the current study, which are outlined in the following paragraphs.

The addition of EEG procedures in the current study required certain changes to the overall structure of the paradigm. Whereas Mimeau and colleagues had participants read 12 consecutive stories containing novel words, our paradigm was broken into three blocks to allow LDT trials and EEG recording to be included intermittently. In the current study, participants read eight stories consecutively in each block, reading a total of 24 stories as opposed to the 12 used by Mimeau and colleagues. The additional novel word stimuli in this study ensured that the number of novel word trials needed to obtain reliable ERP waveforms was achieved. It should be noted that the additional 12 stories were already created, and served as an additional set of stimuli in the study by Mimeau and colleagues (2018).

The addition of EEG also resulted in the exclusion of certain ortho-semantic learning post-tests used by Mimeau and colleagues. For example, after reading a set of three stories, Mimeau and colleagues (2018) had participants spell on paper and orally define each of the three novel words they had just learned. Additionally, after participants read all 12 stories, Mimeau and colleagues (2018) conducted a picture matching test of semantic learning, which was a novel contribution to the literature designed to assess a participant's ability to distinguish between the meanings of the 12 novel words (for details regarding this task, see Mimeau et al., 2018). These post-tests were not included in the current study given the time constraints induced by the addition of EEG procedures; however, the current study did include the ortho-semantic choice tasks (described below) that have been used as primary measures of ortho-semantic learning in several adaptations of the ortho-semantic learning paradigm.

Mimeau and colleagues (2018) also accounted for both immediate recall and delayed retention of novel words by conducting the ortho-semantic choice post-tests immediately after the stories were read and again several days later. The current study focused solely on immediate recall in the interest of relating these scores with EEG measures; however, it is noted that future studies should include both immediate retention and delayed recall to obtain more robust measures of ortho-semantic learning.

3.3.3.2 Exposure Phase

During the exposure phase, participants read 8 stories aloud per block (24 stories total). Each story consisted of a short, five-sentence paragraph, presenting one novel word as an invention and providing semantic context by describing/defining the meaning of the non-word. Each story contained four iterations of the novel word it described, and maintained the same general structure: the first sentence introduced the context, character, and problem; the second sentence depicted the action involving the invention and character; the third sentence described the invention's use; the fourth sentence described an action carried out by the character using the invention to interact with the problem; and the fifth sentence described the action between the character and the invention when the problem was solved as a result of the invention. The following paragraph is an example of one of the paragraphs read during the exposure phase:

Diana was looking in her fridge, and there was an orange but no juice. Diana found the kleb. The kleb is used to get juice from oranges. Diana attached the kleb to the orange. When enough juice came out of the orange, Diana put away the kleb.

3.3.3.3 Novel word Stimuli

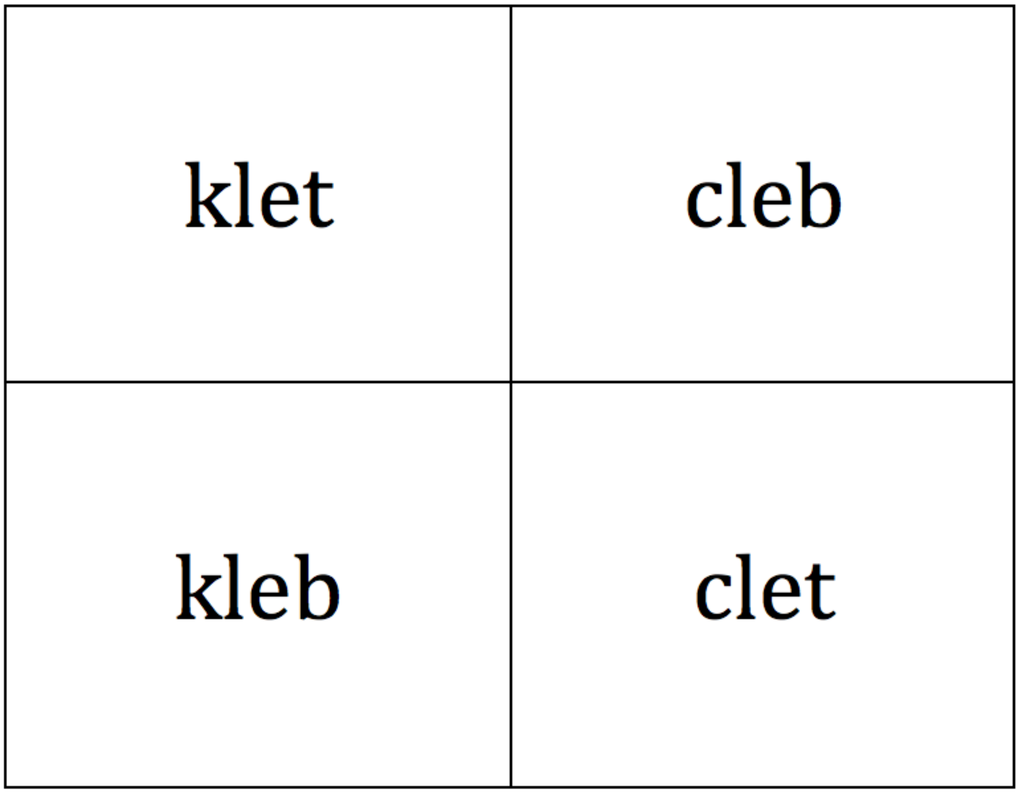
The novel words in the stories represented fictional inventions (e.g., a mechanism to remove juice from oranges). Each novel word was monosyllabic with four letters and contained consonant sounds in the word-initial and word-final positions. Each novel word indicated a target phoneme that was associated with more than one appropriate spelling in English (e.g., target = */i/*, spelling pattern = *ea* or *ee*).

For each of the six target phonemes, there were four pairs of novel words, with two pairs per spelling pattern. Both spelling patterns were used as targets and foils, to control for any bias arising from one of the patterns being used more frequently to represent the phoneme. In each pair, one word was used as the target (the word embedded in the story), and one was used as a homophonic foil during the ortho-semantic choice tasks. Therefore, for each target sound, there were four targets and four homophonic foils.

The novel words were searched in the Children's Printed Word Database (Masterson et al., 2010) to ensure that they did not previously exist in the English language and that children would not have previously had exposure to them. It was ensured that the spelling of each novel word followed a regular grapheme-phoneme correspondence based on rules provided in Rastle and Coltheart (1999).

3.3.3.4 Orthographic Choice Task

After participants read all 8 stories in the block aloud, they were shown four written non-words on a page and asked to identify the correct spelling of the learned non-word that was dictated orally by the experimenter (e.g., “Show me the correct spelling of *clet*”). The three distractors consisted of the homophonic variant of the target (e.g., *klet*), and two non-words that were identical to the target except for either the first or last consonant (e.g., *kleb* and *cleb).* The order of the four items on the page were pre-randomized. An example of the orthographic choice task is shown below in Figure 1.

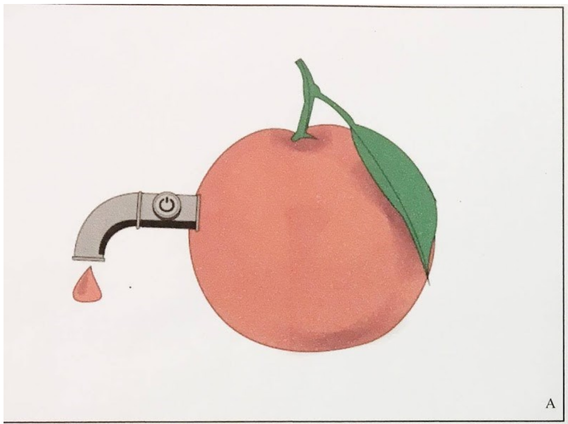


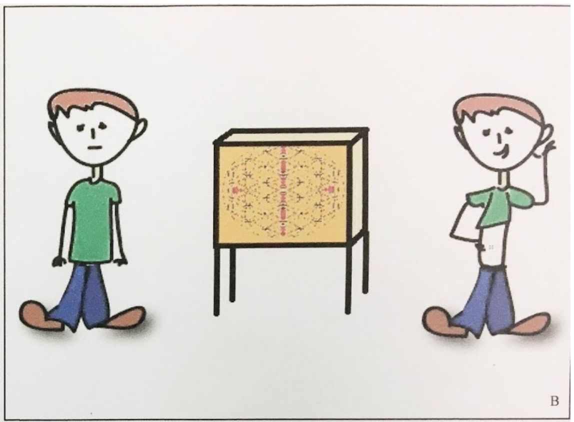
klet	cleb
kleb	clet

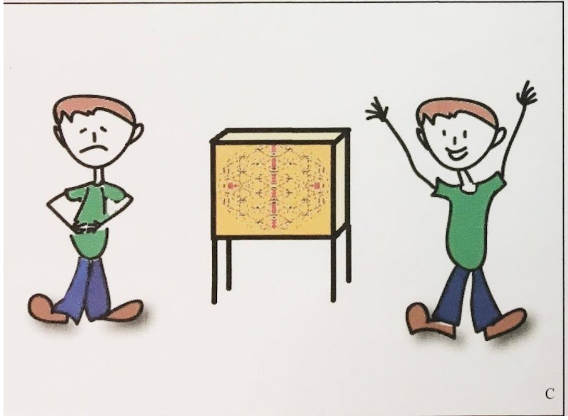
Figure 1 Example Stimuli from Orthographic Choice Task with Target Word Clet.

3.3.3.5 Semantic Choice Task

Following the orthographic choice task, participants were asked to complete a semantic task following the same choice-based format. They were shown four pictures on a page and asked to identify the picture that correctly demonstrated the meaning of the invention that was dictated orally by the experimenter (e.g., “Show me the picture that shows the *clet*”). Again, the order of the items on the page was pre-randomized. One distractor shared some semantic information with the target, depicting an invention involving the same object (e.g., target = *juice remover from oranges*, related distractor = *orange peeler*). The additional two distractors were foils that corresponded to the same unrelated object (e.g., a tummy-ache fixer and a tummy remover for shirts). This example is shown below in Figure 2.







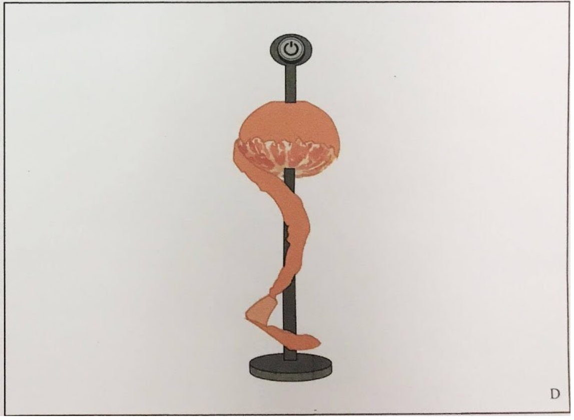


Figure 2 Example Stimuli from Semantic Choice Task with Target Word Clet.

Table 1 provides the complete list of targets novel words and foils, along with the target phonemes they represent. The four novel words that were presented together in both the orthographic and semantic tasks are highlighted in grey and white.

Table 1 Ortho-semantic learning task non-words representing target sounds and their homophonic foils.

Target Sound	**Target Word**	**Homophonic Foil**
/k/	Kleb	Cleb
	Clet	Klet
	Krid	Crid
	Crig	Krig
/o/	Joap	Jope
	Bope	Boap
	Loak	Loke
	Noke	Noak
/e/	Yaif	Yafe
	Vafe	Vaif
	Paib	Pabe
	Zabe	Zaib
/ɝ/	Lerg	Lurg
	Turg	Terg
	Merl	Murl

Target Sound	Target Word	Homophonic Foil
	Burl	Berl
/i/	Veap	Veep
	Feep	Feap
	Seef	Seaf
	Weaf	Weef
/u/	Hewl	Hule
	Zule	Zewl
	Mewd	Mude
	Fude	Fewd

3.4 ERP PREPROCESSING

After recording, the EEG data were exported in binary format and preprocessed using the MNE-python software package (Gramfort et al., 2013; Gramfort et al., 2014). There were several steps involved in the preprocessing procedure for each participant. First, a 0.1 – 40 Hz bandpass filter was applied in order to attenuate frequencies in the data outside of the target range. The continuous data was then visually inspected and any bad channels (i.e., channels containing excessive noise for an extended part of the recording) were identified and removed. After bad channels were removed, ERPs were derived by segmenting the data into epochs, which are segments of the EEG data time-locked to the onset of each stimulus (including 200 ms baseline and 1000 ms post word onset). The segmented data was then visually inspected and trials with excessive noise (e.g., due to head movement) were rejected manually.

Artifact correction was then conducted using Independent Components Analysis (ICA). This technique derives from the fact that the EEG recordings are the sum of many independent sources, including those of neural and non-neural origin. The actual distributions of the multivariate signal are for the most part unknown, as the distributions of these generators may overlap in time and space (Ungureanu, 2004). ICA, which is sometimes referred to as blind signal separation, decomposes the signal into individual components that are considered to be the spatial fixed activations with independent time courses that create the observed signal at the scalp (Makeig et al., 1997; Jung et al., 2000).

ICA decomposition of the ERP data was performed using the Fast ICA algorithm (Hyvärinen, 1999), with the number of components automatically determined to account for 99% of the variance in the data. Scalp distribution, weighting on each epoch, and variance within each epoch were visualized for each independent component, and ocular artifacts along with other visible artifacts were identified and removed by zeroing the weighting of those components in the decomposition matrix. Following this, any electrodes that were manually removed were replaced using spherical spline interpolation. The recordings were then re-referenced to the average of all channels.

3.5 STATISTICAL ANALYSIS

3.5.1 Group-Level Behavioural Data

3.5.1.1 Behavioral Measures

Descriptive statistics for behavioural measures of fluency (TOWRE-2 Sight Word Efficiency subtest), phonemic decoding (TOWRE-2 Phonemic Decoding subtest), orthographic knowledge (orthographic knowledge task), orthographic learning, semantic knowledge (M-PPVT-3), and semantic learning were computed and visualized in order to determine the extent of the variability in these skills across participants. In order to address potential collinearity between these behavioural measures, a correlation matrix was computed containing Pearson's correlation coefficients for the pairwise correlations of all possible pairs. It should be noted that measures of ortho-semantic knowledge and phonemic decoding were included in the correlation analysis not only to investigate collinearity, but to ensure that the relationships between these measures reflected findings documented in the literature; however, as previously mentioned, they were not included in the analysis of the relationships between behavioural and ERP measures.

3.5.1.2 Lexical Decision Task Data

The proportion of correct word/non-word judgments during the lexical decision task was calculated for each condition and for each participant in order to ensure that the participants demonstrated roughly equivalent levels of engagement with the different classes of stimuli.

3.5.2 Group-Level EEG Data

Linear generalized additive mixed-effects (GAM) modeling as implemented by the function *bam*, from the *mgcv* package in R (Version 3.2.1; R Core Team, 2013; Woods, 2006; Newman, et al., 2012; Tremblay & Newman, 2015) was used to investigate the influence of predictor variables Condition (real words, false font, consonant strings, non-words, novel words) and ROI (left and right) on the N170 amplitude in the selected time window. GAM is a non-parametric regression model that has a general additive structure (Woods, 2006). It is an extension of the general linear mixed-effects model that is effective at modeling repeated measures (within subjects and within stimuli) and is well-suited to capturing experimental effects in the non-linear time series, all of which is characteristic of ERP data (Tremblay & Newman, 2015). Linear GAM modeling effectively identifies relationships between independent and dependent variables, while accounting for the unbalanced nature of the trial removals characteristic in the ERP data, as well as the non-sphericity of the data (Newman, et al., 2012), which makes it advantageous over traditional repeated measures ANOVA and AN(C)OVA models. Furthermore, it allows for more effective modeling of random effect variables that represent a nonreproducible sample of the population.

Initially, using linear GAM, the full model was computed. The full model represented the most complex model including all main effects and interactions of the fixed effects variables, as well as random effects (e.g., accounting for unequal variance across hemispheres and participant-specific noise). This model was used to identify and remove outliers in the data (i.e., the data points for which residuals were more than 2.5 standard deviations from the mean). The outliers, accounting for 2.27% of the data, were removed and the full model was updated and recomputed.

Next, a family of models were computed, first for random effects structures and then for fixed effects, in order to determine the optimal model (i.e., the model that accounted for the most variance with the fewest factors and interactions). The family of models included the most complex (e.g., 2 fixed effect variables and a 2-way interaction) and progressively simpler models (e.g., 2 fixed effects variables with no interaction). The optimal model was selected using Akaike Information Criterion (AIC). AIC estimates the relative quality of the models for a dataset. The AIC value for each model represents a weighting of the conditional probability of that model, such that lowest AIC value reflects the optimal model (Wagenmakers & Farrell, 2004). AIC is based on the maximum likelihood estimation technique; however, it better accounts for the trade-off between the quality of the fit and the simplicity of the model (Akaike, 1973).

3.5.3 EEG and Behavioural Data

A family of models was computed including the optimal model described above, as well as models including the addition of fixed-effects predictor variables fluency, semantic learning, and orthographic learning in order to determine the degree of association between N170 amplitude and laterality and behavioural measures of reading. Again, the optimal model in this family of models was selected based on the lowest AIC value.

CHAPTER 4: RESULTS

4.1 BEHAVIOURAL DATA

4.1.1 Behavioural Measures

Descriptive statistics for behavioural measures of fluency, phonemic decoding, orthographic knowledge, orthographic learning, semantic knowledge, and semantic learning are presented in Table 1 below, indicating a range of scores on all behavioural measures. Mean scores on orthographic and semantic learning tasks suggest that participants recognized novel ortho-semantic representations learned in the ortho-semantic learning paradigm and made the appropriate selection for more than half of the items.

Table 2 Descriptive statistics for behavioural measures of fluency, phonemic decoding, orthographic knowledge/learning, and semantic knowledge/learning.

Measure (Maximum Score)	***M***	***SD***	**Range**
Fluency[a]	101.11	13.91	65-128
Phonemic Decoding[a]	103.11	13.68	72-124
Orthographic Knowledge (25)	20.38	3.83	10-25
Orthographic Learning (24)	15.39	2.66	10-22
Semantic Knowledge (51)	34.69	4.60	21-42
Semantic Learning (24)	19.25	2.63	12-24

Note. [a]Age-based standard scores are reported for these measures. Raw scores are reported for all other measures.

4.1.2 Correlation Matrix

The correlation matrix is presented in Figure 3 below, including scatterplots with regression lines for all pairwise correlations. The values in red represent correlations which are significant at $p < .05$. Scores of fluency, phonemic decoding, orthographic knowledge, and orthographic learning were all moderately to strongly positively correlated, with the exception of fluency and orthographic learning, which were weakly correlated ($r = .17$). The strongest correlations were found between fluency and phonemic decoding ($r = .86$), fluency and orthographic knowledge ($r = .72$), and phonemic decoding and orthographic knowledge ($r = .68$). Semantic knowledge and semantic learning showed negligible correlations with all other behavioural measures of reading-related abilities, including with each other.

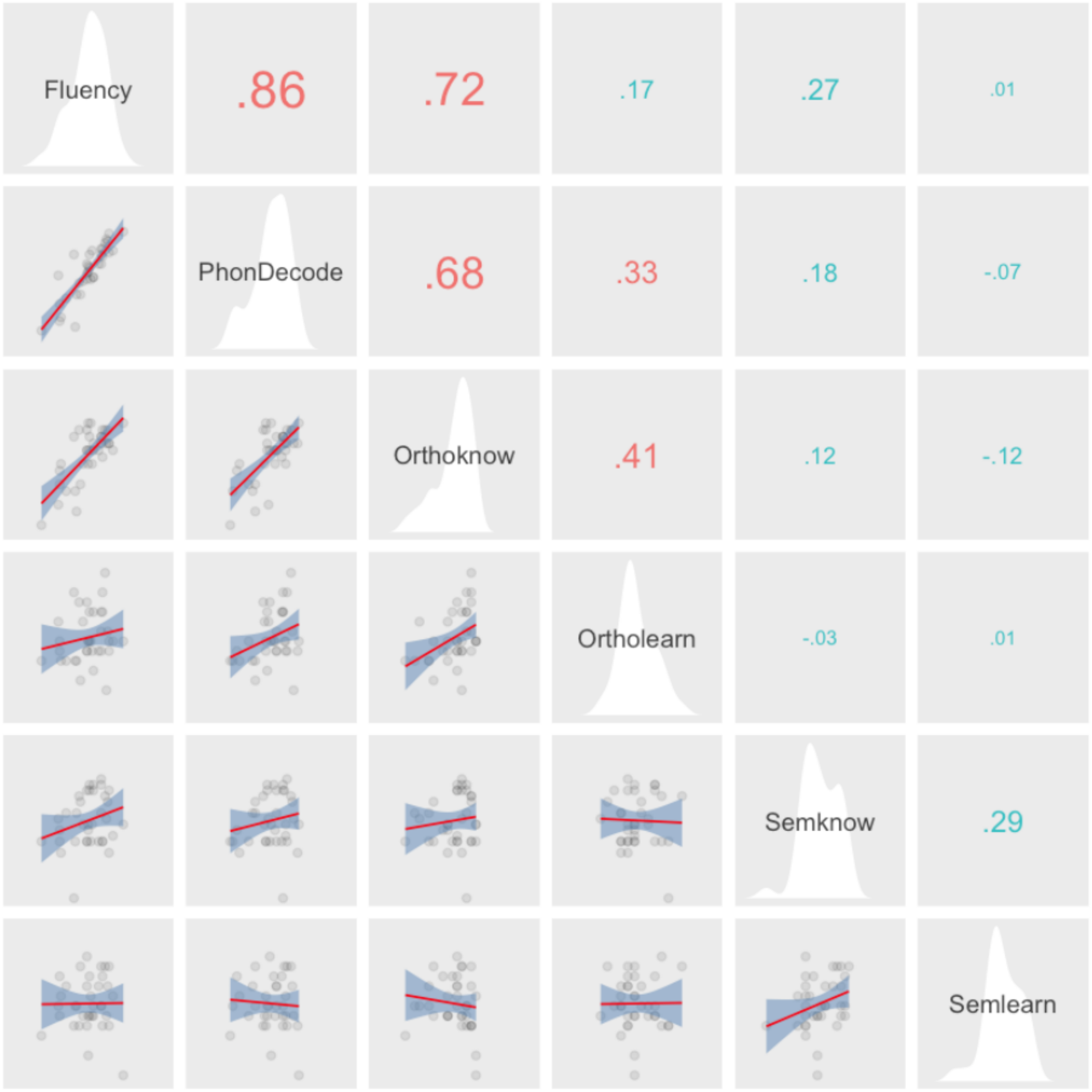


Figure 3 Correlation Matrix containing Pairwise Correlations Between Scores of Fluency, Phonemic Decoding, Orthographic Knowledge/Learning, and Semantic Knowledge/Learning. Correlation values are represented in the top-right section (values in red signify significant correlations at $p < .05$), and the bottom-left section shows scatterplots with linear fits and 95% CIs for each correlation.

4.1.3 Lexical Decision Task

Data from 34 participants were included in the analysis of responses for each condition during the lexical decision task. Data from 2 participants were excluded due to limited response documentation as a result of response pad malfunction. On average, participants correctly identified 91% of consonant strings, 62% of novel words, 92% of real words, 94% of false fonts, and 69% of non-words, indicating that participants were performing the task appropriately and showing adequate levels of engagement for each condition.

4.2 ERP DATA

4.2.1 Group-Level Data

Using the data from all 36 participants, grand average ERP waveforms and scalp voltage topographies were computed and visualized for each condition. A preliminary visualization of the grand average topographic scalp maps (Figure 4) revealed a bilateral negativity (negative amplitude; dark blue) greatest over occipto-temporal regions and peaking at approximately 200 ms for all conditions. The 30 ms delay in N170 onset can be primarily attributed to the lag between stimulus onset in the experimental script, and the point at which the stimulus first appears on the screen. Based on this information, the 190-225 ms time window was chosen as the time window of interest in order to more specifically capture the greatest N170 amplitudes in this sample.

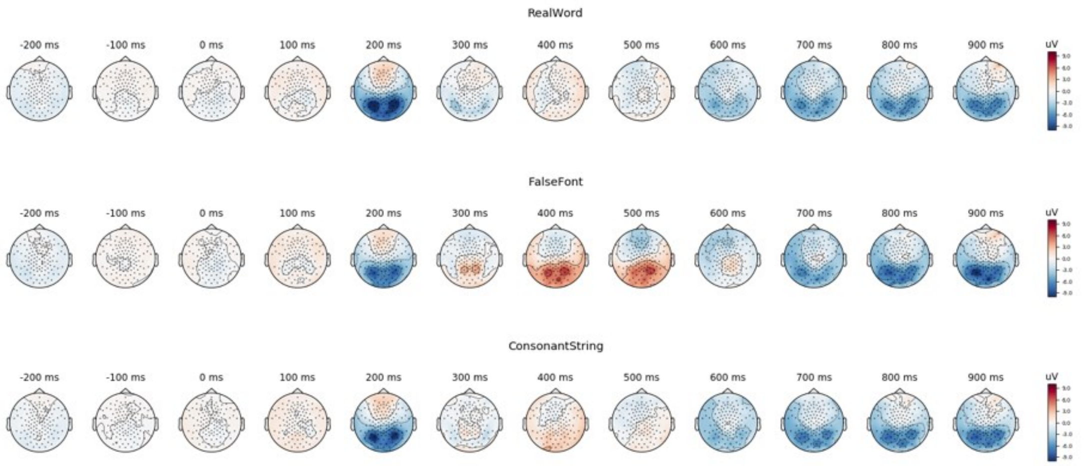


Figure 4 Topographic scalp maps of the grand average ERP waveforms from 200 ms pre-stimulus onset to 900 ms post stimulus onset for the three conditions of interest: real words, false font, and consonant strings.

The topographic map for the real word condition at 200 ms was used to specify the electrodes over which the amplitude of the N170 was the greatest in order to determine left and right hemisphere regions of interest (ROIs) specific to the sample in the current study (see Figure 5).

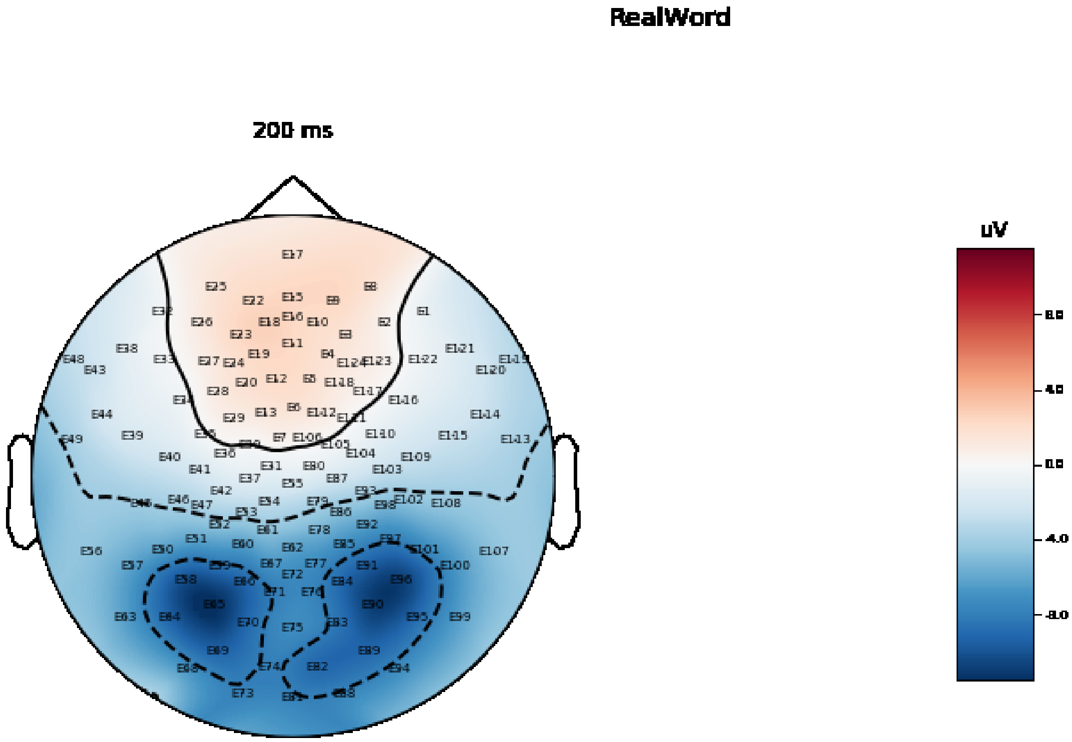


Figure 5 Topographic map representing the grand average ERP waveform at 200 ms following the presentation of real word stimuli. The electrodes for which the mean amplitude was the greatest (largest negativity; dark blue) are outlined by black dotted lines and represent the ROIs selected in the left and right hemispheres.

This method of ROI selection allows for a data-specific account of the spatial distribution of the N170 component while also providing a structured method of interpreting bilateral effects. The ROI in the left hemisphere included electrodes E58, E59, E66, E64, E65, E69, E70. The ROI in the right hemisphere included electrodes E84, E91, E96, E90, E83, E95, and E89. These electrode labels are in accordance with the International 10-20 System. The selected regions of interest are visualized on the

Hydrocel Geodesic Sensor Net 128 Channel Map in Figure 6, represented by stars (yellow stars represent left hemisphere ROI; pink stars represent right hemisphere ROI).

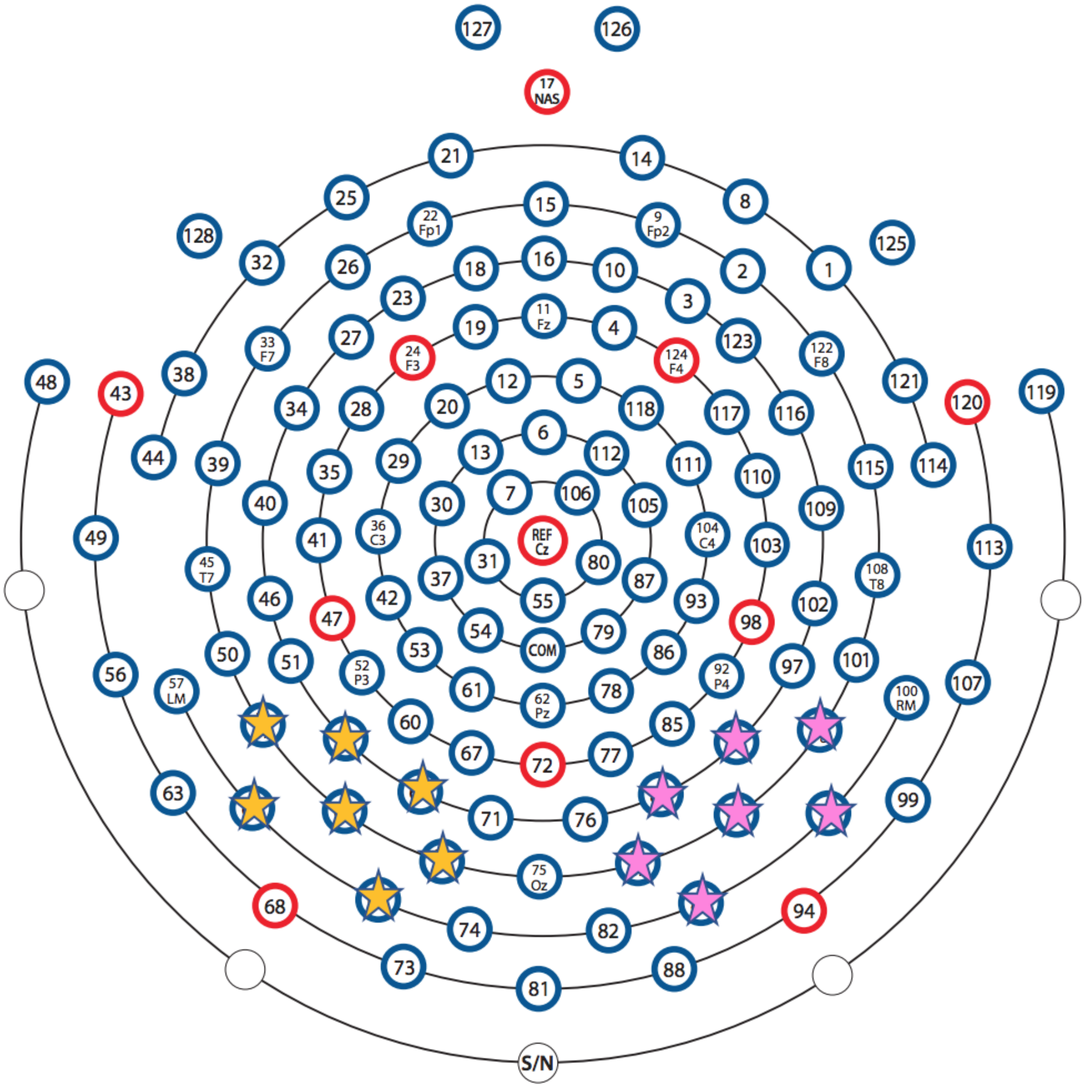


Figure 6 Top-down map of the 128 Channel Hydrocel Geodesic Sensor Net indicating the seven electrodes in both the left (yellow stars) and right (pink stars) hemispheres selected as ROIs based on the grand average ERP data.

Initial visualization of between-condition differences in the 190-225 ms time window within the left and right hemisphere ROIs was conducted using the grand average waveforms for each condition, plotted at one electrode centrally located within the designated ROIs. At the left ROI, grand average waveforms at E65 (Figure 7) show clear negativities peaking around 200 ms for all conditions, indicating the presence of the N170 ERP component. N170 amplitude differences between conditions are also noted, with real words, novel words and nonwords showing the most negative amplitudes, followed by consonant strings and then false font, which shows the least negative N170 amplitude.

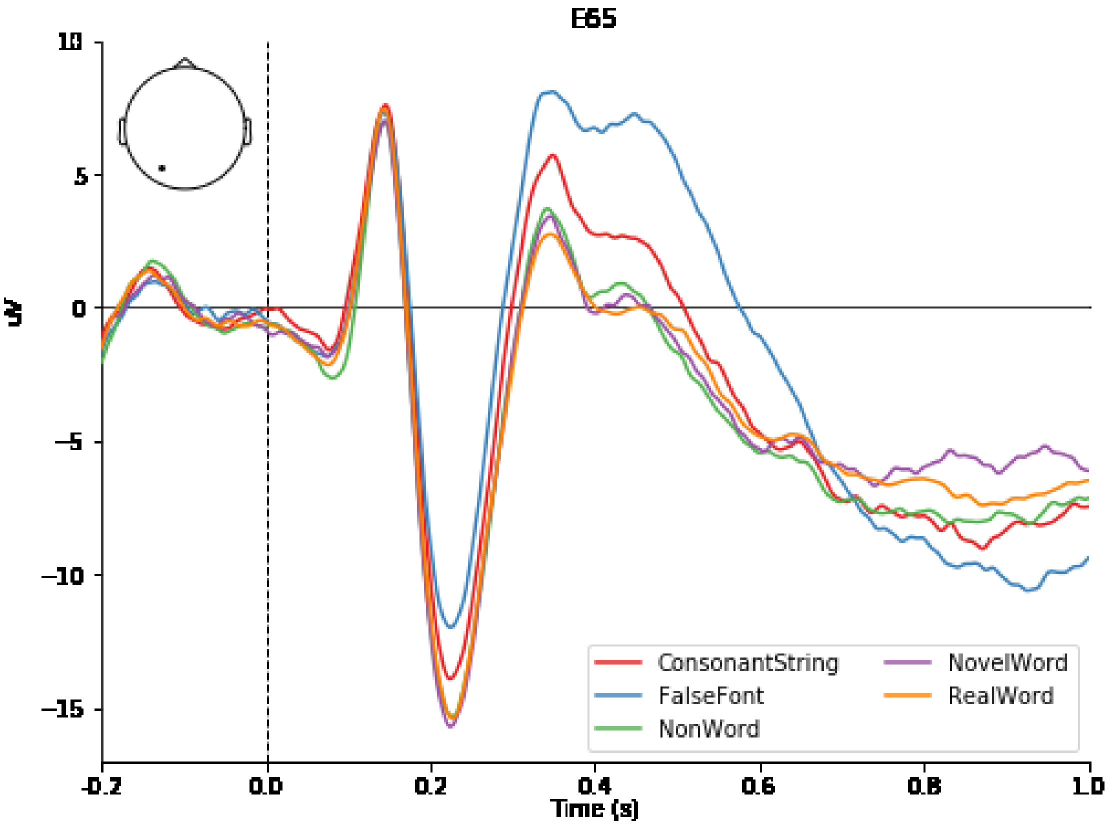


Figure 7 Grand average waveforms for all conditions in the 190-225 ms time window at electrode E6, centrally located within the left hemisphere ROI.

Similar grand average waveforms were noted in the right hemisphere at E90 (Figure 8).

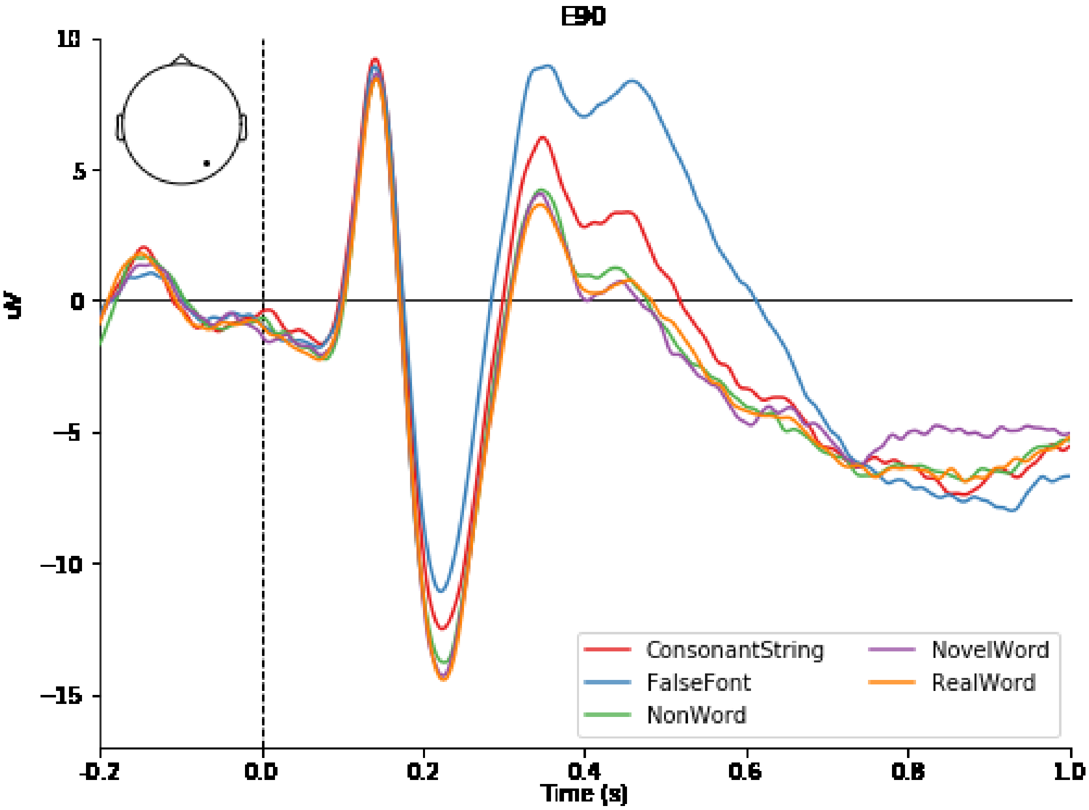


Figure 8 Grand average waveforms for all conditions in the 190-225 ms time window at electrode E90, centrally located within the right hemisphere ROI.

The amplitude and lateralization of the N170 elicited by the different conditions were further investigated using linear GAM modeling. In this analysis, the adaptive mean amplitude (AMA) was used, which accounts for N170 latency differences across participants and across individual trials. This ensures that the process of averaging and contrasting waveforms does not cancel out differences in peak negativities with variable latency, which would result in smaller computed effect than those which truly exist (Nidal & Malik, 2014). In other words, AMA ensures that the means represented in the model more closely represent the true means in the data. The AMA algorithm identified the largest negative peak within the 190-225 ms time window, and then created a new, slightly larger time window centred around this peak (170-290 ms) in order to compute the mean voltage of the ERP waveform. The AMA at the left and right hemisphere ROIs were plotted with 95% confidence intervals (CIs; Figure 9), which further demonstrated differences in the mean amplitudes between the different conditions in both hemispheres.

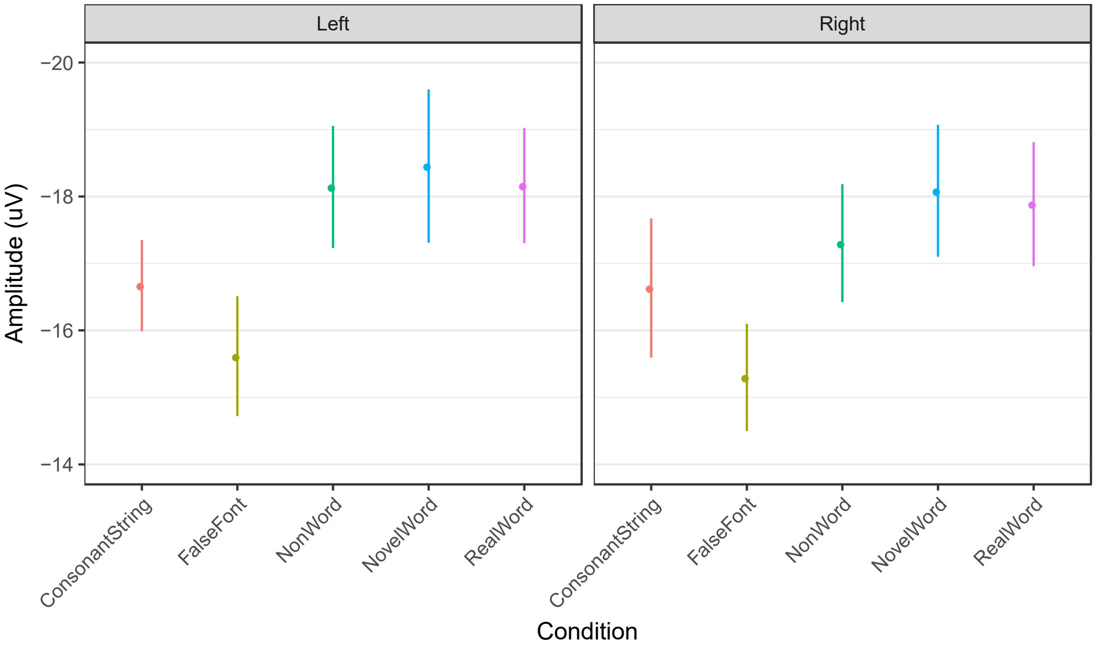


Figure 9 Dot plot depicting the adaptive mean amplitudes of the N170 ERP component with 95% CIs for each condition in the 170-290 ms time window at left and right hemisphere ROIs. Negative is plotted up to emphasize the fact that the most negative amplitude values reflect the largest N170 components.

Hemispheric differences in the AMA for each condition were then computed with 95% CIs and visualized (Figure 10). A significant left-lateralization for non-words was noted, as well as shift toward left lateralization for all other conditions.

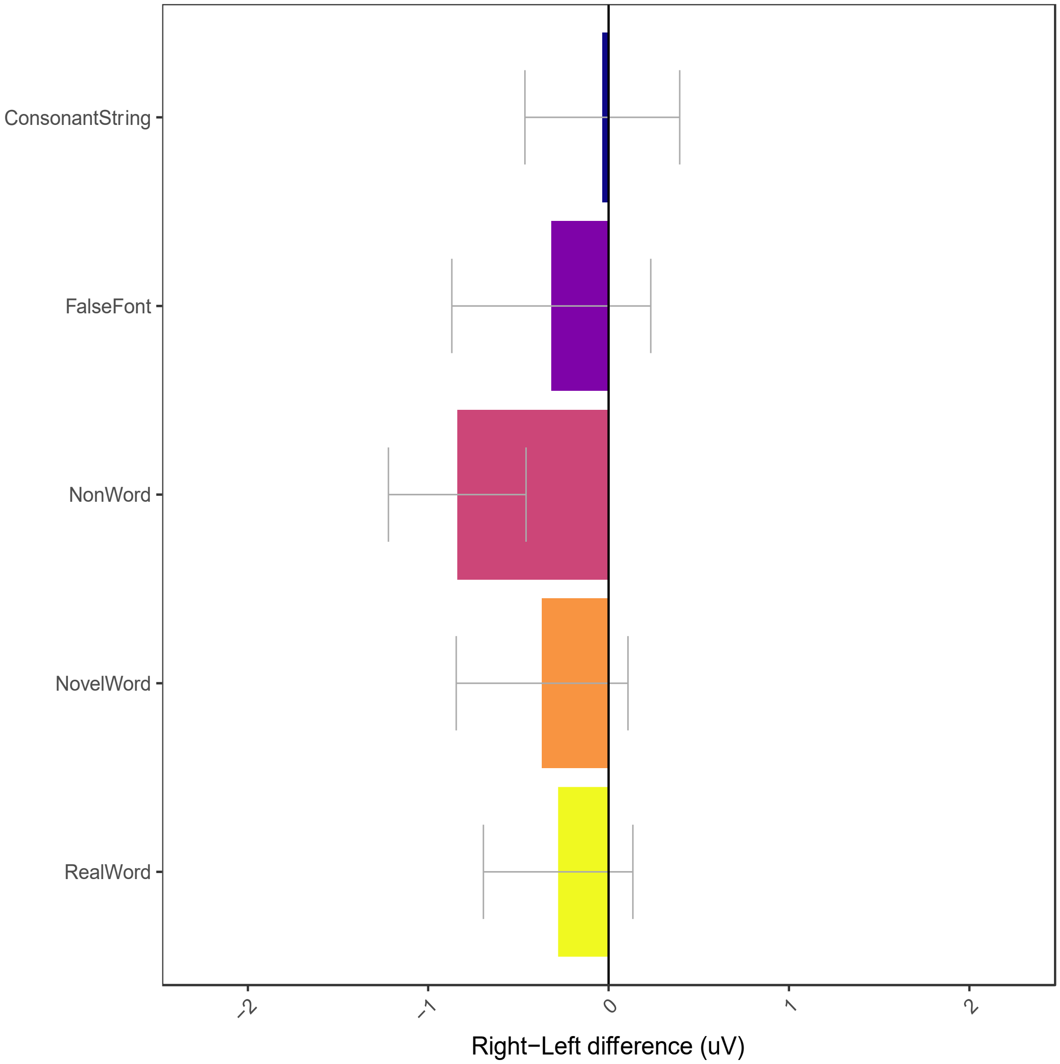


Figure 10 Bar plot representing the laterality (right-left) difference of the adaptive mean amplitude between left and right hemisphere ROIs for each condition in the 170-290 ms time window. Left hemisphere lateralization of the N170 is represented by a negative value (bar extending to the left of zero).

In order to further investigate differences in N170 AMA for each condition in each ROI in the 170-190 ms time window, a family of linear GAM models were computed using fixed effects variables Condition and ROI, as well as a random intercept for Participant, and random slopes for ROI × Participant and Condition × Participant interactions, in order to determine the optimal model for the data. This was first performed for random effects structures. The optimal model included a random intercept for Participant and random slopes for ROI × Participant interactions.

This model was used to consider different fixed effects structures. The best model included a 2-way Condition × ROI interaction with random intercept for Participant and random slopes for ROI × Participant interactions. Analysis of this model yielded a significant main effect of Condition, $F(1, 4) = 82.63$, $p < .001$, but no significant main effect of ROI. There was, however, a significant Condition × ROI interaction, $F(1,4) = 2.63$, $p = .03$, suggesting that amplitude differences between conditions varied between the left and right ROIs.

In order to better understand the nature of these findings, two-tailed paired-samples t-tests were computed to compare the N170 AMA at both ROIs for real words and false font, and for real words and consonant strings - indexing print and lexical tuning, respectively. For these contrasts, the threshold for significance was $p < .05$, corrected for multiple comparisons using the Holm method (Holm, 1979).

The magnitudes of the print and lexical tuning effect at each ROI with 95% CIs are presented in Figure 11. The difference between the mean N170 amplitude for real words and false fonts (print tuning effect) was significant in both the left ($M = 2.51$, CI [2.19, 2.82], $t(4) = 15.41$, $p < .001$) and right ($M = 2.53$, CI [2.22, 2.85], $t(4) = 15.59$, $p < .001$) hemispheres, suggesting a significant bilateral print tuning effect at the group level (because the amplitude values and CIs were virtually identical in both hemispheres, a between-hemisphere *t*-test was not conducted). The difference between the mean N170 amplitude for real words and consonant strings (lexical tuning effect) was also significant in both the left ($M = 1.45$, CI [1.13, 1.77], $t(4) = 8.93$, $p < .001$) and right ($M = 1.22$, CI

[.90, 1.54], *t*(4) = 7.52, *p* < .001), which reflects a significant bilateral lexical tuning effect as well, but with a smaller magnitude than the print tuning effect.

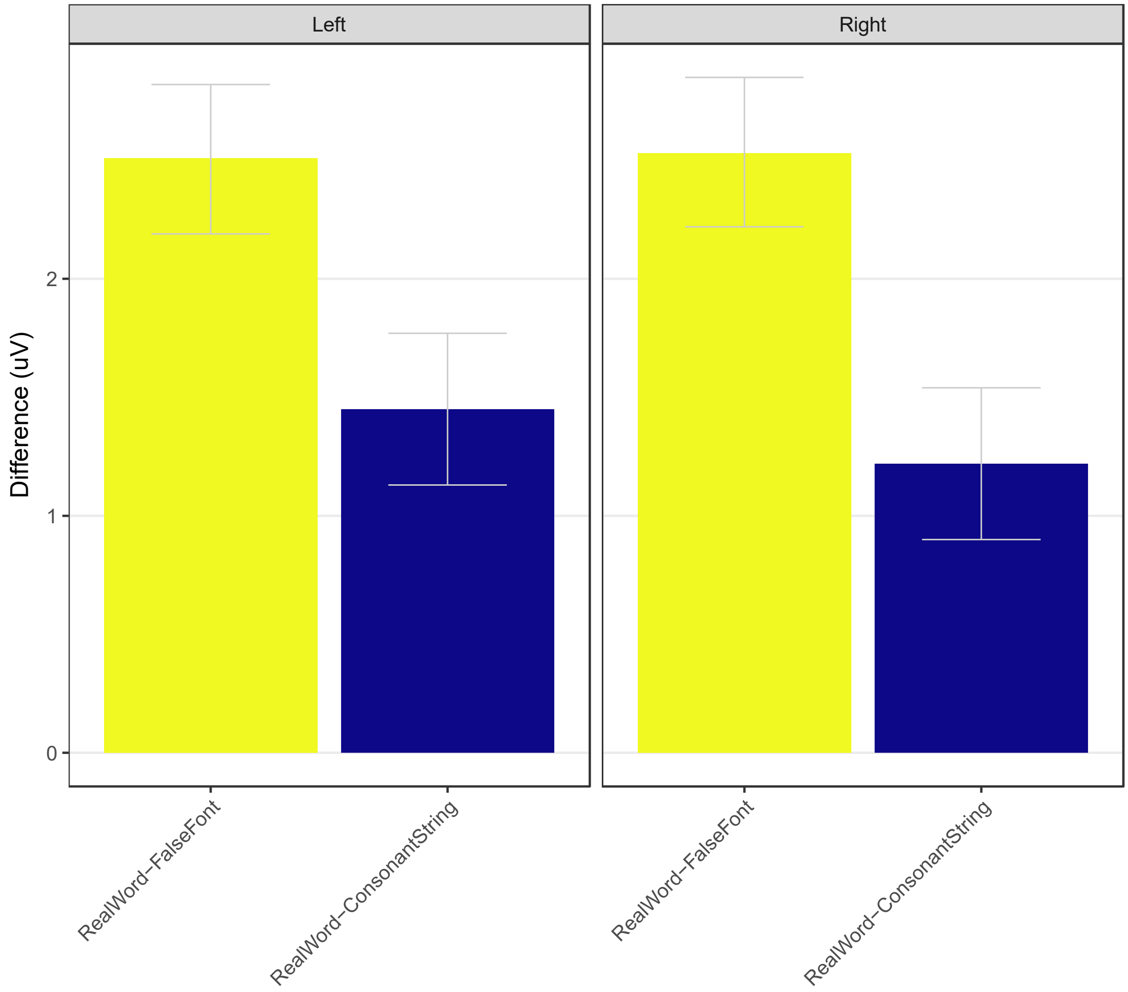


Figure 11 Bar plot representing the magnitudes of the N170 print tuning (real words – false font) and lexical tuning (real words – consonant strings) effects in the left and right hemisphere ROIs in the 190-270 ms time window.

4.2.2 Individual Differences: EEG and Behavioural Data

Individual differences in the magnitude and laterality of the N170 print and lexical tuning effects in the 170-290 ms time window were investigated in relation to individual differences in behavioural measures of reading-related skills: fluency, orthographic learning, and semantic learning. A family of models were computed including the optimal model described above (i.e., without the inclusion of any behavioural measures), as well as a model including 3-way interactions between Condition, ROI, and each of the three behavioural measures (but no interactions between the behavioural measures), and a model including 2-way interactions between Condition and each behavioural measure. The optimal model included 2-way interactions between Condition and each of the behavioural measures, with a random intercept for Participant and random slope for ROI × Participant interactions. Notably, the inclusion of ROI as a fixed effect was not warranted in the model including individual difference variables, suggesting no influence of these individual differences on laterality of the N170 effects.

This analysis revealed a main effect of Condition, $F(1, 4) = 12.33$, $p < .001$, as well as Fluency, $F(1, 1) = 6.94$, $p = .01$, and Semantic Learning, $F(1, 1) = 4.45$, $p = .03$, but no main effect of Orthographic Learning. There was, however, a significant Condition × Orthographic Learning interaction, $F(1, 4) = 4.19$, $p = .002$, as well as a significant Condition × Fluency interaction, $F(1, 4) = 19.42$, $p < .001$, and a significant Condition × Semantic Learning interaction, $F(1,4) = 2.45$, $p = .04$, suggesting that amplitude differences between conditions were modulated by skills in fluency, orthographic learning, and semantic learning.

Again, two-tailed paired-samples *t*-tests were computed to further investigate the relationship between fluency, orthographic learning, and semantic learning and the N170 print and lexical tuning effects across both ROIs in the 170-290 ms time window. For these contrasts, the threshold for significance was $p < .05$, corrected for multiple comparisons using the Holm method.

Table 3 contains the results of the paired-samples t-tests. These analyses revealed that neither fluency nor semantic learning significantly modulated N170 print or lexical tuning. Orthographic learning significantly modulated the print tuning effect (*M* = .11, CI [.02, .19], *t*(4) = 2.43, *p* = .03), but not the lexical tuning effect.

Table 3 Posthoc contrasts between N170 print and lexical tuning and behavioural measures of fluency, orthographic learning, and semantic learning.

Contrast	***Estimate***	***SE***	**CI**	***t*-value**	***p* (Holm)**
PT × FL	-.01	0.01	-.03 - .00	-1.69	.09
LT × FL	-.02	0.01	-.03 - .00	-2.03	.09
PT × OL	.11	.04	.02 - .19	2.43	.03**
LT × OL	-.08	.04	-.17 - .01	-1.83	.07
PT × SL	.08	.16	-.01 - .16	1.79	.14
LT × SL	.03	.11	-.06 - .11	.64	.52

Note. PT = Print Tuning, LT = Lexical Tuning, FL = Fluency, OL = Orthographic Learning, SL = Semantic Learning.

Figure 12 shows the AMA of the N170 print tuning effect as a function of orthographic learning. Participants with higher scores of orthographic learning showed larger amplitude N170 print tuning effects.

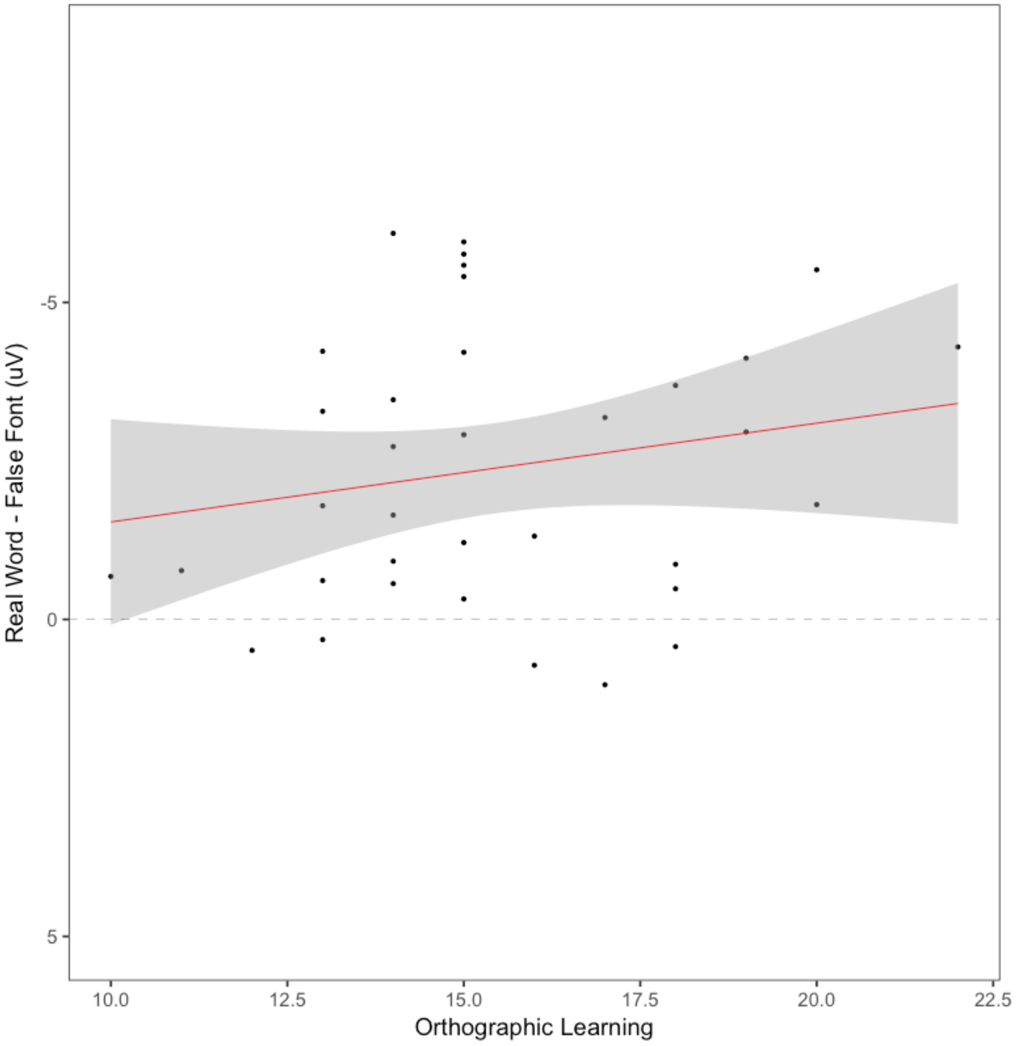


Figure 12 Print tuning (real word – false font) adaptive mean amplitude as a function of scores of orthographic learning with 95% CIs.

Although further investigation of N170 print and lexical tuning AMA as a function of fluency and ortho-semantic learning at each ROI was not justified by the results of the linear GAM modeling (i.e., a lack of significant ROI interactions), these relationships were addressed based on a priori predictions of left-hemisphere dominant effects. The findings from this additional analysis revealed a significant correlation (*p* = .02) between fluency and N170 lexical tuning in the left hemisphere, where children with higher scores of fluency showed a smaller amplitude lexical tuning effect (Figure 13).

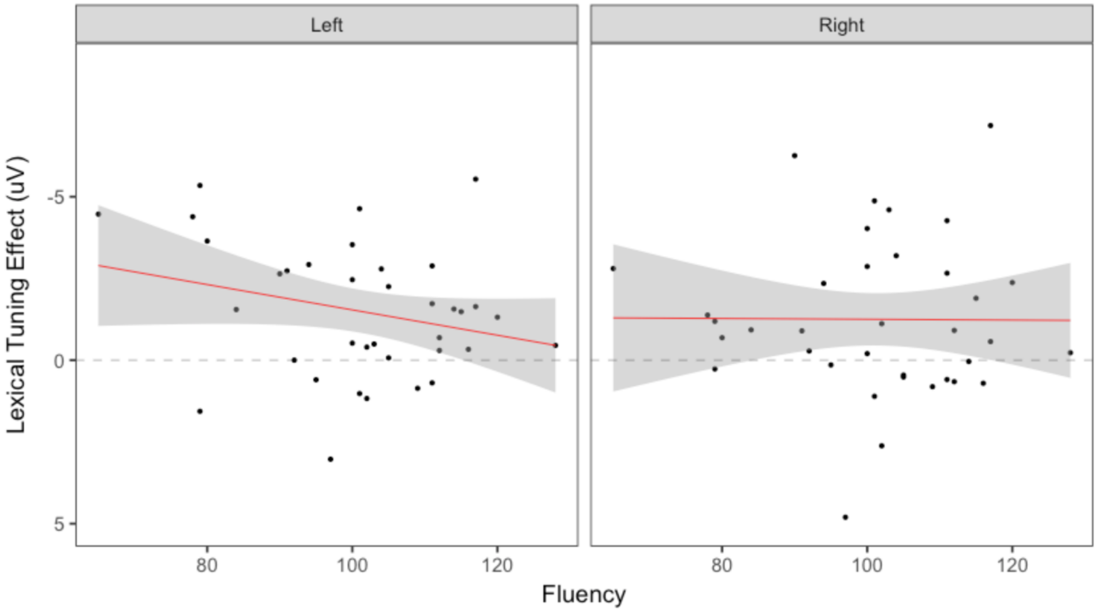


Figure 13 Lexical tuning (real word – consonant strings) adaptive mean amplitude as a function of scores of fluency with 95% CIs. The lexical tuning effect was significantly modulated by fluency (*p* = .02) in the left hemisphere only.

CHAPTER 5: DISCUSSION

5.1 OVERVIEW

Although there exist accounts of reading development in both the behavioural and electrophysiological bodies of research, their findings have been relatively independent of one another, and have been characterized by different measures, constructs, and theories. As such, the purpose of the current study was to bridge the conceptual gaps between these two fields and investigate the potential relationship between behavioural measures of ortho-semantic learning and ERP markers of reading development: N170 print and lexical tuning. Participants completed an ortho-semantic learning task and were then exposed to letter and non-letter stimuli while EEG was recorded during a lexical decision task. The ERP data was analyzed in a time window characteristic of the N170, and the mean amplitude and lateralization of the N170 print and lexical tuning effects were examined at the group level, and then in relation to scores of reading fluency, orthographic learning, and semantic learning.

5.2 RESEARCH QUESTION 1: GROUP-LEVEL AND FLUENCY-MODULATED PRINT AND LEXICAL TUNING

5.2.1 Group-Level N170 Effects

The analysis of group-level ERP data revealed a significant difference between the mean amplitudes in response to real words and false font stimuli with a larger amplitude in response to real words over both left and right ROIs, reflecting a significant bilateral group-level N170 print tuning effect in this sample of grade 3 readers. This finding is consistent with my hypothesis, as well as with reports in the literature indicating a bilateral group-level print tuning effect in grade 2 children (Maurer et al., 2006).

The group-level ERP analysis also revealed a significant lexical tuning effect, indicated by a significant difference between the mean amplitudes in response to real words and consonant strings. Similar to previous findings, the magnitude of this effect was smaller than the magnitude of the print tuning effect; however, interestingly, it differed from reports in the literature in two ways. First, the lexical tuning effect found in the current study was significant over left and right ROIs (i.e., a bilateral group-level effect), unlike the distinctly left-lateralized reports of this effect documented in the literature. Second, the lexical tuning in the current study was characterized by a larger mean amplitude for real words than for consonant strings, which is the reverse of the contrast that typically defines this effect in the literature (i.e., a larger amplitude for consonant strings).

As previously mentioned, studies investigating the development of the lexical tuning effect have examined its characteristics in children ages four, seven, and ten (i.e., preschool, first grade, and fourth grade, respectively; Posner & McCandliss et al., 2000; Zhao et al., 2014). In seven-year-old children, the lexical tuning effect has been reported as absent (Posner & McCandliss, 2000), and present only in the left hemisphere for readers with higher scores of word reading (Zhao et al., 2014). The presence of this effect seems to become more consistent in older children, with studies reporting a left-lateralized lexical tuning effect emerging around ten years of age (Posner & McCandliss, 2000), or following the first five years of reading instruction (Maurer, Brem, et al., 2005; Maurer, Brandeis, et al., 2005; Posner & McCandliss, 2000; McCandliss & Noble, 2003).

Taken together, these reports suggest that lexical tuning is effectively absent until it begins to emerge in the left hemisphere as reading skills progress; however, these findings do not account for the ages and potential differences in reading ability between those that were studied (i.e., grade 3 readers at eight and nine years of age). As such, it may be the case that the data from the current sample of grade 3 readers capture a unique stage in the development of lexical tuning, in which bilateral activation emerges in children at this pivotal stage of reading development and then left lateralizes with continued reading experience and training. This pattern of lateralization, similar to that of print tuning, may reflect initial right hemisphere pattern recognition followed by gradual left lateralization as the rules of printed language (e.g., orthographic regularities, exceptions, and conventions) are acquired and left hemisphere language areas are engaged.

Similarly, the opposing contrast found in the current study (i.e., larger amplitude for real words compared to consonant strings) may also reflect a unique developmental pattern within the characteristics of lexical tuning that has not been fully accounted for by the age groups previously assessed. Specifically, the larger mean amplitude for real words may reflect an early increase in sensitivity and neural recruitment for familiar orthographic patterns, as the lexical rules of the language are still being learned. Future studies should further investigate these findings, particularly in longitudinal studies of readers throughout the elementary school years, in order to account for unique developmental patterns in the N170 lexical tuning effect, which may have implications in terms of the way that this effect is interpreted.

5.2.1.1 Additional Notes about Group-Level Findings

It should be noted that although both the print and lexical tuning effects were bilateral in the current study, the hemispheric lateralization computations suggested a trend toward left hemisphere lateralization for all conditions, which in turn suggests that these findings are indeed precursors to the left lateralized effects that are thought to occur with continued reading experience and training.

It should also be noted that there was a significant interaction between ROI and condition in the statistical analysis of the group-level ERP data, suggesting that differences between conditions varied across the scalp; however, this was not the case for the contrasts of interest in this study. Future analyses of this data should investigate contrasts that include the additional conditions (i.e., non-words and novel words) in order to determine the nature of this interaction.

5.2.2 Fluency-Modulated Print and Lexical Tuning

Next, I hypothesized that individual differences in reading fluency would modulate individual differences in the print and lexical tuning effects, as reported in the literature throughout reading development. First, I predicted that more fluent readers would show a left-lateralized, reduced amplitude print tuning effect compared to less skilled readers, who would show a larger amplitude print tuning effect that was bilateral (i.e., no significant difference between hemispheres). Second, I expected that a left-lateralized lexical tuning effect would be present only for readers with higher scores of fluency, and that the lexical tuning effect in readers with lower scores of fluency would be absent.

Contrary to my hypotheses and to previous findings, reading fluency did not significantly modulate the print tuning or lexical tuning effects in either hemisphere. The lack of relationship between fluency and N170 print tuning was particularly unexpected in the current study, as all of the previous studies investigating this relationship reported significant fluency-modulated effects. That being said, the body of literature relating N170 effects to scores of fluency is still relatively small, with many of the reports stemming from the same group of children over time (Maurer, Brem et al., 2005; Maurer et al., 2006; Maurer et al., 2011), and additional reports coming from the same researchers using different samples of readers (Brem et al., 2006; Maurer & McCandliss, 2007). As such, it could be that more variability exists in the relationship between fluency and N170 effects in young readers than has been documented to date, which highlights the need for further exploration of this relationship using different behavioural measures, ERP stimulus sets, and samples of readers. It is also possible that in grade 3 readers, who typically exhibit substantially variability in reading ability and underlying skills, more robust measures of fluency are needed in order to more accurately determine the existence and extent of the relationship between fluent reading and N170 effects.

It should be noted that in the current study, an exploratory analysis of N170 print and lexical tuning at each ROI was conducted, and the results revealed a significant relationship between N170 lexical tuning and fluency in the left hemisphere, where children with higher scores of fluency showed a smaller amplitude lexical tuning effect than children with lower scores of fluency. Although left-hemisphere fluency-modulated lexical tuning is in line with previous findings, the nature of this modulation is incongruent with typical reports of a *larger* amplitude, left-lateralized lexical tuning effect for more fluent readers. This finding warrants further exploration, as it may provide further evidence for unique developmental patterns in grade 3 readers.

Additionally, it should be noted that in the analysis of N170 effects and behavioural scores, a significant interaction was found between condition and fluency, suggesting that the mean amplitude differences between conditions varied with scores of fluency. It is evident, however, that these interactions were not related to the contrasts of interest in the current study, and so future consideration of the additional experimental conditions (i.e., non-word and novel word stimuli) may further elucidate the relationship between fluency and N170 effects. Notably, it may provide insight into the relationship between fluency and the lexical tuning effect, which has been characterized in previous studies by additional contrasts such as real words and pseudo-words, as well as pseudo-words and consonant strings.

5.3 RESEARCH QUESTION 2: INDIVIDUAL DIFFERENCES IN ORTHO-SEMANTIC LEARNING AND N170 EFFECTS

5.3.1 Orthographic Learning and the N170 Effects

I hypothesized that similar to previous findings involving measures of fluency, orthographic learning would also modulate the N170 print and lexical tuning effects.

First, I expected that readers with higher scores of orthographic learning would show a smaller amplitude, left-lateralized print tuning effect than those with lower scores of orthographic learning, who would show a larger amplitude, bilateral print tuning effect — similar to the fluency-modulated findings in the literature — which would reflect the neural fine-tuning and strengthening of connections between visual and linguistic subsystems involved in processing orthographic structure. Consistent with my hypothesis, orthographic learning significantly modulated the print tuning effect; however, it was found that children with higher scores of orthographic learning showed a *larger* amplitude print tuning effect than children with lower skills of orthographic learning, which was not in line with my predictions. Furthermore, there was no significant difference between hemispheres in terms of the extent to which orthographic learning modulated the print tuning effect, which was also incongruent with what I expected.

The finding that higher scores of orthographic learning corresponded to a *larger* amplitude bilateral print tuning effect is similar to the fluency-modulated individual differences previously reported in grade 2 readers (Maurer et al., 2006). As such, this finding may reflect a similar intermediate stage in the process of right-to-left lateralization, but in this case, specific to orthographic structure. Specifically, it may represent the strengthening of connections between visual (print expertise) and linguistic (knowledge of letters and letter strings) subsystems with continued exposure to and experience with printed language, which may ultimately serve as an extension of the phonological mapping hypothesis (Maurer & McCandliss). The larger amplitude effect for readers with higher scores of orthographic learning also suggests an initial wide-spread neural recruitment for these subsystems before the process of fine-tuning occurs.

Next, I hypothesized that readers with higher scores orthographic learning would show a left-lateralized lexical tuning effect compared to readers with lower scores of orthographic learning, for which the lexical tuning effect would be absent. Contrary to my hypothesis, the lexical tuning effect was not significantly modulated by orthographic learning in either hemisphere; however, as previously mentioned, there are additional contrasts noted in the literature that are thought to reflect later-developing lexical tuning effects (i.e.., real words versus pseudo-words, and pseudo-words versus consonant strings), which were not explored in the current study that may reflect differential relationships with orthographic learning.

5.3.2 Semantic Learning and the N170 Effects

The relationship between semantic learning and N170 print and lexical tuning was more exploratory in the current study, as I expected that semantic learning might reflect a more advanced development of the direct route, where the meaning of a novel orthographic form is learned via associations between different cues and previously stored semantic knowledge — unlike the word-level, visual orthographic and lexical processing indexed by the N170 print and lexical tuning effects, respectively. Consistent with my expectations, semantic learning did not significantly modulate the N170 print or lexical tuning effects in either hemisphere; however, similar to fluency, the analysis revealed a significant interaction between scores of semantic learning and condition, suggesting that conditions that were not included in the current analysis were significantly modulated by semantic learning. The nature of this interaction should be addressed in future studies.

5.3.2.1 Additional Notes about Behavioural Measures and N170 Effects

Although it was not the goal of the current study, potential differences in N170 amplitude and behavioural measures of reading ability were examined between participants in English and French Immersion school programs. Children in French Immersion programs typically receive initial academic and literacy instruction in French with no formal English reading instruction until grade 3 or 4 (Turnbull et al., 2001), and so it was recognized that group differences in English reading ability and corresponding underlying brain activity may have been present in our grade 3 participant sample.

A preliminary investigation of these differences revealed that group-level N170 amplitudes for participants in French Immersion were qualitatively smaller (i.e., less negative) for all conditions, although this finding was not statistically significant. Furthermore, when these waveforms were reduced to condition contrasts (i.e., print and lexical tuning effects), this between-group difference was further mitigated. Additionally, school program did not significantly modulate relationships between the N170 print and lexical tuning effects and the behavioural measures of reading and underlying skills.

These findings should be interpreted with caution in the context of this study, however, as the groups based on school program were imbalanced (10 of the 36 participants were in French Immersion), which reduces the validity of any statistical analyses in this context. Furthermore, the total sample size (N = 36) was too small to generate groups based on school program that were large enough to ensure adequate power for between-group analyses. As such, future studies should consider recruiting additional participants in both English and French Immersion school programs in order to further investigate differences between these groups.

5.3.3 Correlations between Behavioural Measures

Correlations between the behavioural measures of both reading ability and underlying skills were not investigated in detail in the current study, as the focus of the study was on the relationships between behavioural and ERP measures; however, a basic correlational analysis was conducted to ensure that the relationships between the behavioural measures reflected findings documented in the literature. The results of this analysis revealed certain discrepancies between the findings in the literature and the current sample, which are important to address as they may have implications in terms of the way the overall findings from the current study can be interpreted.

First, the correlational analysis indicated strong positive correlations between fluency, phonemic decoding, and orthographic knowledge. This finding is congruent with reports suggesting that phonemic decoding and existing orthographic knowledge serve as the foundation of skilled reading development (Share, 1995; Bowey & Miller, 2007).

In contrast, correlations involving ortho-semantic learning were not in line with previous findings. Unlike the well-documented relationship between reading ability and orthographic learning in the behavioural literature (Share, 1995; Bowey & Miller, 2007; Mimeau et al., 2018), orthographic learning was only weakly-to-moderately positively correlated with fluency, phonemic decoding, and orthographic knowledge in the current sample of readers.

Similar to orthographic learning, correlations between semantic learning, semantic knowledge, and fluency were also negligible, which is inconsistent with the well-documented finding that semantic knowledge is a strong predictor of semantic learning (Cain et al., 2004; Ewers & Brownson, 1999), and the finding that readers who are more fluent are better able to learn novel semantic representations by taking advantage of contextual cues (Landi et al., 2006).

It is clear that taken together, these findings do not align well with existing theories of reading development that relate ortho-semantic learning to other skills. Specifically, they are incongruent with the self-teaching hypothesis (Share, 1995), which suggests that phonemic decoding skills drive orthographic learning — a skill that in turn predicts reading ability (Mimeau et al., 2018), as well as with the lexical quality hypothesis (Perfetti & Hart, 2002), which posits that the ability to learn orthographic, phonological, and semantic representations of a word reflects the quality of the stored representation of this word, ultimately influencing skilled reading abilities such as fluency and comprehension.

Given that the basic relationships documented in the behavioural literature between ortho-semantic learning, reading ability, and additional underlying skills were not reported in the current study, it is somewhat difficult to accurately interpret the findings related to ortho-semantic learning and N170 effects, as it unclear a) whether the ortho-semantic measures obtained in this study truly reflect ortho-semantic abilities within these grade 3 readers, and b) how these findings relate to other reading-related skills. For example, the finding in the current study that children with higher scores of orthographic learning showed a larger bilateral print tuning effect than children with lower scores of orthographic learning reflected a similar pattern to the fluency-modulated findings reported by Maurer and colleagues (2006); however, because of the negligible relationship between fluency and orthographic learning in this study, and because fluency did not modulate the print or lexical tuning effects, it was difficult to determine whether this finding is specific to the processing of orthographic structure, accounting for unique connections of underlying subsystems involved in the development skilled reading, or whether this effect was essentially a reflection of the fluency-modulated patterns in amplitude and lateralization that have previously been documented. In a more general sense, it is even difficult to determine whether this finding accurately reflected orthographic-learning modulated neural activity, as the measure of orthographic learning obtained in the current study may not have adequately captured this ability in the current sample, given the lack of characteristic relationships between this measure and other reading-related abilities. Similarly, the lack of relationship between semantic learning and semantic knowledge calls into question the extent to which semantic learning ability was truly captured in the current data, which confounds interpretations of the lack of relationships between semantic learning and N170 effects.

There were limitations in the protocol of the current study that may have contributed to nature of the relationships (or lack thereof) found between behavioural measures, and consequently, between behavioural measures and N170 effects.

5.4 LIMITATIONS OF THE CURRENT STUDY

5.4.1 Adaptations of the Ortho-semantic Learning Paradigm

One limitation of the current study was the adaptations made to the ortho-semantic learning paradigm given then time constraints induced by EEG procedures. In previous studies using adaptations of this paradigm, including the adaptation used in the research by Mimeau and colleagues (2018) on which this study was based, orthographic and semantic learning were assessed by administering the ortho-semantic choice tasks immediately after the learning paradigm, as well as at different delays following the initial exposure (e.g., three days following initial exposure, one week following initial exposure). Furthermore, in previous studies, ortho-semantic learning was assessed not only using the choice tasks, but also using post-tests such as spelling tasks, oral definitions, and picture matching. Because the current adaptation of the paradigm implemented only one modality of ortho-semantic assessment at one time point, it may be the case that this adaptation did not adequately assess and/or reinforce ortho-semantic learning abilities. Although no feedback was given during the post-tests in previous adaptations, it could still be that children who completed these tasks of spelling and defining the novel words had a greater opportunity to establish higher quality lexical representations of these words, which is pivotal not only for learning the orthographic forms and their meanings, but also for retaining them so that they can be accessed during future encounters. Limitations in the current adaptation of the ortho-semantic learning paradigm may offer a possible explanation as to the weak correlations found between ortho-semantic learning and other reading-related skills. As such, in future studies including both EEG and ortho-semantic learning paradigms, it is suggested these procedures be conducted during separate sessions in order to ensure the most robust accounts of both the ortho-semantic learning and ERP measures, which will allow for a more precise and detailed study of their relationships.

5.4.2 Behavioural Measures of Reading Skills

Another limitation of the current study was the selection of behavioural assessments used to obtain measures of reading ability and underlying skills in orthography, phonology, and semantics. Although some of the skills were measured using standardized assessments (e.g., TOWRE-2 for phonemic decoding and word reading fluency), other skills were assessed using subtests from a standardized battery meant to serve as part of a composite score (C-TOPP-2 for phonemic decoding), modifications of standardized tests (M-PPVT-3 for semantic knowledge), and non-standardized procedures (e.g., the orthographic/semantic knowledge homophone assessments). While these assessments have all been used individually in previous studies, and while they all provide some measure of individual abilities in target areas, they do not allow for an accurate comparison from one individual to another and they vary in robustness, and consequently, interpretability. As such, it is more difficult to determine whether each measure is a representative account of that particular skill and how an individual's score compares to same aged peers, which may provide an additional explanation as to the behavioural findings in the current study that were incongruent with existing findings in the literature. In order to obtain a more robust and interpretable account of the relationship between behaviorally measured skills involved in reading and the neural fine-tuning for printed words, futures studies should employ a more structured, robust, standardized compilation of behavioural measures to account for these reading-related skills.

5.5 FUTURE DIRECTIONS

In addition to addressing the limitations of the current study by implementing an extended adaptation of the ortho-semantic learning paradigm (Mimeau et al., 2018) and obtaining more robust behavioural measures of reading ability and underlying skills, the following considerations should be made in future studies of behavioural measures of reading-related skills and N170 effects.

5.5.1 Additional Experimental Conditions

The current study focused on investigating relationships between behavioural measures of reading and the N170 print and lexical tuning effects, which were characterized by contrasts between real words and false font, and real words and consonant strings, respectively; however, as previously mentioned, additional contrasts between different conditions (i.e., non-words and novel words) should be investigated in the future, as significant interactions between condition and ROI, as well as condition and scores of fluency and semantic learning were not accounted for by the contrasts indexing print and lexical tuning in the current study.

Notably, contrasts including the novel word condition may provide interesting insights into ERP contrasts that have not previously been investigated, given that this study was the first to introduce a semantic learning component to the paradigm in which participants learned the meanings of a subset of the pseudo-words (i.e., non-words in the context of this study). For example, the contrast between real words and novel words should reflect the extent to which these novel words have been learned, whereby a smaller amplitude difference between these conditions might suggest that the novel words are being processed similarly to real words, indicating that learning of these novel words has occurred. Furthermore, the contrast between novel words and non-words (i.e., lexically valid letter strings that have not been learned) may also index learning processes, where no amplitude difference between these two conditions would suggest that the novel words have not been successfully learned and continue to be processed similarly to other non-words. The lateralization of these contrasts would also be important to investigate, given the significant interaction found in the current study between condition and ROI that was unaccounted for by print and lexical tuning.

Also, as previously suggested, future analyses should consider additional contrasts indexing the lexical tuning effect (i.e., real words and non-words and non-words and consonant strings in the context of the current study) in order to clarify the nature of these contrasts given the unexplained variability findings in the literature (Bentin et al., 1999; Wydell et al., 2003; Maurer, Brem, et al., 2005; Hauk et al., 2006; Maurer et al., 2006); however, because of the semantic learning component in the EEG paradigm, the non-words may be processed differently than in typical studies, which may limit the ability to relate findings related to lexical tuning using this paradigm to findings in previous studies.

5.5.2 Additional Predictor Variables

Future studies should also consider additional factors such as demographics (i.e., age, sex, socioeconomic status, school program), working memory, nonverbal intelligence, print exposure, explicit instruction, comprehension, morphology, syntax, and writing. All of these factors are have been found to contribute to the development of reading abilities, and so in order to progress toward a universal model of reading, it is important that the relative contributions of each of these skills are investigated, particularly in relation to underlying neural processes.

The inclusion of additional variables may also help to elucidate the nature of the relationships between ortho-semantic learning and other reading-related cognitive and linguistic skills, which will in turn provide further insight into the relationship between these measures and N170 ERP effects. For example, as previously discussed, there is evidence in the behavioural literature to suggest that while accurate phonemic decoding and successful word reading provide an *opportunity* for orthographic learning to occur, these skills may not be sufficient alone to account for successful orthographic learning (Nation et al., 2007). As such, it may be the case that other cognitive skills and environmental factors involved in reading and learning (e.g., working memory or exposure to print) may also contribute to the extent to which orthographic learning occurs, which is not accounted for by measures of fluency or phonemic decoding.

5.5.3 Additional Studies Including Grade 3 Readers

Prior to the current study, investigations of the relationships between behavioural measures of reading-related skills and N170 ERP effects had not included samples of grade 3 readers. As previously discussed, grade 3 is thought to be a transitional stage in reading development, which is reflected by a high level of variability in reading ability and underlying skills. The findings in the current study support this idea, as the data from this sample of grade 3 readers seem to capture a unique stage in the development of lexical tuning, in which bilateral activation emerges with a larger activation for real words, and then left lateralizes with continued reading experience and training. As such, although this report serves as preliminary evidence for differential patterns of development in grade 3 readers, additional studies targeting this age and grade level are needed in order to develop a more in-depth understanding of the nature of the potential patterns of print and lexical tuning development that are unique to these readers.

Additionally, longitudinal studies of the developmental patterns related to behavioural and electrophysiological measures of reading that include data from all of the elementary school grades would help to integrate the findings from grade 3 readers into a more general account of behavioural and N170 print/lexical tuning changes throughout the development of skilled reading.

5.5.4 Print and Lexical Tuning as Novel Contributions

In recent years, researchers investigating relationships between behavioural and ERP measures of reading have acknowledged that causal relationships between these measures throughout reading development are difficult to determine (Zhao et al., 2014). Subsequently, they noted the possibility that the development of neural sensitivity to print indexed by N170 print and lexical tuning may represent its own unique contribution to the acquisition and development of skilled reading ability.

In order to address this hypothesis, future research should investigate reading ability as a function of underlying skills of orthography, phonology, and semantics (including ortho-semantic learning), with the addition of N70 print and lexical tuning effects as predictor variables. Considering skilled reading as the dependent variable would allow for consideration of the possibility that N170 effects may account for additional variance in skilled reading beyond behavioural skills such as phonemic decoding, ortho-semantic learning, and ortho-semantic knowledge.

CHAPTER 6: CONCLUSION

The goal of the current study was to bridge the conceptual gap between the behavioural and electrophysiological bodies of literature on skilled reading development by investigating the relationship between orthographic and semantic learning — skills thought to be directly involved in the transition to skilled reading — and N170 print and lexical tuning, established neurophysiological markers of visual word expertise and higher-level lexical processing of print.

Findings from this study provide novel insights into the patterns of group-level N170 effects in grade 3 (eight- and nine-year-old) readers — a grade and age group that had not previously been investigated. The bilateral group-level lexical tuning effect reported in the current study suggested that contrary to previous reports of left-hemisphere-specific emergence and fine-tuning of this effect, the development of lexical tuning may exhibit a pattern of right-to-left lateralization, reflecting initial right hemisphere pattern recognition followed by gradual left lateralization as the rules of printed language are acquired and left hemisphere language areas are engaged.

The current study also provides preliminary evidence for a functional relationship between orthographic learning and the N170 print tuning effect, indicated by a *larger* amplitude bilateral print tuning effect for children with higher scores of orthographic learning. This finding may represent the strengthening of connections between visual (print expertise) and linguistic (knowledge of letters and letter strings) subsystems with continued exposure to and experience with printed language, which serves as an extension of the phonological mapping hypothesis (Maurer & McCandliss).

The relationship between orthographic learning and N170 print tuning is interpreted with caution in the context of the current study, however, as the basic relationships documented in the behavioural literature between ortho-semantic learning, reading ability, and additional underlying skills (i.e., the relationships that drive the behavioural theories and investigations of reading development) were not accounted for in this data. This absence of these characteristic relationships confounds the overall interpretation of the findings in two ways. First, it brings into question whether the ortho-semantic learning measures obtained in this study truly reflect the extent of these skills in the sample of readers, as the measures used in the current study were novel adaptations of an existing paradigm that may have been limited in their ability to adequately target these skills. Second, the absence of these relationships makes it difficult to determine how the findings noted in this study relate to other reading-related skills (e.g., fluency).

As such, future studies should further investigate the relationship between ortho-semantic learning and N170 effects by employing a more extensive adaptation of the ortho-semantic learning paradigm and obtaining more robust measures of reading ability, as well as underlying skills of orthography, phonology, and semantics. Future studies should also examine alternative contrasts between experimental stimulus conditions and consider additional cognitive, linguistic, and environmental variables implicated in previous studies of reading development. Furthermore, additional studies of behavioural and electrophysiological measures in grade 3 readers should be conducted in order to further explore the potential patterns of print and lexical tuning development that are unique to this age and grade level. Additional longitudinal studies including data from all of the elementary school grades would help to integrate the findings from grade 3 readers into a more general account of behavioural and N170 print/lexical tuning changes throughout reading development.

This study, along with future research, will ultimately help us to develop a better understanding of the functional relationships between ERP data and behavioural measures of reading, which may in turn have several long-term, real-world benefits. First, in the future, we may be able to integrate our knowledge of these relationships to develop a technique/tool that allows us to identify problem skills for each individual child based on patterns noted in their electrophysiological and behavioural data. This would in turn help to develop maximally effective ways of teaching children to read, ensuring that each child's education is structured to optimize their learning based on their identified skills and weaknesses. Maximizing reading abilities based on individual levels of ability would ultimately improve overall children's academic success, which would have additional far reaching positive consequences (e.g., vocational achievement and social integration; Lloyd, 1978; Hernandez, 2011; Cohen et al., 2018).

Additionally, this body of research could help us to develop methods of detecting the emergence of deficits in printed word processing (McCandliss and Noble, 2003), as well as methods of testing the effects of corresponding educational approaches and intervention techniques by investigating pre- and post- intervention brain correlates of reading and their relationships with behavioural outcomes (Maurer et al., 2006).

Ultimately, the long-term goal is to use these findings to optimize our general understanding of skilled reading and the variability that exists across children, in order to develop tools and techniques that maximize each child's reading abilities and consequently, their academic outcomes.

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