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AN FMRI STUDY OF FLUENT AND NONFLUENT BEGINNING READERS

by

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An fMRI Study of Fluent and Nonfluent Beginning Readers

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ABSTRACT

Although reading fluency has been identified as an important component of skilled reading, few studies have examined the underlying neural processes. The purpose of the current study was to compare the neural systems for reading in fluent and nonfluent beginning readers. The Goldberg and Costa (1981) theory of hemisphere differences provided a theoretical framework for conceptualizing the development of reading fluency. This theory proposes that the right hemisphere processes novel stimuli and assembles new descriptive systems while the left hemisphere utilizes fully formed and well-routinized codes, and that a right-to-left shift in hemisphere superiority occurs during skill development. Children between 6 and 7 years of age participated in an fMRI experiment. Low and high fluency groups were based on level of fluency in grapheme-phoneme mapping. fMRI reading tasks were modeled on curriculum based measurement tests of reading fluency. Three different tasks involved letter-phoneme, word-spoken word, or picture-spoken word matching. In high fluency as compared to low fluency beginning readers, there was greater activation in the left parietotemporal area during letter and word reading tasks, an area involved in phonological processing, grapheme-phoneme mapping, and word decoding. Also, in the high fluency as compared to the low fluency group, there was greater activation in the left inferior frontal area during the word reading task, another area involved in phonological processing. Within the framework of the Goldberg and Costa theory, the greater left hemisphere involvement in the high fluency group may reflect the utilization of more routinized descriptive codes for phonological processing skills. There was greater activation in high fluency as compared to low fluency beginning readers in bilateral occipitotemporal areas during letter and word reading tasks, an area involved in visual recognition of letters and words. Within the Goldberg and Costa framework, this may reflect right hemisphere involvement in assembling a new descriptive system for visual recognition in the high fluency group, and a shifting in relative hemisphere superiority from the right hemisphere to the left hemisphere in the course of fluency development. In conclusion, the present study provides preliminary evidence that fluent and nonfluent beginning readers may engage neural systems for reading differently.

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CHAPTER 1: INTRODUCTION

Reading is an essential skill in today's world. Written language is used to communicate with others, record information, share knowledge, and entertain. It could be argued that being able to read is critical for success. Written language is fundamentally different from spoken language. Whereas spoken language abilities develop naturally from exposure to a natural speaking environment, reading and writing need to be acquired and taught (Shaywitz & Shaywitz, 2008). While humans have been speaking and listening for hundreds of thousands of years, written language has only existed for about 6000 years, and the alphabet for about 4000 years (Dehaene, 2009). This indicates that the human brain was not designed to read (Dehaene, 2009). Instead, the plasticity of our brain has allowed for us to invent written language (Dehaene, 2009). It has been suggested that brain structures and neural circuits designed for other purposes are "recycled" to support reading (Frey & Fisher, 2010).

Studying the neural systems that underlie reading acquisition offers a unique opportunity to study brain plasticity. Furthermore, understanding the neurobiology of reading will increase our understanding of the component processes, the functional organization, and the development of this ability (Schlaggar & McCandliss, 2007). There are important applications as well. Understanding the neural changes associated with learning to read and in response to reading instruction can provide guidance for education and the development of effect teaching strategies for reading (Frey & Fisher, 2010). Identifying differences in the brains of individuals with reading disabilities will provide further understanding of these disorders and their development, and may assist with developing effective treatment strategies (Schlaggar & McCandliss, 2007). Advances in technology have now provided us with the ability to study the functioning of the brain in vivo. Functional neuroimaging techniques, such as functional magnetic resonance imaging (fMRI), have contributed to our understanding of the neural systems involved in reading, the development of these systems as we learn to read, and their differences in individuals with reading disabilities (Schlaggar & McCandliss, 2007).

The aim of the current study was to further contribute to the understanding of the neural systems involved in reading and the changes that take place as children learn to read. The purpose of the current study was to compare the neural systems for reading in fluent and nonfluent beginning readers. Although reading fluency has been identified as an important factor for skilled reading, few studies have tried to examine the underlying neural processes. The technique of fMRI was used to investigate the neural systems. This study focused on beginning readers in order to examine the neural systems for reading at the early stages of development. The Goldberg and Costa (1981) theory of hemisphere differences provided a theoretical framework for conceptualizing the development of reading fluency. This theory proposes a right-to-left shift in hemisphere superiority as a function of increased skill. The current study also aimed to develop a reading paradigm that could be used in fMRI research on reading fluency. The goal was to design a paradigm similar to measures commonly used in education to assess reading fluency. Before providing a more detailed description of the current study, the following will be reviewed: definition and description of reading and writing, reading development, skilled reading, reading disability, neural systems for reading, the Goldberg and Costa theory, and lastly an overview of fMRI.

Definition and Description of Reading and Writing

Reading is a language-based skill and complex cognitive activity (Kamhi & Catts, 2012). Multiple definitions of reading exist. Broad views define reading as "comprehending texts" (Kamhi & Catts, 2012, p. 3) or "the process of gaining meaning from print" (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001, p. 34). The problem with broad views of reading is that they confound different abilities. The Simple View of Reading claims that reading consists of two component processes: decoding words and linguistic comprehension (Hoover & Gough, 1990). Some advocate for a narrow view which restricts the definition of reading to word decoding (Kamhi & Catts, 2012). The advantages of this view is that it restricts reading to a narrow set of processes that can be taught or studied, and removes the complexity of comprehension which includes many thinking and reasoning processes and is domain dependent (Kamhi & Catts, 2012). How reading is defined will impact instruction, assessment, and research. Regardless of definition, many agree that skilled reading involves "on-line comprehension of meaning from running text" (Vellutino, Fletcher, Snowling, & Scanlon, 2004, p. 5).

Writing systems use graphic units to represent abstract language units that are used in spoken language (Rayner et al., 2001). Written words are representations of spoken words and spoken words are representations of objects and experiences (Vellutino et al., 2004). Bloomfield (1933) stated, "writing is not language, but merely a way of recording [spoken] language by visible marks" (as cited in Shaywitz & Shaywitz, 2008). Through history, graphic units have moved away from directly representing meaning and toward representing sound (Rayner et al., 2001).

Different writing systems have different language units represented by the graphic units (Rayner et al., 2001). English is an alphabetic writing system in which the language units, phonemes, are represented by the graphic units, letters (Rayner, et al., 2001). Phonemes are the smallest sound units of spoken language (Schlaggar & McCandliss, 2007). This association of letters to phonemes is called the 'alphabetic principle' (Rayner et al., 2001). Alphabetic writing systems are economic because written units are mapped onto a small set of elements, the phonemes (Rayner et al., 2001). They are also productive since a small set of symbols can be used to write an infinitely large number of words (Rayner et al., 2001). Languages can be described in terms of *phonology*, or the sound structure of language, and *orthography*, or the graphic structure of language (Schlaggar & McCandliss, 2007). English is a deep orthography, meaning the symbol-sound correspondences are more variable (Rayner et al., 2001). In contrast, in a shallow orthography the correspondences between letters and sounds are highly consistent (Rayner et al., 2001).

Research has suggested that word recognition is the basic process that all other reading processes are built upon (Bjaalid, Hoien, & Lundberg, 1997). A number of cognitive models of word reading have been proposed. The two major categories of these models are the dominant dual-route model and its rival connectionist models (Share, 2008). These models were inspired by the distinction between words that follow the rules and words that do not follow the rules of grapheme-phoneme correspondences (Share, 2008).

The dual-route model has been a highly influential theory and has been applied to skilled reading, reading development, dyslexia, spelling, and neuroimaging research

(Share, 2008). Dual-route models assume there are two different procedures (or two separate routes) for reading printed words: the *direct route* and the *indirect route* (Bjaalid et al., 1997). The direct route, or lexical or visual-orthographic route, is used for words the reader has learned (Coltheart, Curtis, Atkins, & Haller, 1993). Every word an individual has learned is represented in a mental dictionary or internal lexicon (Coltheart et al., 1993). These words are read by direct connection of the visual form of the word to the meaning of the word, which was formed by practice (Bjaalid et al., 1997). The meaning of the word is accessed directly from its orthographic form (Bjaalid et al. 1997). The indirect route, or nonlexical or phonological route, is used for words not represented in the lexicon (Coltheart et al., 1993). Each letter of the word is sequentially translated into sound using letter-sound rules. This allows for recognition of the word, which then gives access to the word's meaning (Bjaalid et al., 1997). Readers can read words they have never seen before by using the nonlexical route as long as the word follows the spelling-sound rules of English (Coltheart et al., 1993).

Connectionist models claim that there is a single, interconnected system for reading all words (Share, 2008). Both whole word recognition and rule-based decoding reflect underlying patterns of activation and resonance across the network (Bjaalid et al., 1997). These models have typically focused on the process for computing the phonological pronunciation from the orthographic representation (Share, 2008). Connectionist models attempt to explain the computational mechanisms underlying reading (Seidenberg, 2005). The goal of these models is to provide a computational model that acts as the interface between reading behaviour and its brain bases (Seidenberg, 2005). These computational models produce simulations of the reading process (Perry, Ziegler, & Zorzi, 2007). Different connectionist models have been proposed, each with its own limitations and problems in accounting for all word reading behaviours (Perry et al., 2007).

Some have criticized the dual-route and connectionist models arguing that they only apply to the English language, which is an irregular orthography, and do not generalize to other languages (Share, 2008). Share (2008) argues for a universal theory of reading that applies to all languages and orthographies. He proposes that reading is a developmental transition from unfamiliar to familiar. Every word is unfamiliar at some point whether regular or irregular, real word or pseudoword, and requires the application of some sort of decoding or learning algorithm at first. This applies to beginning readers learning how to read, and skilled readers encountering a new word. Eventually words become familiar and can be retrieved automatically leading to skilled reading. This theory can be applied to all words in all orthographies.

Learning to Read

Learning to read builds on previously developed cognitive, linguistic, and social skills (Rayner, et al., 2001). It depends on “the acquisition of a variety of different types of knowledge and skills, which, themselves, depend on normal development of reading-related linguistic and non-linguistic cognitive abilities” (Vellutino et al., 2004, p. 3). Research on reading development has identified a number of child characteristics, abilities, and types of knowledge that are involved in learning to read. Research also suggests that different skills are important at different time points in reading development (Muter, Hulme, Snowling, & Stevenson, 2004).

Learning to read can be viewed from two different perspectives (Rayner et al., 2001). The more traditional "reading readiness" approach focuses on the skills children need to have mastered (e.g., letter recognition, rhyming) before they can benefit from formal reading instruction (Whitehurst & Lonigan, 1998). Young children are directly taught the necessary prerequisite skills to prepare them for formal reading instruction (Foorman, Anthony, Seals, & Mouzaki, 2002). This perspective separates "prereading" behaviours from "real" reading that children are taught in school (Whitehurst & Lonigan, 1998). A more recent approach referred to as "emergent literacy" views literacy as being acquired naturally through language and literacy experiences that normally occur (Foorman et al., 2002). In this perspective, learning to reading occurs on a developmental continuum and passes through a series of developmental stages (Rayner et al., 2001). Reading related behaviours that occur before formal instruction are seen as "real" and important aspects of reading; there is no separation between "prereading" and reading (Whitehurst & Lonigan, 1998).

Knowledge and Skills Associated with Learning to Read

Research has identified a number of factors that play a role in learning to read. The most important skill in learning to read is the child's language abilities (Rayner et al., 2001). A great deal of evidence demonstrates that children's oral language skills are critical for their progress in learning to read (Muter et al., 2004). Most of this research has focused on phonological skills, which will be discussed shortly. Two other language abilities that may be important for reading development are vocabulary knowledge and grammatical knowledge. Both of these skills are important for developing reading comprehension skills (Muter et al., 2004). Vocabulary knowledge may also be important for word decoding skills in the very early stages of learning to read (Whitehurst & Lonigan, 1998). If a child tries to decode a word that he does not have in his vocabulary, there is no semantic representation to which the phonological code can be mapped and the word will not be recognized (Whitehurst & Lonigan, 1998). Oral vocabulary growth is also associated with growth in phonological sensitivity in young children (Foorman et al., 2002). This may reflect increasingly segmental structure of word recognition, which supports increasingly higher levels of phonological sensitivity (Foorman et al., 2002).

It has been well established that phonological processing skills are closely related to the development of reading skills (Muter et al., 2004). Phonological processing refers to using the phonological or sound structure of oral language when processing oral and written language (Wagner et al., 1997). Many believe that phonological skills are the language skills that directly cause development of word reading skills (Muter et al., 2004). In particular, phonological awareness has received a great deal of attention (Castles & Coltheart, 2004). Phonological awareness (or phonological sensitivity) refers to the ability to "attend to or manipulate the sound structure of language" (Foorman et al., 2002, p. 175). Phonological sensitivity follows a developmental hierarchy such that children become sensitive to increasingly smaller units of language: words, then syllables, then large intrasyllabic units, and lastly, phonemes (Foorman et al., 2002). There is also a developmental progression in the types of phonological tasks children can perform: first children can detect similar and dissimilar sounding words, next they can blend sounds together, then they can remove sounds from words, and lastly they can substitute sounds (Foorman et al., 2002). The causal link from phonological awareness to learning to read has been debated (Castles & Coltheart, 2004; Hulme, Snowling, Caravolas, & Carroll, 2005). Research has demonstrated that it is likely phonemic awareness that plays a causal role in reading development (Castles & Coltheart, 2004). Hulme et al. (2005) believe a causal pathway does operate but it depends on other aspects of children's knowledge. They argue that learning to read depends on a number of different language skills and phonological skills are just one important aspect (Hulme et al., 2005).

It has been argued that mastery of the alphabetic principle is essential for learning to read an alphabetic language (Hulme et al., 2005). Research has demonstrated that knowledge of letter-sound correspondences is a primary skill in learning to read and it has been proposed that it is the key skill for learning to read (Castles & Coltheart, 2004). Understanding the alphabetic principle depends on both phonemic awareness and letter-sound knowledge (Hulme et al., 2005). Again, Hulme et al. (2005) argue both phonemic awareness and letter-sound knowledge are necessary for learning to read, but these skills are part of a system of wider language skills that are important.

Research has consistently shown that letter name knowledge is a strong predictor of learning to read (Foulin, 2005). Children generally learn letter names before they learn letter sounds (Foorman et al., 2002). Letter name knowledge has an indirect effect on learning to read and its exact contribution is uncertain (Foulin, 2005). It has been suggested that letter name knowledge may promote the emergence of the phonological processing of print, may facilitate the learning of letter-sound correspondences, or may be a developmental stage in phonemic sensitivity skills (Foulin, 2005).

Research has demonstrated that rapid naming ability influences word reading skill at early ages but the influence fades with development (Wagner et al., 1997). Research also suggests that poor rapid naming may discriminate poor readers from good readers independent of phonological awareness (McBride-Change & Manis, 1996). Rapid naming (or phonological naming) refers to the rapid retrieval of phonological codes from memory, typically names of items (Wagner et al., 1997). The efficiency with which children can retrieve phonological codes associated with letters, word segments, and whole words from memory should influence their ability to use phonological information in reading (Wagner et al., 1997).

There is some evidence that children's knowledge of print concepts is related to reading acquisition (Foorman et al., 2002). Print concepts refer to reading conventions that are independent of word decoding such as reading from left to right and from top to bottom on the page (Foorman et al., 2002). However, one study found that knowledge of print concepts did not independently predict reading abilities. It has been suggested that knowledge of print concepts may instead represent a proxy measure for other skills and reflect exposure to print and literacy activities (Foorman, et al., 2002). Lastly, children's interest and motivation in reading and literacy activities may play an important role in reading acquisition and preliminary research on children's print motivation does support this idea (Foorman et al., 2002).

Theories of Learning to Read

Theories of reading development have often viewed progress in learning to read as passing through a series of stages (Rayner et al., 2001). These different stages are often defined by different types of reading strategies (Rayner et al., 2001). Other non-stage theories highlight the incremental nature of reading acquisition and assert that "many types of knowledge are acquired gradually on the basis of many experiences" (Rayner et al., 2001, p. 39).

Chall's (1996) model of reading development provides a comprehensive view of the reading process. Chall proposed six stages, each emphasizing a certain aspect of reading development. The first stage encompasses emergent literacy behaviours that are developed prior to formal reading instruction. Second, is the beginning of formal reading instruction. In this stage, instruction is focused on teaching basic sound-symbol correspondences and development of decoding skills. Third, beginning readers develop fluency in reading. They also begin to make use of the prosodic features of print. The fourth stage is the shift from reading for enjoyment to reading for instruction. In this stage, most information is presented from a single viewpoint. In the fifth stage, the reader begins to deal with multiple viewpoints on a topic and learns to evaluate the sources. In the sixth and final stage, the individual begins to synthesize material presented in text and forms her own viewpoint on a subject.

Frith's (1986) model of normal reading development assumes there are multiple routes from print to meaning, "letter to sound, word to sound, morpheme to sound, and from all of these directly to meaning, or alternatively, indirectly via sound to meaning" (p. 72). She proposed three different strategies for reading: Logographic, Alphabetic, and Orthographic. The beginning reader has to master all of these strategies to become literate. Logographic refers to word recognition on the basis of salient graphic features. Alphabetic refers to letter-sound by letter-sound analysis of a word. Orthographic refers to instant recognition of whole words or morphemes that make up words without taking into account letter sounds. In this model, reading acquisition is not a gradual change but instead a qualitative change. The strategies build on each other and previous strategies may be used for certain situations.

Ehri's (1995, 2005) theory focuses on the development of sight word reading. Ehri distinguishes between four different ways to read words, three for reading unfamiliar words and one for reading words seen before. Phonological recoding or decoding is the "process of transforming graphemes into phonemes and blending the phonemes into pronunciations" (p. 116). Reading by analogy refers to reading new words by using words we already know that share letters. Reading by prediction refers to guessing words by using context or initial letters. Words we have read before are recognized by memory or sight. Sight reading is used the most because it is fast and automatic. Ehri (1995, 2005) proposes that all words become sight words once they have been read several times. It is not just irregular words that are read by sight. The term 'sight' indicates "that sight of the word triggers that word in memory, including information about its spelling, pronunciation, and meaning" (Ehri, 1995, p. 117).

The development of sight reading consists of four phases each characterized by the involvement of alphabetic knowledge (Ehri, 1995, 2005). In the *pre-alphabetic phase*, readers remember words by forming connections between non-alphabetic, visual attributes of words and their pronunciations or meanings and storing these in memory. In the *partial alphabetic phase*, readers remember words by forming alphabetic connections between some letters and their sounds. Usually first and final letters are the cues remembered. In the *full alphabetic phase*, words are remembered by forming connections between letters and phonemes. In the *consolidated alphabetic phase*, readers retain complete information about the spellings of sight words in memory and their print lexicons grow. Multi-letter units such as morphemes and syllables also become consolidated and expedite their word learning.

Although stage theories provide a useful framework for understanding the changes that occur as children learn how to read, they have a number of shortcomings (Kamhi & Catts, 2012). Some criticisms include focusing on the knowledge needed rather than the mechanisms underlying reading development, associating only one type of reading approach with each stage, and failure to describe the actual development of knowledge from the beginning to the ending of each stage (Kamhi & Catts, 2012). These theories may apply only to English and not to other languages or orthographies (Share, 2008). Lastly, research evidence does not appear to support the actual stages (Ehri, 2005).

One alternative to stage theories is the "self-teaching hypothesis" (Share, 1995). This theory proposes that "phonological recoding (print-to-sound translation) functions as a self-teaching mechanism enabling the learner to acquire the detailed orthographic representations necessary for rapid, autonomous, visual word recognition" (Share, 1995, p. 152). Each successful identification of a new word provides an opportunity to acquire the word's orthographic representation that is the foundation of skilled visual word recognition (Share, 2004). Letter-by-letter decoding is critical for the formation of an orthographic representation because it draws the reader's attention to the order and identity of letters (Share, 2004). The self-teaching hypothesis has three key features (Share, 1995). First, in contrast to stage-based theories, the self-teaching hypothesis argues that the development of word recognition is item-based (Share, 1995). Word recognition will depend on frequency of exposure to a word along with success of item identification.   Second, during reading development, phonological recoding becomes increasingly "lexicalized" meaning simple one-to-one grapheme-phoneme correspondences become modified in light of expanding orthographic knowledge and evolve into more complete, accurate, and sophisticated relationships between orthography and phonology (Share, 1995). Third, the self-teaching hypothesis proposes two independent components that contribute to the development of word recognition: the phonologic and the orthographic components. Individual differences in phonological processing and orthographic processing can account for individual differences in reading acquisition. Share (1995) makes sure to note that phonological decoding skill is not a guarantee for self-teaching but "only provides opportunities for self-teaching" (p. 168), and other factors such as exposure and motivation determine the extent to which these opportunities are used. Research conducted by Share and colleagues has supported the self-teaching hypothesis by demonstrating that successful word recognition was determined by what the child said when decoding the word and not by what the child merely saw (Share, 2004). The self-teaching hypothesis also has its criticisms including research findings that suggest it may not provide a complete account of orthographic learning (Khami & Catts, 2012).

Skilled Reading

The goal of learning to read is to become a skilled reader (Rayner et al., 2001). Skilled reading depends on two processes: word identification and language comprehension (Vellutino et al., 2004). Word identification involves "visual recognition of a uniquely ordered array of letters as a familiar word and retrieval of the name and meaning of that word from memory" (Vellutino et al., 2004, p.5). Comprehension involves integration of the meanings of words, which leads to understanding and integration of sentences, and results in understanding the concepts and ideas represented by print (Vellutino et al., 2004). Reading comprehension depends on spoken language comprehension and it involves a number of different interacting processes such as knowledge and working memory (Rayner et al., 2001).

Reading Fluency

More recently, another factor important for skilled reading has received a great deal of attention, the concept of *fluency*. "Reading fluency is one of the defining characteristics of good readers and a lack of fluency is a common characteristic of poor readers" (Hudson, Lane, & Pullen, 2005, p. 702). Research has found moderate to high positive correlations between reading fluency and reading comprehension (Klauda & Guthrie, 2008). The direction of causality between fluency and comprehension has been debated (Wolf & Katzir-Cohen, 2001). Historically, it has been proposed that fluency contributes to comprehension (Klauda & Guthrie, 2008). A more current view proposed by some researchers is that fluency and comprehension have a reciprocal relationship with fluency contributing to and resulting from comprehension (Pikulski & Chard, 2005). Although, fluency has often been viewed in terms of oral reading, definitions of fluency need to apply to silent reading as well since most reading is silent (Pikulski & Chard, 2005).

Reading fluency is a complex, multifaceted construct and there is currently no consensus on its definition (Hudson, Pullen, Lane, & Torgesen, 2009). It has been defined from a number of different approaches (Wolf & Katzir-Cohen, 2001). There is disagreement as to whether fluency is a dependent variable that represents the quality of reading or, whether it is an independent variable that affects the quality of reading (Breznitz, 2006). There now appears to be agreement on the key elements of fluency: *accuracy* in decoding, *automaticity* in word recognition, and appropriate use of *prosody* (Kuhn & Stahl, 2003). Different definitions of fluency place varying emphasis on these three components (Kuhn, Schwanenflugel, & Meisinger, 2010). Kuhn et al. (2010) offer a definition of reading fluency which attempts to integrate previous knowledge and definitions: "Fluency combines accuracy, automaticity, and oral reading prosody, which, taken together, facilitate the reader's construction of meaning. It is demonstrated during oral reading through ease of word recognition, appropriate pacing, phrasing and intonation. It is a factor in both oral and silent reading that can limit or support comprehension" (p. 240).

Fluency can also be viewed in terms of the levels at which one is fluent (Klauda & Guthrie, 2008). Wolf and Katzir-Cohen (2001) describe fluency as occurring at the levels of "letter, letter pattern, word, sentence, and passage" (p. 218). They also stress that fluency should not be seen as the outcome of learned reading skill but viewed from a developmental perspective. Fluency develops in initial skills such as letter recognition and phoneme awareness and progresses to higher-level skills such as word recognition and text comprehension. Some have argued that fluency should be seen as part of reading development instead of as a proxy for it (Kuhn et al., 2010). Wolf and Katzir-Cohen (2001) describe fluency as developing from multiple underlying processes including perceptual, phonological, orthographic, morphological, semantic, and syntactic processes. Consequently, problems with fluency can result from impairment in one or more of these processes. Another approach to fluency views it as the outcome of the effectiveness of biological and cognitive systems involved in reading (Breznitz, 2006).

Automaticity

The terms fluency and automaticity are often used interchangeably but automaticity is a separate construct that is one essential element of reading fluency. Similar to fluency, there is no agreement on the definition of automaticity (Rawson, 2004). The term implies that a behaviour is “automatic”, meaning that it is effortless, autonomous, fast, outside of conscious control, and uses few processing resources (Hudson et al., 2009). The most consistent observation of increased automaticity is a speed-up in performance that occurs with practice (Rawson, 2004). Many have conceptualized automaticity in terms of the properties that are necessary or sufficient to define it (Rawson, 2004). The problems with this approach are that it simply describes behaviour and there is a high level of inconsistency between researchers regarding the properties that define automaticity (Rawson, 2004). A different approach is to conceptualize automaticity in terms of its underlying processes (Rawson, 2004). The advantage of this approach is that it can explain and predict behaviour (Rawson, 2004). Process theories have proposed different mechanisms for automaticity including computational efficiency and memory retrieval (Rawson, 2004). Computational efficiency theories propose that every time a process is performed, there is a combination of sequences so that it is completed in fewer steps, resulting in a strengthening of the process (Rawson, 2004). Memory retrieval theories propose that each time a stimulus is encountered, memory traces are strengthened, and the interpretation is more likely to come from long-term memory than initial computational mechanisms (Rawson, 2004).

Similar to fluency, automaticity in reading follows a developmental pattern starting with letter recognition, progressing to word reading, and finally semantic encoding (Hudson et al., 2009). Automaticity is item-specific and is based on each letter, each letter pattern, and each word (Hudson et al., 2009). As processes become more automatic, they require less processing resources, which allows other processes to proceed (Hudson et al., 2009). When word reading becomes automatic, more processing resources are available for more complex reading comprehension processes (Hudson et al., 2009).

Fluent reading results from automaticity in a large number of subskills that interact with each other (Breznitz, 2006). Developmentally, readers first develop fluency in decoding (Hudson et al., 2009). Automaticity in phonemic awareness and knowledge of grapheme-phoneme relationships are critical to developing decoding fluency. Automaticity in the recognition of letter group patterns is also a critical development to become a fluent decoder (Hudson et al., 2009). Next, readers develop fluency in word reading (Hudson et al., 2009). Readers develop automaticity in visual word recognition. If a word cannot be read by sight, then a reader must rely on fluent decoding to read and identify the word. Automaticity of orthographic knowledge, or the visual spelling patterns in words, also plays a role in fluent word reading, separate from grapheme-phoneme decoding (Hudson et al., 2009). Fluent word reading, due to automaticity in visual word recognition, decoding, and orthographic knowledge, contributes to fluent reading of text (Hudson et al., 2009). Last, readers develop fluency in accessing meaning (Hudson, et al., 2009). Fluent word reading leads to automaticity in semantic retrieval (Hudson et al., 2009). Automaticity in decoding, word reading, text reading, and accessing meaning, allows more processing resources to be available for the reader to engage in reading comprehension processes.

Assessing Reading Fluency

How reading fluency is defined will influence how it is assessed (Kuhn et al., 2010). In most cases fluency is assessed as reading rate with speed serving as the proxy for the automaticity of word or text reading (Fletcher, Lyon, Fuchs, & Barnes, 2007). Fluency can be assessed at different levels by measuring the amount of time needed to accurately read single letters, single words, sentences, short passages, or longer texts (Fletcher et al., 2007). Those who place an emphasis on prosody or comprehension argue that assessment should include a measure of these components so that reading fluency does not become quick decoding at the expense of comprehension (Kuhn et al., 2010).

The most common method for assessing reading fluency is Curriculum Based Measurement of Oral Reading Fluency (Hudson et al., 2009). Curriculum based measurement (CBM) was designed to monitor student progress in an academic area and to evaluate the effects of instruction on that progress (Deno, 1985). It was developed to provide teachers with a way to assess academic skills that was quick, easy to administer, inexpensive, unobtrusive, sensitive to small changes in progress, reliable, valid, and that could be given frequently (Kuhn et al., 2010). Concerns regarding technical adequacy and practicality of evaluation measures inspired the initial research into the development of CBM (Deno, 1985). CBM has been found to have high reliability and validity (Wayman, Wallace, Wiley, Tichá, & Espin, 2007). Research has found positive academic outcomes when CBM is used for progress monitoring and to inform instructional planning (Fletcher et al., 2007). Measuring prosody is more difficult and so it is done less frequently, and psychometric measures are rare (Hudson et al., 2009).

Reading Disability

Learning to read can be challenging and some individuals experience difficulties with acquiring this skill. Reading disability commonly refers to a heterogeneous group of individuals who have difficulty with learning how to read (Kamhi & Catts, 2012). Reading disability is also known by other terms including specific reading disability, reading disorder, specific reading disorder, dyslexia, and developmental dyslexia, or may be generalized under more broad terms such as learning disability or language-learning disability. Some add the word “developmental” in order to distinguish between acquired dyslexia and developmental dyslexia (Kamhi & Catts, 2012). In acquired dyslexia, the individual was previously able to read but due to some type of brain injury, is no longer able to read efficiently. Although the terms reading disability and dyslexia may be used interchangeably, the term “dyslexia” has become synonymous with word-level reading disability (Fletcher et al., 2007). Reading disability, and learning disability in general, has been difficult to define and a great deal of variability exists in definitions affecting identification, assessment, treatment, and research on reading disability (Kamhi & Catts, 2012). In general, learning disabilities are defined by a deficit in a specific academic skill (Fletcher et al., 2007). Historically, a central concept of learning disabilities was unexpected underachievement meaning that other factors are not the primary cause of the learning disability (Fletcher et al., 2007). More recently, some definitions have added the idea that individuals with learning disabilities have a lack of response to adequate instruction (Fletcher et al., 2007). Research on learning disabilities has identified different subgroups including three forms of reading disability involving problems with word recognition and spelling, reading comprehension, and reading fluency and automaticity (Fletcher et al., 2007).

Among those identified as having a learning disability, 80-90 percent had a reading disability (as cited in Fletcher et al., 2007). Learning disability involving word recognition, or dyslexia, is the most common type of learning disability and also the most researched (Fletcher et al., 2007). Prevalence rates for dyslexia have been reported from 5 to 17.5 percent (as cited in Shaywitz & Shaywitz, 2005). Recent studies have estimated the gender ratio as ranging from 1.4-2 to 1 in favor of males (as cited in Fletcher et al., 2007). Epidemiologic data has shown that reading ability fits a dimensional model with reading ability and reading disability occurring along a continuum (Shaywitz et al., 1992). Prevalence rates depend on the definition and criteria for identification (Shaywitz & Shaywitz, 2008). As well, since reading ability occurs along a continuum, prevalence rates depend on where the cutoff point for disability is set (Fletcher et al., 2007). Reading disability and dyslexia in particular, are persistent difficulties and not developmental lags.

Dyslexia

Developmental dyslexia refers to an unexpected problem in learning to read in individuals who possess all the factors necessary for reading (Shaywitz & Shaywitz, 2005). Definitions of dyslexia have evolved over time from vague and general terms that focused on what dyslexia was not, to more focused definitions that describe inclusionary criteria. The International Dyslexia Association defines dyslexia as follows: “Dyslexia is a specific learning disability that is neurobiological in origin. It is characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities. These difficulties typically result from a deficit in the phonological component of language that is often unexpected in relation to other cognitive abilities and the provision of effective classroom instruction. Secondary consequences may include problems in reading comprehension and reduced reading experience that can impede growth of vocabulary and background knowledge" (Lyon, Shaywitz, & Shaywitz, 2003, p. 2). Longitudinal research has shown that dyslexia is a persistent, chronic condition, and is not a transient, developmental lag (as cited in Shaywitz & Shaywitz, 2005). Individuals do not outgrow reading difficulties. However, the expression of the reading difficulty may change with time. Difficulties with reading accurately may evolve into accurate reading but difficulties with reading fluently (Shaywitz & Shaywitz, 2008).

Theories of Dyslexia

The underlying cognitive and biological causes of reading disabilities are still debated (Ramus et al., 2003). Reading is a complex skill that involves many cognitive abilities and problems could be caused by impairments in any of these abilities (Rayner et al., 2001). Furthermore, there could be variability in causes and subgroups with multiple causes (Rayner et al., 2001). Research on causes of reading disabilities has included children with broad reading difficulties including children with deficits in word recognition and children with deficits in comprehension (Kamhi & Catts, 2012).

A number of theories of dyslexia have been proposed and different versions of each theory exist (Ramus et al., 2003). There may be one theory that accounts for every individual, or different theories may be true for different individuals and different subtypes of dyslexia may be explained by different theories (Ramus et al., 2003).

Proposed theories include: the phonological theory, the rapid auditory processing theory, the visual theory, the cerebellar theory, and the magnocellular theory (see Ramus et al., 2003 for a review). The phonological theory of dyslexia currently has the most support (Shaywitz & Shaywitz, 2005).

The phonological theory proposes that the impairment lies in the representation, storage, and/or retrieval of speech sounds which affects the learning of grapheme-phoneme correspondences and consequently the foundation for learning to read (Ramus et al., 2003). Support for the phonological theory comes from evidence that individuals with dyslexia perform poorly on tasks requiring phonological awareness and more basic phonological skills. Phonological theories of dyslexia propose that the deficit is specific to phonology. Other theories of dyslexia do not dispute the presence of a phonological deficit but propose that the phonological deficit is one consequence of a more general disorder which has its roots in general sensory, motor, or learning processes (Ramus et al., 2003). Many studies have found other cognitive deficits in individuals with dyslexia and some have proposed that a multiple neurocognitive deficit model is needed to understand dyslexia (Menghini et al., 2010). The major criticism of the phonological theory is that it does not explain the presence of motor and sensory deficits in individuals with dyslexia (Ramus et al., 2003). The phonological theory acknowledges that other deficits may co-occur with the phonological deficit, but argues that these deficits are not part of the core features of dyslexia and do not play a causal role (Ramus et al., 2003).

The Neuroanatomy of Reading

The beginning of our understanding of the brain areas involved in reading came from the observations of Dejerine reported in 1891 and 1892. He suggested that two different posterior brain areas, corresponding to the more recently identified parietotemporal and occipitotemporal areas, were critical for reading after observing that lesions in these areas lead to acquired dyslexia (Shaywitz & Shaywitz, 2008). Since then, many cases of acquired dyslexia resulting from lesions in one of these two posterior brain areas have been documented (Shaywitz & Shaywitz, 2008). Now our understanding of the neural systems for reading has largely come from neuroimaging techniques, in particular, functional magnetic resonance imaging.

Many studies have attempted to identify brain areas associated with different component processes of skilled reading (Schlaggar & McCandliss, 2007) including visual word processing, mapping spelling to sound, and semantic processing. Differences in study tasks and stimuli, the language used in the study, anatomical labels, and theoretical interpretations of results create difficulty in comparing studies and combining results from multiples studies, and also result in discrepancies in research findings. But in spite of these difficulties, converging data from numerous studies using brain imaging techniques have identified three brain regions that appear to be involved in skilled reading in adults (for reviews see Sandak, Mencl, Frost, & Pugh, 2004; Schlaggar & McCandliss, 2007; Shaywitz & Shaywitz, 2005). Two of these subsystems are found in posterior regions of the brain, the occipitotemporal system and parietotemporal system, and one is located in anterior regions, the inferior frontal system (Figure 1). Research has also tried to identify the ways these regions interact, and different reading networks and routes have been proposed.

Occipitotemporal Area/ Ventral System

This system includes the left hemisphere occipitotemporal area, fusiform gyrus, and middle and inferior temporal gyri (Sandak et al., 2004). It is believed that initial visual processing of text takes place in bilateral extrastriate regions which then feed into a more anterior left-lateralized region which has been termed by some “the visual word form area” or VWFA (Schlaggar & McCandliss, 2007). This area has been associated with activation typically involving a left occipitotemporal region centered on the mid-fusiform gyrus (see McCandliss, Cohen, & Dehaene, 2003 for a review). This area is one of the most consistently activated areas in meta-analysis studies of adult reading (Schlaggar & McCandliss, 2007). Multiple neuroimaging studies that have contrasted visual words with other complex visual stimuli have observed increased activity in the VWFA (McCandliss et al., 2003). This area has been proposed to process presemantic visual representations of letter patterns within words and pseudowords (Schlaggar & McCandliss, 2007). More anterior regions in this system in the middle and inferior temporal gyri appear to play a role in semantic processing (Sandak et al., 2004).

There is debate as to whether the VWFA is specific for reading, or whether it plays a role in non-reading visual tasks, as well as debate over the specific functional involvement of this area in word recognition (Schlaggar & McCandliss, 2007). Research appears to support a preferential, but not specific, processing of word-forms in the VWFA (Schlaggar & McCandliss, 2007). Different studies have provided support for different hypotheses of VWFA functional involvement: the VWFA stores lexical representations, stores prelexical representations of letter patterns within words, or acts as an interface between visual form information and higher order stimulus properties (Devlin, Jamison, Gonnerman, & Matthews, 2006).

Research examining timing and stimulus-type effects suggests that early in processing posterior extrastriate regions respond to any letter string; then the more anterior VWFA responds preferentially to pseudowords and words over nonpronounceable letter strings, and pseudowords over words; and late in processing the most anterior region responds preferentially to real words as compared to other types of letter strings (Sandak et al., 2004).

Parietotemporal (Temporoparietal) Area/ Dorsal System

This system is located around the parietotemporal junction and encompasses the supramarginal gyrus and angular gyrus in the inferior parietal lobule, and the posterior aspect of the superior temporal gyrus (including Wernicke's Area) (Sandak et al., 2004; Shaywitz & Shaywitz, 2008); this area may also be called the perisylvian region (Schlaggar & McClandiss, 2007). In imaging studies, this system tends to have greater activation while reading pseudowords as compared to real words (Schlaggar & McCandliss, 2007). This system is believed to be involved in word analysis or transforming the orthography into the underlying phonology, operating on individual units of words such as phonemes (Shaywitz & Shaywitz, 2008) and the integration of orthographic and phonological information (Schlaggar & McCandliss, 2007). This area is also involved in phonological processing (Church, Coalson, Lugar, Petersen, & Schlaggar, 2008). Research has suggested that the supramarginal gyrus may be more involved in general phonological processing that in orthography-to-phonology transformation (Church et al., 2008). The angular gyrus has also been found to be involved in semantic processing (Price, 2012; Seghier, Fagan, & Price, 2010).

Inferior Frontal Area/ Anterior System

The anterior area includes the inferior frontal gyrus (including Broca's area) and extends into the premotor cortex (Shaywitz & Shaywitz, 2008). The left inferior prefrontal cortex is involved in a wide range of language tasks (Poldrack et al., 1999). It is proposed to be involved with speech production, active analysis of phonological elements within words (Schlaggar & McCandliss, 2007), silent reading, naming (Shaywitz & Shaywitz, 2008), phonological memory, and syntactic processing (Sandak et al., 2004). Phonological processing not mediated by print or reliant on auditory processing may primarily take place in the ventrolateral prefrontal cortex (Katzir, Misra, & Poldrack, 2005). Within the left inferior prefrontal cortex, the posterior region of the inferior frontal gyrus corresponding to Brodmann Area 44 may be more specialized for phonological processing while the anterior region of the inferior frontal gyrus corresponding to Brodmann Area 45 may be more specialized for semantic processing (Poldrack et al., 1999).

Reading Networks

Research has suggested that there may not be brain regions specific to reading but rather brain areas that perform functions useful to reading (Vogel et al., 2013) and that functional specialization comes from the network of regions that are activated (Price 2012). How these brain areas interact and how these networks account for different reading processes or approaches is still not fully understood. It may be that there are multiple brain regions and multiple networks that underlie reading that have yet to be identified or appreciated in cognitive models (Price, 2012). One study using fMRI found multiple pathways from occipital lobe vision areas to higher-order temporal lobe language areas, each possibly involved in different reading processes (Richardson, Seghier, Leff, Thomas, & Price, 2011).

A meta-analysis of 35 neuroimaging studies conceptualized the findings within the framework of the dual route theory of reading (Jobard, Crivello, & Tzourio-Mazoyer, 2003). The results suggested that brain areas were involved in one of two routes to access words. The "graphophonological" conversion route involved the left superior temporal areas, supramarginal gyrus, and the opercular part of the inferior frontal gyrus. This route corresponded to the indirect route and performed grapheme-phoneme computations. The "lexicosemantic" route involved co-activation of the left occipitotemporal region (visual word form area) and the basal inferior temporal area, the posterior part of the middle temporal gyrus, and the triangular part of the inferior frontal gyrus. This route corresponded to the direct route and directly accessed the word's meaning by visual processing of the visual form of the word.

A recent review of neuroimaging studies of language examined brain areas associated with reading (Price, 2012). This review separated reading research into studies that examined visual word processing and those that examined mapping of orthography to phonology (Price, 2012). Visual word processing studies examined brain areas that are activated more by reading than auditory word processing or visual object naming. This review found that visual word processing involved the ventral occipitotemporal cortex with posterior areas performing visual feature extraction and anterior areas performing lexico-semantic processing of the whole word (Price, 2012).

Findings from studies that examined pathways for converting orthography to phonology were divided into sublexical, lexical, and semantic routes. Similar to the 2003 meta-analysis, this review proposed two routes, a lexico-semantic reading route that involved the left ventral occipitotemporal cortex and the left ventral inferior frontal gyrus, and a non-semantic phonological decoding route that involved the superior temporal cortex, ventral inferior parietal cortex, and dorsal precentral cortex (Price, 2012).

Other Brain Areas

Different neuroimaging studies of reading have also reported activations in other brain areas. Differences in research questions, theoretical frameworks, experimental methods, reading paradigms, and participant samples likely caused different brain areas to be activated, and lead to differences and discrepancies in findings between labs and studies. Furthermore, other brain areas may be activated due to involvement of other cognitive processes in the reading task used in the study such as working memory and response selection. Other brain areas that may be involved in reading include the insular cortex, the superior parietal lobule, and the putamen. One study examining lexical and sublexical reading processes suggested that the insular cortex is sensitive to phonological processing, particularly sublexical spelling-to-sound processing (Borowsky et al., 2006). Some studies have suggested that the superior parietal lobule (also referred to as the posterior or dorsal parietal cortex) may also play a role in skilled reading, specifically visual recognition through its contribution to visual attentional processes (Cohen, Dehaene, Vinckier, Jobert, & Montavont, 2008; Pammer, Hansen, Holliday, & Corenelissen, 2006; Peyrin, Demonet, N’Guyen-Morel, Le Bas, & Valdois, 2011).

Lastly, many neuroimaging studies have reported activations in the putamen (Seghier & Price, 2010). One study examined its role more specifically and found two possible pathways for reading words aloud, a direct pathway and another which involved a pathway from the ventral occipitotemporal cortex to articulatory areas in the prefrontal cortex through the putamen (Seghier & Price, 2010).

Studies of Individuals with Reading Disabilities

fMRI has also been used to investigate differences in the functional organization of the brain for reading in individuals with dyslexia as compared to individuals with non-impaired reading ability. A number of studies have found significant differences in the brain activation patterns between readers with and without reading disabilities. While there are some similarities in the findings, there are also some discrepancies (Maisog, Einbinder, Flowers, Turkeltaub & Eden, 2008). These discrepancies are likely due to differences in task paradigms between studies (Maisog et al., 2008). Many studies have demonstrated disruption in left hemisphere posterior reading systems and overactivation in other parts of the reading system (Shaywitz & Shaywitz, 2008). Hypoactivation in left hemisphere posterior reading systems in dyslexia has been found in posterior parietal cortex, inferior occipitotemporal cortex, and superior temporal gyrus (Maisog et al., 2008). A review of the literature by Schlaggar and McCandliss (2007) found that studies that targeted phonological processing skills demonstrated reduced or absent activation in left perisylvian regions, while studies that isolated visual processing of words demonstrated reduced activation in left ventral occipitotemporal regions, in adults with reading disability. Differences in the left hemisphere anterior reading system have been inconsistent with some studies finding hyperactivation, some studies not finding hyperactivation, and some studies finding hypoactivation, in adults with dyslexia as compared to normal readers (Maisog et al., 2008). One meta-analysis found greater activation in left hemisphere brain areas in normal readers as compared to readers with dyslexia, and greater right hemisphere brain activity in readers with dyslexia as compared to normal readers (Maisog et al., 2008). Another meta-analysis found underactivation in left occipitotemporal regions, left posterior superior temporal regions, and left inferior frontal language regions, and overactivation in precentral and subcortical regions, in adults with dyslexia (Richlan, Kronbichler, & Wimmer, 2011).

Development of Neural Systems for Reading

Studying reading in adults has provided knowledge regarding the neural systems for skilled reading, but does not provide an understanding of how these systems formed. It is important to study children in addition to adults in order to understand how the neural systems for reading emerge and change with development of this skill. It is particularly interesting because reading is a recent human invention and our brains were likely not designed to read. Studying how reading is acquired within the developing brain will help us understand how this skill emerges from preexisting visual and language areas. Since reading needs to be taught, instruction and learning likely cause the development of reading systems in the brain.

Neuroimaging studies of reading in children have begun to emerge in the last decade, in particular, investigating reading difficulties. A meta-analysis of fMRI studies of reading in children found that children engaged brain regions very similar to those in adults (Houdé, Rossi, Lubin, & Joliot, 2010). These regions included left frontal, temporoparietal, and occipitotemporal regions including the visual word form area in the occipitotemporal area, the inferior frontal gyrus and precentral gyrus, and the inferior, middle, and superior temporal gyri and inferior parietal gyrus (Houdé et al., 2010). However, the subjects of the studies included in this meta-analysis had a mean age of 10.8 (±2.3) years, with only two studies including participants less than 7 years of age. The findings from this meta-analysis likely reflect reading systems that are almost fully developed, and not the early development of these systems. The following brief review summarizes research on differences between children and adults, beginning reading skills in children, and early beginning readers, as these studies are most relevant to the current study.

Differences between Children and Adults

Several studies have used a cross-sectional approach comparing adults to children on reading tasks in order to study the differences in functional neuroanatomy underlying reading. Overall, these studies have shown that children use similar neural networks for reading as adults but with some differences in activation patterns. One fMRI study compared children 7 to 10 years of age to adults on a single word processing task that required reading the words aloud (Schlaggar et al., 2002). This study only focused on comparison of left frontal and left extrastriatal activations and separated comparisons into performance-related and age-related regions. They found two age-related regions: one left extrastriate region showed greater activation in children as compared to adults and one left frontal region had greater activation in adults as compared to children. They suggested that the functional neuroanatomy underlying reading is still developing during early school years.

Another fMRI study of individuals from 6 to 22 years of age used an implicit word processing task that involved detecting tall letters within words and matched false font strings; participants were not instructed to read the words and reading was assumed to occur obligatorily (Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). This study found that young readers primarily activated the left posterior superior temporal cortex and that this activity was modulated by the child's phonological abilities. This suggests that the temporoparietal system is involved early in the course of reading development. It was also found that learning to read was associated with increased activity in the left middle temporal and left inferior frontal gyri and decreased activity in the right inferotemporal area.

A more recent study by Church, Coalson, Lugar, Petersen and Schlaggar (2008) found some results different from the previous two studies. This study compared adults to 7- to 10-year-old children while reading single words aloud or repeating aloud an aurally presented word. This study found greater activation in children in many brain areas as compared to adults. The authors suggested that adult brains become more "efficient" and specialized with maturation. Activity in the supramarginal gyrus was weaker in adults as compared to children and activity in the angular gyrus was not present in adults although it was in children. They concluded that this indicated less reliance on phonological processing in children. Also, in children the extrastriate regions showed activity for both the read and repeat tasks suggesting that there is increasing tuning of visual mechanisms with age. This study, in contrast to the two studies described above, did not find increasing left lateralization for single-word reading with development nor did it find any regions showing greater activation in adults as compared to children.

Studies of Beginning Reading Skills in Child Readers

Since phonological skills play a critical role in learning to read and deficits in phonological skills have been shown to play a role in the development of learning disabilities, many neuroimaging studies have specifically focused on these skills. Frost et al. (2009) examined the relationship between phonological awareness and functional activation during speech and print processing in beginning readers 6 to 10 years of age using fMRI. Participants were presented with a picture and had to respond whether it matched or mismatched a spoken or printed word. Printed words consisted of real words, pseudowords, and non-pronounceable consonant strings. They found that behavioural measures of phonological awareness were positively correlated with activation levels in the left superior temporal and occipitotemporal regions for print relative to speech. Activity in the left occipitotemporal area increased in response to print and decreased in response to speech as phonological awareness increased suggesting that the left occipitotemporal area becomes increasingly specialized for the processing of print as individuals acquire reading skills. Also, increasing phonological awareness was related to greater overlap in the activations for print and speech in the left superior temporal gyrus suggesting this region is important in the connection between print and speech.

A study by Bitan, Cheon, et al. (2007) used fMRI to examine developmental changes in activation during a phonological processing task in children ages 9 to 15. Participants had to determine whether two visually presented words rhymed. These word pairs differed in their phonological and orthographical similarity. They found language-specific increases in activation in the left inferior frontal gyrus coupled with decreases in activation in the dorsal superior temporal regions suggesting a shift from using auditory phonological skills in young children to a greater use of phonological segmentation and articulation in older children. Also, they found increased activation in the posterior parietal region with age, an area suggested to be involved in the mapping between orthography and phonology.

In addition to phonological processing skills, reading involves the association of these language sounds with visual print. In a series of studies with adults, Booth and colleagues found that interactions among phonology and orthography were mediated by posterior heteromodal regions including the supramarginal and angular gyrus (Booth et al., 2004). Continuing this research with children, Booth et al. (2004) performed an fMRI study comparing adults to 9- to 12-year-old children. Participants were required to perform word judgment tasks on spelling and rhyming presented in both visual and auditory modes. Adults showed greater activation in the angular gyrus as compared to children during cross-modal tasks suggesting that better reading skill is associated with a more elaborated system for integrating orthographic and phonologic representations.

An important first step in learning to read is to learn the associations between letters and speech sounds, or grapheme to phoneme matching. A study by Blau et al. (2010) specifically investigated the neural correlates associated with the integration of letters and speech sounds in early readers without impairment and readers with dyslexia, 8 to 9 years of age. Participants underwent an fMRI while presented with unisensory letters and speech sounds, and multisensory congruent or incongruent letter-speech sounds pairs. They found that the dorsal part of the left superior temporal gyrus near the primary auditory cortex (planum temporale/Heschl sulcus) and the bilateral superior temporal sulci were involved in the integration of letters and speech sounds. Although, this was consistent with their previous findings with adults, the extent of activation was reduced in children. Also, they found reduced activation in the children with dyslexia as compared to the nonimpaired readers suggesting that letter-speech sound integration develops inadequately in children with dyslexia.

Studies of Early Beginning Readers

Few studies have attempted to examine the emergence of the neural systems for reading in children at the very beginning stages of learning to read. All these studies have compared children demonstrating on track reading development to children at risk of developing reading difficulties, although one study then pooled all results into one analysis (Brem et al., 2010).

One of the first studies to examine children younger than age 7 used fMRI to investigate the neural networks involved in reading in young children (Gaillard, Balsamo, Ibrahim, Sachs, & Xu, 2003). In this study, children 5.8 to 7.9 years old read passages adjusted for reading level. This study found significant activation in similar areas found in adults such as the left inferior occipitotemporal region, left fusiform gyrus, middle temporal gyrus, and premotor areas, and concluded that the neural networks for reading are present by age 7. They also found left-hemisphere lateralization. Their results were similar to those obtained in a similar study with older (8-12) children and adults. Compared to the older children from their previous study, mild decreases in lateralization were observed in the younger children in the frontal regions.

Brem et al. (2010) investigated the emergence of sensitivity to print in the visual-word-form system using fMRI and event-related potentials. In a longitudinal study, brain activity in non-reading 6-year-old kindergarten children was compared in response to words and false fonts before and after grapheme-phoneme training. Prior to training, words and false fonts activated a bilateral, ventral posterior occipitotemporal network. After training, activation was enhanced for print in the left hemisphere posterior visual-word-form area. These results suggest that print sensitivity in the occipitotemporal system emerges during the learning of grapheme-phoneme correspondences and also suggests that this region may first adopt a role in mapping print and sound.

Specht et al. (2009) investigated the differences in brain activations in 6-year-old children considered at risk of developing dyslexia as compared to those not considered at risk while viewing visual stimuli that differed in the required amount of literacy processing. This study took place in Norway where children do not receive formal reading instruction until age seven. The visual stimuli presented in this study fell into four different levels of processing: object recognition (nameable pictures), logographic (brand logos), alphabetic (words with regular spelling), and orthographic (words with irregular spelling). They found differences in the activations between the two groups suggesting that children at risk for dyslexia have different brain responses prior to formal reading instruction. In general, they found increased activations in reading areas in the control group as compared to the at risk group, as the level of literacy processing increased.

Only one study to date has examined children under the age of six in an attempt to examine the emergence of reading circuits at the start of formal schooling (Yamada et al., 2011). This study examined reading networks in 5-year-old children with on-track pre-literacy skills (n=7) or at risk for later reading difficulties (n=7), at both the beginning of kindergarten and at the end of the first semester of kindergarten, using fMRI. Participants were placed into groups based on their scores on the Letter Naming Fluency and Initial Sound Fluency subtests of the Dynamic Indicators of Basic Early Literacy Skills (DIBELS). Participants performed a one-back task with letter versus false font stimuli in order to examine the neural systems supporting letter-name knowledge. At the beginning of kindergarten, the on track group showed increased activation in both the left and right temporoparietal regions during letter processing as compared to false font processing. Children in the at-risk group did not show any differential activation in this region. At the end of the semester, the on track group showed left lateralization of activation in the temporoparietal region. The at-risk group showed bilateral activation in the temporoparietal region as well as bilateral activation of frontal regions. The findings suggest that reading development is associated with initial recruitment of bilateral regions and subsequent disengagement of right hemisphere regions. Also, atypical reading development may be associated with bilateral recruitment of frontal regions. Interestingly, this study did not find greater activation for letters as compared to false fonts in the visual-word-form area or posterior ventral system for any of the groups.

Development of Reading Disabilities

Neuroimaging studies of developmental dyslexia are being extended earlier into development (Schlaggar & McCandliss, 2007). Studies of children with dyslexia are important in order to determine whether the differences in functional neuroanatomy are already present and not simply the result of a lifetime of poor reading (Shaywitz & Shaywitz, 2008). These studies offer insight into the typical development of the neural systems for reading as well.

Many neuroimaging studies have found differences in brain activation patterns during reading tasks between children without reading impairments and children with dyslexia; more specifically, many studies using functional imaging have found dysfunction in the left hemisphere posterior reading systems in children with dyslexia suggesting that differences in reading systems are already present (Shaywitz, Lyon, & Shaywitz, 2006). More recent studies of young children identified as at-risk of developing reading problems have suggested that neural differences between normally developing and at-risk children are already present prior to formal reading instruction (Raschle, Zuk, & Gaab, 2012; Specht et al., 2009; Yamada et al., 2010). Studies have also found greater activation in the right occipitotemporal area in readers with dyslexia suggesting the use of compensatory systems (Shaywitz & Shaywitz, 2005).

A meta-analysis identified left occipitotemporal dysfunction in children with dyslexia but temporoparietal dysfunction was not as clear (Richlan et al., 2011). This meta-analysis also identified overactivation in the left precentral gyrus in children with dyslexia. There was, however, less overactivation than in adults with dyslexia suggesting there may be increases in overactivation with age reflecting increasing reliance on compensatory processes (Richlan et al., 2011).

Intervention Studies

Perhaps the most exciting neuroimaging studies of reading have found that the brain can change in response to reading instruction and intervention. There have been several neuroimaging studies that have investigated changes in brain activity before and after different reading interventions. For example, a number of studies with children (Aylward et al., 2003; Simos, Fletcher, Bergman, et al., 2002; Temple et al., 2003) have found increased activation in the formerly underactive left parietotemporal cortex, following reading intervention which led to improvements in reading skills as measured behaviourally. Another study (Shaywitz et al., 2004) also found increased activation in the occipitotemporal region. A study with adults found increased activation in left hemisphere reading areas as well as increased compensatory activation in the right hemisphere in adults with dyslexia who had received intervention (Eden et al., 2004). In summary, these studies found that following intervention, brain activation patterns became more like those seen in typical readers.

Summary

A complete understanding of how the neural systems for reading develop and how the brain changes as reading is acquired is still in progress. A number of studies have furthered our understanding but there are still some variations in the findings. These variations are likely due to differences in experimental paradigms and differences in the interpretation of brain activations. Brain maturation, skill level, and performance on the in-scanner task all affect activation responses and separating out the relative contributions of each variable presents a challenge (Schlaggar & McCandliss, 2007). Overall, it appears that the neural systems for reading are present by around seven years of age

(Church et al., 2008; Gaillard et al., 2003) but are not fully developed (Schlaggar et al., 2002). Many studies report increasing left lateralization with age (Gaillard et al., 2003; Turkeltaub et al., 2003) although this is not a consistent finding (Church et al., 2008). Differences in the levels of activation with age have also been reported. Greater activations in children as compared to adults have been reported in the extrastriate regions (Schlaggar et al., 2002) and temporoparietal regions (Church et al., 2008). Greater activations in adults as compared to children or with increasing age have been reported in the parietotemporal / supramarginal / angular gyrus regions (Bitan, Cheon, et al., 2007; Booth et al., 2004) and the inferior frontal gyrus (Booth et al., 2004; Schlaggar et al., 2002). These differences in activation levels are difficult to interpret as they could mean a number of things. Increased activation with age could represent a more elaborated system (Booth et al., 2004), reorganization, new representations, or a change in strategy (Bitan, Cheon, et al., 2007). Decreased activation with age could represent less engagement of a cognitive process, or increased neural efficiency (Bitan, Cheon, et al., 2007). Lastly there have been differences in the systems reported as being involved in reading tasks in early readers with some studies reporting recruitment of the parietotemporal areas (Turkeltaub et al., 2003; Yamada et al., 2010), occipitotemporal areas (Brem et al., 2010), or both (Church et al., 2008; Frost et al., 2009).

Goldberg and Costa's Theory of Hemisphere Differences

One theory that may provide a framework for understanding the acquisition of skilled reading and that accounts for findings from neuroimaging research on reading is Goldberg and Costa's theory of hemisphere differences. Goldberg and Costa (1981) propose a functional dichotomy between the two hemispheres based on neuroanatomical differences between the hemispheres and that is consistent with a large amount of experimental data. They propose differential roles for the hemispheres in the development and use of descriptive systems. A descriptive system is defined as “any set of discrete units of encoding or rules of transformation which can be successfully applied to the processing of a certain class of stimuli” (p. 151, Goldberg & Costa, 1981). This theory hypothesizes that the right hemisphere is designed for the processing of novel material for which no descriptive system exists in the individual’s cognitive repertoire, and in the assembling of new descriptive systems. The left hemisphere is designed for the storage of compact codes and utilization of descriptive systems which are fully formed and which are relevant to specific classes of tasks. In the process of acquiring a new skill, the right hemisphere plays a critical role in the initial stages while the left hemisphere is important for the use of well-routinized codes. They propose a right-to-left shift of hemisphere superiority for cognitive skills in the course of their development. Rather than fixed hemisphere specificity for particular tasks, this model proposes “a gradient of relative hemispheral involvement” (p. 165) in cognitive processes, reflecting their degree of routinization. This theory does not treat the brain as two separate processors but appreciates that interaction occurs between the hemispheres in every process.

Reading can be viewed as a descriptive system. Skilled readers would have a fully formed and well-routinized descriptive system for reading available. According to the theory, the left hemisphere would store this code and utilize this descriptive system for reading. Research has demonstrated that the neural systems for reading in skilled adult readers are lateralized in the left hemisphere (Schlaggar & McCandliss, 2007).

Children who have not learned to read would not have a descriptive system for reading available. As they learn to read, they assemble a descriptive system for reading, and with practice this system becomes routinized. According to this theory, children would initially use the right hemisphere to assemble a new descriptive system for reading. As they learn to read and the system becomes routinized, there would be a right-to-left shift of hemisphere superiority. Research has suggested that reading is less left lateralized in children learning to read than in skilled adult readers, and has suggested that children also use the right hemisphere (Gaillard et al., 2003; Turkeltaub et al., 2003). Lastly, some individuals might experience difficulty in assembling a descriptive system for reading and routinizing the code. Based on this theory, it would be predicted that individuals with reading disabilities would use the right hemisphere more and the left hemisphere less, as there would be no fully formed or well-routinized descriptive system for reading stored in the left hemisphere. Research on reading disabilities has found that individuals with dyslexia show less left lateralization than individuals without reading disabilities, and use right hemisphere regions (Maisog et al., 2008; Shaywitz & Shaywitz, 2008).

Functional Magnetic Resonance Imaging (fMRI)

As the current study used fMRI, it is helpful to understand the basic concepts of this technique (see Appendix A for a glossary of fMRI terms). Information processing within the brain depends on the electrical activity of neurons. To investigate brain function, this neuronal activity needs to be measured. This can be done directly by using electrodes to measure electrical changes in neurons. However, implanting electrodes inside the human brain is an invasive procedure and placing them on the outside on the scalp limits spatial resolution. Neuroimaging takes a different approach and assesses neuronal activity *indirectly* by measuring its metabolic correlates (Song, Huettel, & McCarthy, 2006). The leading technique, functional magnetic resonance imaging (fMRI), uses magnetic resonance imaging (MRI) to produce images of the functioning brain (Goebel, 2007).

MRI uses magnetic excitation of body tissue and measurement of returned electromagnetic signals from the body to produce anatomical images of the human body (Goebel, 2007). The most common fMRI method is based on the BOLD (blood oxygenation level dependent) effect and the measured signal is called the BOLD signal (Goebel, 2007). The BOLD effect "measures increased neuronal activity indirectly via a change in local magnetic field homogeneity, which is caused by an oversupply of oxygenated blood" (Goebel, 2007, p. 18).

Neuronal activity uses energy, which comes from glucose and oxygen (Goebel, 2007). These substances are supplied to the brain by the vascular system. Oxygen is transported in the blood via hemoglobin. Oxygenated hemoglobin has different magnetic properties than deoxygenated hemoglobin. An increase in neuronal activity results in increased oxygen use. This also leads to an increase in local blood flow and increased blood volume. The increased need for oxygen results in an increased local supply of oxygenated blood. This response of the vascular system to increased neuronal activity is called the *hemodynamic response* (Goebel, 2007). The increased ratio of oxygenated to deoxygenated blood affects the local magnetic field and leads to a stronger MRI signal in the activated state as compared to a resting state. Thus, changes in the ratio of oxygenated to deoxygenated blood and associated changes in magnetic fields allow for indirect measurement of neuronal activity changes.

In an fMRI experiment, the participant performs cognitive tasks inside the scanner while BOLD images of the brain are collected (Amaro & Barker, 2006). These images illustrate changes in signal level in different areas of the brain (Amaro & Barker, 2006). Signal strength is influenced by a number of factors including natural metabolic rate and distance from the coil (Culham, 2006). The absolute level of activation signal is relatively meaningless on its own. Thus, activation signal in one condition needs to be evaluated relative to another condition (Culham, 2006). By using these images and statistical analyses, the neuronal activity associated with a particular cognitive task can be indirectly measured and brain areas associated with the behaviour can be detected (Amaro & Barker, 2006). fMRI should not be thought of as a single technique as there are many approaches to the collection of fMRI data (Song et al., 2006).

One of the main advantages of fMRI as compared to other techniques for measuring brain activity is its non-invasive nature (Goebel, 2007). Spatial and temporal resolution are also better than other functional neuroimaging techniques (Goebel, 2007). Spatial resolution of a few millimeters and temporal resolution of a few seconds can be achieved (Matthews & Jezzard, 2004). There are also some issues to consider with fMRI experiments. Although it has been demonstrated that the BOLD signal indirectly reflects neuronal activity, the exact relationship and the causal mechanism are still unknown (Song et al., 2006). fMRI is quite sensitive to participant movement which creates artifacts in the images (Matthews & Jezzard, 2004). Spatial resolution, temporal resolution, and amount of brain tissue sampled have a triangular relationship necessitating a compromise between these factors (Amaro & Barker, 2006). fMRI signal changes are small (leading to potential false negative results) and the number of voxels is very large (leading to potential false positive results) (Matthews & Jezzard, 2004). Lastly, there are a number of considerations for statistical analyses including correcting for motion, aligning brains spatially so that different individuals can be compared, and improving the signal to noise ratio (Amaro & Barker, 2006). Despite these limitations and methodological considerations, “fMRI is currently the best tool we have for gaining insights into brain function” (Logothetis, 2008, p. 877).

The noninvasive nature, lack of radiation or exogenous contrast agents, and safe nature of fMRI make it well suited for research with children, offering the opportunity to study the developing brain. However, using fMRI with children is associated with a number of unique methodological considerations (Poldrack, Paré-Blagoev, & Grant, 2002). Probably the largest problem is greater head movement in children while performing an fMRI experiment (Poldrack et al., 2002). Another challenging problem is anxiety about the testing situation and entering the scanner (Poldrack et al., 2002). The paradigm to be used in the scanner needs to be age-appropriate and interesting enough to keep the child engaged for enough time to collect data (Davidson, Thomas, & Casey, 2003). Also, the overall structure and length of the scanning session needs to be developmentally appropriate in order to keep the child’s attention and focus (Davidson et al., 2003). The task needs to be easy to explain, and relatively easy to complete (Davidson et al., 2003). Another consideration is the ability to interact with and provide feedback to the child. Children may require extra encouragement or direction but interaction between the researcher and the child is quite difficult during an fMRI experiment (Davidson et al., 2003). Taking these considerations into account can help in obtaining valid data (Poldrack et al., 2002).

Current Study

Although reading and reading disabilities have been the focus of a great deal of neuroimaging research, how the neural systems for reading develop is still not well understood. Many studies have investigated different component processes of reading such as phonological processing and visual recognition and have tried to link these skills to underlying brain regions and networks. Developmental studies have tried to examine when and how these underlying brain regions and networks emerge and change as these different component processes develop. Many other studies have looked for differences between the brains of skilled readers and individuals with reading disabilities. The current study took a different approach and examined a different aspect of reading: reading fluency. Although reading fluency has been identified as an important component of skilled reading, few studies have tried to examine the underlying neural processes. The few neuroimaging studies on reading fluency examined fluent reading of sentences and focused on neural processes underlying comprehension and reading speed. No published study has investigated the neural processes underlying the development of fluency in young children within the context of a theory.

The purpose of the current study was to compare the neural systems for reading in fluent and nonfluent beginning readers using fMRI, within the framework of the Goldberg and Costa theory of hemisphere differences. This study used a cross-sectional approach to compare low fluency and high fluency readers to try to examine the early development of reading fluency. Beginning readers were divided into low and high fluency groups by their level of fluency in grapheme-phoneme knowledge. Knowledge of grapheme-phoneme correspondences has been proposed to be the key skill in learning how to read and it is one of the first skills to develop automaticity (Castles & Coltheart, 2004; Hudson et al., 2009). This study focused on beginning readers in order to examine the neural systems for reading at the early stages of development. There has been relatively little research on the early development of reading systems.

The Goldberg and Costa (1981) theory of hemisphere differences provided a theoretical framework for conceptualizing the development of reading fluency, accounted for previous neuroimaging findings, and offered predictions that could be examined in the current study. Learning to read can be conceptualized as assembling a new descriptive system. With practice and skill development this code becomes well-routinized. Goldberg and Costa propose that the right hemisphere is used to assemble new descriptive codes while the left hemisphere utilizes fully formed and well-routinized codes. They propose a right to left shift in hemisphere superiority with skill development. Based on this theory, it was predicted that the low fluency group would show less left lateralization and the high fluency group would show more left lateralization, while completing reading tasks.

The current study also aimed to develop a reading paradigm that could be used in fMRI research investigating reading fluency that was similar to measures used in education to assess student's level of reading fluency. Curriculum based measurement (CBM) of reading fluency is a commonly used approach, and is used to monitor student progress and identify students at risk of developing reading difficulties (Deno, 1985; Fletcher et al., 2007). For the current study, CBM letter sound fluency and word identification fluency tests were adapted for use during an fMRI experiment. Letter sound fluency is the first task developmentally used to assess reading fluency followed by word identification fluency (Fuchs & Fuchs, n.d.). The letters task required reading individual letters by mapping graphemes to phonemes. The words task used regularly spelled words that could be read by mapping orthography to phonology, or visual recognition. These tasks also required phonemic awareness, another skill proposed to be essential to learning how to read (Castles & Coltheart, 2005). The aim was to use a paradigm that would engage neural systems in a similar way as measures used in education, so as to examine brain processes for reading fluency as it is commonly conceptualized and measured in education and research.

Advantages of the Current Study

The current study improved on some of the other limitations of previous research. Few neuroimaging studies have examined reading development in very young children. Previous research has suggested that the neural systems for reading may be present by 7 years of age (Church et al., 2008; Gaillard et al., 2003) and may be fairly similar to adults by around 10 years of age (Houdé et al., 2010). The current study focused on children between 6 and 7 years of age in order to examine reading networks at the early stages of development. Many other neuroimaging studies of reading have included participants with a large age range. The current study included participants within a narrow age range in order to reduce any possible confounding effects of brain maturation and task performance. Additionally, the current study used strict inclusion and exclusion criteria to help reduce other possible confounds. For example, this study included only right-handed participants and native English speakers who were not bilingual or attending a second language school or program.

Many neuroimaging studies of reading with children have focused on reading disabilities. Some studies have included a reading disability group or at-risk group based on a family history or genetic risk for reading disability (Brem et al., 2010; Raschle et al., 2012; Specht et al., 2009). The problem with this approach is that these children may not go on to develop a reading disability. Many studies have used clinical measures to assign participants to a reading disability group but there has been considerable variation in the definitions of reading disability, diagnostic criteria, clinical measures, and cutoff scores used. The current study took a different approach and compared children with different levels of reading fluency. Children were assigned to experimental groups using a reading fluency measure commonly used within education to identify children at risk for developing reading difficulties. Reading fluency has been identified as an important factor for skilled reading and poor fluency may underlie some reading disabilities.

There is considerable variability in the tasks used in neuroimaging studies of reading. Some studies have used tasks that involved letter naming (Temple et al., 2001) or word rhyming which may examine skills related to reading development, but did not involve actual reading and may involve other brain areas and networks. Other studies have used "implicit" reading tasks that make the assumption that the participant is reading while completing some other task (Ben-Shachar et al., 2011; Turkeltaub et al., 2003). Some studies have not included a response or a way to evaluate reading accuracy and have assumed that the participant was attending to the task or reading accurately. Many studies have used reading tasks modeled on cognitive psychology research rather than tasks modeled on real-life reading measures used in education or clinical psychology (Bach et al., 2010). Lastly, some tasks may place large demands on other cognitive skills for example, n-back tasks or mental substitution tasks that place large demands on working memory (Bach et al., 2010; Booth et al., 2004). The current study attempted to design a reading task for use during the fMRI experiment that avoided these issues. The task was designed to model tests used in education to measure reading fluency, and to be developmentally appropriate. The task was also designed to be relatively simple to limit demands on other cognitive abilities such as working memory. The task was designed to include a response in order to provide a way to monitor and evaluate engagement in the task, and performance accuracy. Lastly, the reading task underwent a pilot study to evaluate its feasibility and validity prior to the fMRI experiment.

Research Questions

In summary, the following research questions were investigated: Are there differences in brain functional activations between fluent and nonfluent beginning readers in response to letter reading and word reading tasks? Are there differences in lateralization in the reading systems between fluent and nonfluent beginning readers? What brain areas of the reading network will show differences between fluent and nonfluent beginning readers? Based on the previous research (Gaillard et al., 2003; Turkeltaub et al., 2003; Yamada et al., 2011) and the Goldberg and Costa theory, it was predicted that fluent readers would show more left lateralization of activations in the reading systems. Also, based on previous research (e.g. Brem et al., 2010; Frost et al., 2009; Turkeltaub et al., 2003; Yamada et al., 2011), it was predicted that both the parietotemporal and occipitotemporal systems would show differences between the groups. Furthermore, it was expected that the parietotemporal system would show greater difference between the groups due to the focus on grapheme-phoneme mapping and phonemic awareness in the reading tasks. It was also predicted that the inferior frontal system would show differences between the groups and would show greater activation in fluent readers.

CHAPTER 2: METHODS

Participants

Participants were children between 6 and 7 years of age and in Grade 1 or 2. Twenty-four children participated in part one of the study and completed neuropsychological testing. Of these, three participants were not invited to participate in the fMRI experiment as they did not meet eligibility requirements (IQ less than 80 = 2, diagnosis of ADHD = 1) and one participant was lost to follow-up. Twenty children were invited to participate in visit two to complete the fMRI experiment. At the second visit, two participants declined to try the fMRI experiment. Eighteen children attempted the fMRI experiment. Of these, two participants were excluded from data analyses due to excessive movement during scanning (n = 1) or failure to provide responses during the fMRI reading task (n = 1). In total, sixteen children completed neuropsychological testing and the fMRI experiment, and were included in the data analyses. Please refer to Figure 2 for a schematic representation of participant flow through the experiment. Informed consent of the parent or legal guardian and assent of the child were obtained at the start of the first appointment prior to participation. Ethics clearance for this study was obtained from the University of Windsor Research Ethics Board and Wayne State University Institutional Review Board.

The inclusion criteria were as follows: between 6 and 7 years of age and in Grade 1or Grade 2; native English speaker; attending an English language school; right-handed (verified); normal or corrected-to-normal vision; normal hearing; IQ greater than or equal to 80 (assessed as part of the neuropsychological testing). The exclusion criteria were as follows: no significant medical or neurological conditions past or current; no history of or current psychiatric problems including attention deficit hyperactivity disorder (ADHD); never experienced a significant head injury (defined as loss of consciousness greater than 2 minutes and side effects following the injury); no history of major surgeries; not taking medication that affects the nervous system at the time of the study; and no metal in the body, which could interfere with the magnetic field of the MR system during the fMRI experiment.

Participant Recruitment and Initial Screening Process

Participants were recruited by the following methods: letters sent home with all Grade 1 students at 15 schools in the Windsor-Essex Catholic District School Board; advertisements placed in the Windsor Activity Guide, Windsor Parent magazine, and Learning Disability Association of Windsor Essex (LDAWE) newsletter; advertisements placed online (Kijiji, mom2mom classifieds, LDAWE website, Child Neuropsychology Research Group website); posters placed around the community (University of Windsor campus, LDAWE office, Windsor Public Libraries, Ontario Early Years Centres, community centres, bookstores, toy stores, grocery stores, bowling alleys); posters and fliers placed at learning centres (Sylvan Learning Centre, Oxford Learning Centres, Kumon, Enhanced Learning Centre, Colachi Inc. Tutoring, Head of the Class Education Centre); fliers included with registrations packages at the Windsor Lancers, St. Clair College, and LDAWE summer camps; information tables set up at mom2mom community sales and fliers included in the gift bags handed out to attendants; an information table set up at an LDAWE conference on dyslexia; and word of mouth. Recruitment materials and activities asked interested parents to contact the principal investigator via phone or email. Upon initial contact, parents were asked a series of questions to determine their child’s eligibility for the study. The study procedures, participation requirements, and compensation were explained and parents were given the opportunity to ask questions. The initial phone call script and email, and screening questions are included in Appendix D. If parents were interested in participating and their child met eligibility requirements, the first appointment was scheduled.

Approximately 110 parents contacted the principal investigator about the study. Of these, 48 children did not meet eligibility requirements (not between 6 and 7 years of age = 8, left-handed = 7, non-native English speaker = 12, attending French language or French Immersion school = 19, diagnosed with ADHD = 2), 8 parents declined to participate, and 30 were lost to follow-up after receiving information about the study.

Neuropsychological Testing

Neuropsychological testing was performed to verify that participants met the inclusion and exclusion criteria, to determine their reading fluency ability for assignment to experimental group, and to assess cognitive skills believed to be important for reading development or which may have affected performance on the in-scanner reading task. Neuropsychological testing was completed at the first appointment at the University of Windsor. At the start of this appointment, informed consent of the parent or legal guardian and assent of the child were obtained, and the inclusion/exclusion criteria of the study and MR exclusion criteria were reviewed.

Participants were assessed on the following abilities: estimated IQ, attention and working memory, processing speed, phonological processing abilities, symbol processing ability, and reading ability. The parent(s) or legal guardian(s) completed an interview and the Parent Rating Scales of the Behaviour Assessment System for Children, Second

Edition (BASC-2) in order to gather relevant background information related to the child's reading development and to further verify that the child met the inclusion and exclusion criteria of the study. The parent interview script is included in Appendix E. The following is the list of measures that was administered, along with a brief description of each.

Curriculum Based Measurement (CBM) Tests of Reading Fluency

The Vanderbilt University CBM Letter Sound Fluency Test and Word Identification Fluency Test were used in the current study. Curriculum based measurement tests are assessment tools that are used to monitor student progress through the curriculum across an entire school year (Fuchs & Fuchs, n.d.). These measures are given at regular intervals and are used to assess short and long-term student gains toward year-end goals (Fuchs & Fuchs, n.d.). The Letter Sound Fluency Test is used to assess accuracy and speed in identifying letter sounds and beginning decoding in beginning readers (Fuchs & Fuchs, n.d.). The child is presented with a page of 26 random letters and has one minute to say as many letter sounds as he or she can. The Word Identification Fluency Test is used to assess word reading skills in early readers (Fuchs & Fuchs, n.d.). The child is presented with a list of 100 words and has one minute to read as many words as he or she can. For both tests, the score is obtained by subtracting the number of errors from the total number of items read. An adjusted score is calculated if the student reads all of the items in less than one minute.

Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV)

The Wechsler Intelligence Scale for Children – Fourth Edition (WISC-IV; Wechsler, 2003) is a measure of general intellectual ability. In consists of 10 core subtests and 5 supplemental subtests. It provides 4 index scores, which reflect different aspects of intelligence, and an overall IQ score. For the current study, a two-subtest short form of the WISC-IV was administered to estimate Verbal, Nonverbal, and Full Scale IQ; it consisted of the Block Design and Vocabulary subtests. These two subtests have good reliability, correlate highly with the Full Scale IQ, and are good or fair measures of *g* (Sattler & Dumont, 2004). This short form has satisfactory reliability and validity (r_{xx} = 0.92 and r = 0.87) (Sattler & Dumont, 2004). Two other subtests from the WISC-IV were also administered: Digit Span and Coding, to provide estimates of auditory attention and working memory, and visuomotor scanning and processing speed.

Block Design

Block Design is a core subtest of the Perceptual Reasoning Index (PRI). The child is asked to reproduce a geometric pattern illustrated by a model or picture, using blocks with different coloured sides, as quickly as possible. It requires visual analysis, visual-motor coordination, and nonverbal reasoning. Block Design is a reliable subtest with reliability coefficients above 0.83. It contributes substantially to the PRI (average loading = 0.65), and is a fair measure of *g* (49% of its variance can be attributed to *g*) (Sattler & Dumont, 2004).

Vocabulary

Vocabulary is a core subtest from the Verbal Comprehension Index (VCI). The child is asked to orally provide definitions of words. This subtest assesses language development, learning ability, memory, and concept formation (Sattler & Dumont, 2004). This subtest is an excellent estimate of intellectual ability (Sattler & Dumont, 2004). Vocabulary is a reliable subtest with reliability coefficients above 0.82. It contributes substantially to the VCI (average loading = .80), and is the best measure of *g* in the scale (69% of its variance can be attributed to *g*) (Sattler & Dumont, 2004).

Digit Span

Digit Span is a Working Memory Index (WMI) subtest. It assesses short-term auditory memory and attention (Sattler & Dumont, 2004). The child is asked to repeat back a sequence of numbers that becomes increasingly longer. The numbers are repeated back in the same sequence (forward) or the reverse sequence (backward). The Digit Span subtest is considered reliable, having a reliability coefficient above 0.81. It contributes substantially to the WMI (average loading =.54) (Sattler & Dumont, 2004).

Coding

Coding is a subtest from the Processing Speed Index (PSI). It assesses processing speed, visual scanning, and psychomotor speed (Sattler & Dumont, 2004). The child is provided with a key that pairs geometric shapes with special marks. Using this key, the child needs to copy the special mark that corresponds with each geometric shape within each blank test square, as quickly as possible. Coding is a reliable subtest with reliability coefficients above 0.72, and contributes substantially to the PSI (average loading = 0.63) (Sattler & Dumont, 2004).

Wechsler Individual Achievement Test - Third Edition (WIAT-III)

The WIAT-III is a comprehensive test of academic achievement. It assesses 8 areas of academic achievement and consists of 16 subtests. In addition to standard scores, age and grade equivalents can also be calculated. It was designed to identify academic strengths and weaknesses, to inform decisions regarding diagnosis of learning disabilities or eligibility for services, and to design instructional objectives and plan interventions (Miller, 2010). Validity studies of content evidence, convergent evidence, and special group studies have provided evidence of validity for the first two uses (Miller, 2010).

Four subtests from the WIAT-III were used for the current study. The Word Reading subtest assesses accuracy of single word recognition. The Pseudoword Decoding subtest measures phonological decoding abilities. The Early Reading Skills subtest is a new subtest to the WIAT-III. It assesses letter name knowledge, letter sound knowledge, rhyming abilities, word segmentation, sound blending, identification of consonant blends, and basic sight word recognition. Lastly, the Spelling subtest measures letter-sound awareness and written spelling of regular and irregular words. The split-half reliability coefficients for the selected tests are: word reading 0.97, pseudoword decoding 0.96, early reading skills 0.90, and spelling 0.95.

Auditory Closure Test

The Auditory Closure Test is an auditory-linguistic test. Research has shown that performance on the Auditory Closure Test is related to performance on reading measures (Richardson et al., 1980). The child listens to a tape recording of words that have been broken down into their component phonemes and syllables. He or she needs to blend the sounds together of progressively longer chains and identify the word (Kass, 1964 as cited in Rourke & Finlayson, 1978). There are 23 items in total, each worth one point, for a total score of 23 points.

Auditory Analysis Test (AAT)

The Auditory Analysis Test is a test of phonological processing (Baron, 2004). The AAT has been shown to be an indicator of potential language or reading impairment

(Baron, 2004). The child is asked to repeat a word, then repeat the word again but this time after being told to eliminate a particular phoneme or syllable within the word. There are 40 items, each worth 1 point for a correct response, for a maximum score of 40 (Rosner & Simon, 1971).

Sentence Memory Test

The Sentence Memory Test is also known as the Sentence Repetition Test. It requires linguistic knowledge and auditory working memory. It is useful for assessing impairments in phonological working memory and language (Strauss, Sherman, & Spreen, 2006). Children are asked to repeat sentences of increasing length. There are several versions of the test, both individual tests and those included as a subtest in larger measures (Strauss et al., 2006). For the current study, the 26-item version was used (Straus et al., 2006). Each sentence increases in length by one syllable from 1 syllable to 26 syllables. There are 26 sentences in total, each worth one point, for a total score of 26 points. The child must repeat the entire sentence correctly in order to earn the point.

The Underlining Test

The Underlining Test assesses visuomotor speed and attention (Baron, 2004), as well as speed and accuracy of visual discrimination for verbal and nonverbal visual stimuli (Rourke & Orr, 1977). The child is asked to visually search for target stimuli printed within rows of distracters while being timed. The entire test consists of 14 subtests. In general, the target stimuli become more verbal and more complex with each subtest (Rourke, van der Vlugt, & Rourke, 2002). The number of correct targets, the number of incorrect targets (errors), and the net correct (correct targets – errors) are scored. For the current study, 6 of the 14 subtests were administered. The visual stimuli consisted of a single letter, a single geometric shape, a sequence of 4 shapes, a 4-letter non-pronounceable letter sequence, a 4-letter pronounceable nonsense word, and a 4-letter word.

Behaviour Assessment System for Children – Second Edition (BASC-2)

The Behaviour Assessment System for Children, Second Edition (BASC-2; Reynolds & Kamphaus, 2004) provides assessment of a child's behaviours and emotions. The entire measure consists of three different rating scales and two different forms that can be completed by the parent/guardian, teacher, and child to provide three different perspectives. It assesses both strengths and weaknesses across a wide variety of domains. For the current study, the Parent Rating Scales was used to screen for behavioural or emotional problems that may indicate psychiatric or developmental disorders that would exclude the child from participating in the study (e.g., ADHD). It was also used to screen for behavioural or emotional difficulties that would interfere with the child's ability to successfully participate in the fMRI experiment such as anxiety or hyperactivity. Information provided on the BASC-2 was considered along with information provided in the parent/caregiver interview.

Hand Preference Test

The Hand Preference Test from the Harris Tests for Lateral Dominance (Harris, 1947 as cited in Rourke, van der Vlugt, & Rourke, 2002) was used to confirm handedness. On this measure, the child is asked to demonstrate the hand he/she would use to complete 7 different tasks. All children included in the study used their right hand for all 7 tasks. Questions regarding handedness were also included in the parent interview and all children were reported to be right-handed.

Experimental Groups

Two experimental reading groups were compared in data analyses: high fluency reading group and low fluency reading group. Grouping was based on the participant's score on the CBM Letter Sound Fluency Test, which measured fluency of grapheme-phoneme correspondences. Due to the small sample size, participants were assigned to groups by a median split of CBM letter sound fluency scores.

Since IQ, attention and working memory, and processing speed may have affected performance on the fMRI reading task, the reading fluency groups were compared on these abilities. Groups were also compared on their scores on the other neuropsychological testing measures to examine whether there were any differences between the groups in reading ability, phonological processing ability, symbol processing ability, or emotional and behavioural characteristics. Due to the small sample size and the non-normal distribution of scores, the groups were compared using nonparametric statistical tests.

fMRI Reading Paradigm

The fMRI reading tasks were designed to model curriculum based measurement tests of reading fluency. Letter sound fluency and word identification fluency tests were adapted for use in an fMRI experiment. The letters task required reading individual letters by mapping graphemes to phonemes. The words task used regularly spelled words that could be read by mapping orthography to phonology, or visual recognition. All words were the same length (three letters). Stimuli were taken from the Peer-Assisted Learning Strategies (PALS) Kindergarten reading program (Fuchs et al., n.d.), an evidence-based early intervention reading program used school wide in the

Windsor-Essex Catholic District School Board. Visual stimuli consisted of twenty letters, sixty words, and sixty pictures.

Silent reading was chosen over reading aloud to reduce noise from motion in the functional images. A block-design was used for the reading paradigm. A block design was chosen as it allowed for the insertion of pauses between successive scans providing "silent" periods (i.e. periods without scanner noise). The sound stimuli that were part of the reading task were played during these "silent" periods. This allowed for the sounds to be heard more clearly, reduced interference from scanner noise, and reduced selective attention demands. This design is suggested when using auditory stimuli in fMRI experiments with children (Gaab, Gabrieli, & Glover, 2007). A response from the participant following each trial was incorporated into the task design in order to engage attention and to allow for assessment of accuracy and reaction time. Delivery of the reading paradigm was controlled by Presentation software (Neurobehavioral Systems, Inc., Berkeley, CA, USA).

The reading paradigm is depicted in Figure 3. Three different fMRI tasks were administered.

1) Letters: Participants saw individual letters and heard individual phonemes. They needed to indicate whether the letter they saw matched or did not match with the phoneme they heard. For the non-matching trials, the phoneme presented may have been similar sounding (e.g. see a "d" and hear a "t" sound) or non-similar sounding (e.g. see an "l" and hear an "s" sound) to the correct phoneme.

2) Words: Participants saw individual words and heard individual spoken words. They needed to indicate whether the word they saw matched or did not match with the

word they heard. In the non-matching trials, the visual word and spoken word differed either by the beginning sound (e.g. see “man” hear “pan”) or the ending sound (e.g. see “man” hear “mat”).

3) Pictures: Participants saw pictures and heard spoken words. They needed to indicate whether the picture they saw matched or did not match with the word they heard. The pictures task was designed to involve similar cognitive processes as the letters and words tasks including visual processing, speech processing, response selection, and motor response, but not to involve reading.

All visual stimuli were presented in white at the centre of a black screen. All letters and words were in lower case. Auditory stimuli were digitally recorded by a female voice student at a University of Windsor audio recording studio. Sound files were digitally edited using Audacity (version 2.0.2) software to remove noise. As well, sound files were shortened if needed in order to fit within the silent periods in the scanning.

Each task was presented twice, in a separate run, in a counter-balanced order. Each task was presented for two shorter runs rather than one longer run as children tend not to sustain attention as long as adults (Davidson et al., 2003). Multiple shorter runs also provided more opportunity for breaks and for re-engagement of attention. Short rest breaks were provided in between runs. During these breaks, participants were given encouragement, reminded to lie still, and were provided with the task instructions for the next run. The entire experiment consisted of six runs, presented in the following order: pictures, letters, words, letters, words, pictures. The runs alternated between different tasks so as to re-engage attention and to break up easy and difficult tasks. As the pictures task did not involve reading, it was predicted to be the easiest of the three tasks so it was presented first and last so that participants could start and end feeling successful. The letters task was predicted to be the second easiest task so it was presented second, and the words task the most difficult so it was presented third.

For each run, the scan time was 4.5 minutes. Each run was made up of ten blocks and each block was 15 seconds in length. Blocks were separated by fixation rests in which the participant fixated on a visual stimulus at the center of the screen. This fixation rest was a “#” sign for the letters task, “# # #” for the words task, and a 4x4 checkerboard for the pictures task. Each fixation rest was 12 seconds long. Each block contained five trials and contained 80% matching or “congruent” trials or 80% non-matching or “incongruent” trials. One odd trial was randomly placed within each block to help ensure participants maintained attention and did not enter into a response set. Each run consisted of 5 congruent blocks which alternated with 5 incongruent blocks. For each task, half the trials were congruent (matches) and half the trials were incongruent (non-matches). Each run consisted of 50 trials in total, 25 congruent trials and 25 incongruent trials. In summary, for each of the three tasks, there were two separate runs; 20 blocks in total of which 10 were congruent blocks and 10 were incongruent blocks; and 100 trials in total of which 50 were congruent and 50 were incongruent. The overall number of trials and the total length of each run were chosen so as to try to balance collecting enough data for statistical power but not being too long for the young participants. It has been recommended that runs and scanning sessions be kept as short as possible when working with children and some have found 4 to 5 minutes to be an effective length of time for each run (Davidson et al., 2003).

Each trial was 2.6 seconds long. The visual stimulus was presented first and remained on the screen for the entire 2.6 seconds. After one second, the sound stimulus was presented during a 0.4 second silent period in the scanning. Participants then had 1.2 seconds to make a response before the next trial started. Children responded by pressing a button on a handheld fMRI two-button response device. A "match" was indicated by pressing the left button with the index finger, and a "non-match" was indicated by pressing the right button with the middle finger. All participants used their right hand to respond on all trials. Trials were separated by a 0.4s inter-trial interval that consisted of a blank black screen.

At the end of each run, a number of stars corresponding to the number of the run was shown on the screen to indicate to the child that they had completed the run and to indicate how many runs in total had been completed.

Response accuracy and reaction time for each trial of the fMRI reading task was recorded by the Presentation software. Accuracy and reaction time over the course of the experiment were examined for each participant to look for inconsistencies. This may have indicated misunderstanding of instructions, moments of inattention, or a decrease in performance with time. Accuracy and reaction times were also compared between the reading fluency groups.

Pilot Study

A pilot study was conducted to develop and evaluate the fMRI reading paradigm. The pilot study was conducted at two elementary schools in the Windsor-Essex Catholic District School Board during regular school hours. Parent(s) or guardian(s) provided written consent and students provided written assent to participate. Forty-six Grade 1 students with varying levels of reading fluency participated. No background information was collected and participants were not tested on any other abilities. Participants completed the fMRI reading paradigm on a laptop computer. This preliminary study demonstrated that Grade 1 students could easily understand and perform the tasks. Participants were generally able to maintain the speed of stimuli presentation, respond within the response time for each trial, sustain attention for the length of the runs, and did not confuse the response buttons. Participants performed the tasks with accuracy rates of 83% on the pictures task, 77% on the letters task, and 71% on the words task. This pilot study demonstrated that the reading tasks could be easily performed by most Grade 1 students. In order to make group comparisons, it is important that tasks are performed at a similar level by all participants in all groups in order to reduce the possible confound of performance in the functional activation data (Church, Petersen, & Schlaggar, 2010; Davidson et al., 2003).

fMRI Experiment Procedure

The second appointment for the fMRI experiment was scheduled as close in time to the first appointment as possible. The average amount of time between appointment 1 (neuropsychological testing) and appointment 2 (fMRI experiment) was 35 days with a range of 1 to 168 days. The average amount of time between appointments for the high fluency group was 34 days (range = 4-168), and for the low fluency group was 36 days (range = 1-143). An independent-samples Mann-Whitney U Test indicated that there was no significant difference between the groups (U = 32, p = 1.00). In three cases, scheduling conflicts resulted in the two appointments being completed more than one month apart. For these cases, the CBM letter sound fluency measure was repeated at the second visit in order to obtain a more current measurement of fluency at the time of the scan, and group assignment was based on this score.

The fMRI experiment was performed on a 3 Tesla Siemens Magnetrom Verio whole-body scanner located at the Wayne State University MR Research Facility, Harper University Hospital, using a 12-channel volume head coil for the fMRI data collection. The “quality assurance” procedure provided by Siemens under service tools to assess S/N ratio, RF and gradient stability, Eddy current compensation and coil performance, are performed weekly by the technologist (“Tune-up” service is conducted if any of these tests fail).

Prior to the fMRI scanning session, children were acquainted with the scanning environment and procedure to help reduce anxiety and increase compliance. Participants were shown an MR simulator and the procedures were explained. The MR simulator mimics the physical environment of the scanner and the actual sounds of the scanner are played with an audio system. The MR simulator helps to familiarize the child with the MR imaging system. The child was given the instructions for the reading tasks and completed two practice blocks of each task on a laptop computer using a computer mouse to respond, outside of the scanner. All participants were able to learn the fMRI reading tasks quickly and easily.

A certified and registered technologist, who has extensive experience working with children, performed all fMRI data collection. Prior to entering the scanning room, the technologist reviewed the MR exclusion criteria with the participants and their parent(s) or guardian(s). For the experiment, the participant’s head was positioned in the coil and foam pads were used as cushions and to increase motion stability. To help reduce anxiety during the scan, a parent or staff person was present at the foot of the MR table for comforting. The participant was monitored by audio and video link throughout the experiment. The instructions for the task were given prior to each run, as well as reminders to remain as still as possible. Any runs that were quit due to excessive motion were repeated. The fMRI and the anatomical MRI data (T1-weighted images for co-registration) were collected in a single 1-hour session.

Anatomical MRI Acquisition

At the start of scanning, and prior to starting the fMRI experiment and the collection of functional imaging data, high-quality 3D T1-weighted anatomical MRI images were acquired for later co-registration with the fMRI images. Anatomical images were acquired using a 3D Magnetization Prepared Rapid Gradient Echo (MPRAGE) sequence (TR= 2.2s, TE= 3.5ms, TI= 1100ms, flip-angle= 8, FOV= 256x256mm^2, 160 axial slices of thickness= 1mm, matrix= 160x256). The anatomical images were collected first in order to allow the participant time to become familiar with the MR environment and the noise.

fMRI Data Acquisition

A 9 second, 3-plane acquisition sequence was first obtained to ensure the mid-line of the brain coincided with the anterior posterior direction and to verify the subject's cooperation and image quality. The BOLD fMRI data was collected using the gradient echo planar imaging sequence (EPI) with the following parameters: TE= 29ms, TR= 2.6s (with a 0.4s silent period between successive scans), Matrix= 128x128, 95 slices, nominal voxel size 2.0x2.0x3.0mm^3. The high resolution EPI scan reduces partial-volume effects and increases the reliability and specificity of assessing smaller regions of interest. Visual stimuli were presented via a projector system and auditory stimuli were presented though MR compatible headphones, controlled by Presentation software. The participants' responses were collected by a handheld fMRI compatible two choice button box.

fMRI Data Processing and Analyses

fMRI data were preprocessed and analyzed with Statistical Parametric Mapping version 8 (SPM8) software (Functional Imaging Laboratory, London, United Kingdom) and the WFU PickAtlas version 3.0 tool (ANSIR Laboratory Wake Forest University School of Medicine, Winston-Salem, NC, USA) to select regions to include in the region of interest analysis. The dependent measurement for statistical analysis was the fMRI BOLD activity. The preprocessing and statistical procedure is schematically depicted in Figure 4.

Preprocessing

Only participants who had completed at least one entire run of each task were included in the analyses. To determine data quality, each run was examined for motion artifacts. Runs with more than 25% of volumes contaminated by motion or runs with a standard deviation of head motion greater than 5 mm for translation or 5 degrees for rotation were excluded from analyses. fMRI preprocessing included motion correction, co-registration, normalization, and smoothing. For motion correction, functional images were realigned to the first volume using a six-parameter rigid body transformation, and a mean image was created. The mean image was co-registered to the T1-weighted anatomical image. The realigned and co-registered image was corrected for deformations (unwarped) to further remove motion artifacts. The motion corrected and co-registered image was then spatially normalized into standard stereotactic space (MNI template). The computed transformation parameters were applied to all functional images, interpolated to isotropic voxels of 2 x 2 x 2 mm. The resulting images were smoothed (4-mm FWHM, isotropic Gaussian kernel) for statistical analyses.

Statistical Analyses

After preprocessing, first level fixed effects analyses were performed on the images to contrast periods of activation with associated rest periods. Planned contrasts were performed to assess differences between reading-related activity in the letters, words, and pictures tasks, relative to the associated fixation rest. To control for possible effects of motion in pediatric populations, the six movement vectors (three for translation and three for rotation) were included as covariates in the first level analyses. The output from this step is a statistical map for each participant which indicates those areas in the image where the brain activated in response to the stimulation (Smith, 2004).

Second level statistical analyses were performed to combine results across participants to increase the sensitivity of the experiment and to compare the two groups of participants (Smith, 2004). Second level random effects analyses were performed to examine differences in activations between the low and high fluency reading groups on the letters, words, and pictures tasks. To control for potential confounding effects, age and gender were included as covariates.

Areas showing significant difference between the high and low fluency groups were identified using a combination of individual voxel probability thresholding and minimum cluster size thresholding (Ward, 2000). Thresholding refers to the process of selecting and applying values (either voxels or clusters) above a set threshold level of significance to the statistical map. Individual voxel probability threshold was used to identify significant clusters of contiguous voxels meeting the minimum cluster size threshold (Poldrack, Mumford, & Nichols, 2011). The underlying theory is that true activations tend to occur over contiguous voxels, whereas noise is less likely to form clusters of activated voxels (Ward, 2000). The minimum cluster size needed to achieve an overall significance level of $\alpha = 0.05$ was determined by Monte Carlo simulation using Program AlphaSim (Ward, 2000). An uncorrected individual voxel probability threshold of $p < 0.05$ was used. After performing the simulations, the cluster extents that yielded an overall significance level of $\alpha = 0.05$ were identified at the cluster-level significance of $p < 0.05$. Brain labels for significant clusters were determined by converting the MNI coordinates of peak voxels to Talairach coordinates using GingerALE version 2.3.2 (Research Imaging Institute, San Antonio, TX, USA), then using Talairach Client version 2.4.3 (Research Imaging Institute, San Antonio, TX, USA) to label the location of the voxels.

Region of Interest Analyses

A region of interest analysis was performed in order to limit the number of statistical tests and control for multiple comparisons and Type I error (Poldrack et al., 2011). In this approach, analyses are limited to predefined regions of interest (ROIs) (Poldrack et al., 2011). Regions of interest were selected based on the research literature and included brain regions that have been found to be involved in reading and language tasks. Regions of interest were defined using Montreal Neurological Institute (MNI) stereotactic space. The WFU PickAtlas version 3.0 tool (ANSIR Laboratory Wake Forest University School of Medicine, Winston-Salem, NC, USA) was used to select regions to include in the ROIs. All regions were dilated by 2mm. These ROIs were applied as masks in the Monte Carlo simulations to indicate which voxels to include in the cluster formations and to limit the number of voxels available for clustering. For each ROI, a separate Monte Carlo simulation was performed to determine the minimum cluster size for the threshold of $p < 0.05$. This was done to take into account size differences between the ROIs.

Regions of interest included the three brain regions found to be involved in skilled reading. These ROIs were defined as follows: the parietotemporal area consisting of the inferior parietal lobule including angular gyrus and supramarginal gyrus (Brodmann's Areas 39 and 40), as well as the superior and middle temporal gyri including Wernicke's Area (Brodmann's Areas 21, 22, and 42); the occipitotemporal area including the fusiform gyrus (Brodmann's Areas 19 and 37); and the inferior frontal area including the inferior frontal gyrus and Broca's Area (Brodmann's Areas 44 and 45). Other areas that may be involved in reading and included as ROIs were the superior parietal lobule (Brodmann's Areas 5 and 7) and the insular cortex. Lastly, brain areas involved in cognitive processes also needed to perform the fMRI reading paradigm were included as ROIs. These included the dorsolateral prefrontal cortex (Brodmann's Areas 9 and 46) found to be involved in working memory; the anterior cingulate cortex (Brodmann's Areas 24 and 32) found to be involved in response selection, error detection, and conflict monitoring; and the striatum (caudate and putamen) which has been found to be involved in a wide variety of cognitive tasks, including reading. Differences in activations in these brain areas may reflect differences in difficulty and working memory demands between reading tasks and the reading fluency groups. Brain regions excluded from the analyses included the primary motor cortex (Brodmann Area 4), primary visual cortex (Brodmann Area 17), and primary auditory cortex (Brodmann Area 41).

CHAPTER 3: RESULTS

Participant Characteristics

Participant demographic and background information was collected for each participant via parent interview. Information for the total sample and for each reading fluency group is presented in Table 1. Information collected from the interview also confirmed that participants met inclusion and exclusion criteria. An independent-samples Mann-Whitney U Test indicated that there was no significant group difference for age (U = 18, p = 0.161).

Mean estimated IQ scores and subtest scores for the total sample and for the low and high fluency reading groups are presented in Table 2. Independent-samples Mann-Whitney U Tests indicated that there were no significant differences between the low and high fluency groups on estimated IQ, the Block Design subtest, the Vocabulary subtest, the Digit Span subtest, or the Coding subtest (see Table 2 for *p* values). This suggests that any difference between the groups on the fMRI experiment are not due to group differences in IQ, verbal or nonverbal abilities, auditory attention and working memory, or processing speed.

Participants' parent(s) or guardian(s) completed the BASC-2 Parent Rating Scales questionnaire to screen for potential behavioural or emotional difficulties. Mean scores for the total sample and for each reading fluency group are presented in Table 3. There were no significant differences between the low and high fluency groups on any of the BASC-2 subscales or composite scores (see Table 3 for *p* values).

Reading Ability

The high fluency group consisted of 6 students from the Windsor-Essex Catholic District School Board (WECDSB) and 2 students from the Greater Essex County District School Board (GECDSB), while the low fluency group consisted of 6 students from the GECDSB and 2 students from the WECDSB. An independent-samples Mann-Whitney U Test indicated that there was no significant group difference for months of Grade 1 completed (U = 20.5, p = 0.234).

Mean scores on the CBM reading fluency tests and the WIAT-III subtests for the total sample and for each reading fluency group are presented in Table 4. The CBM Letter Sound Fluency Test was used to classify participants into low and high fluency reading groups. Not surprisingly, scores on the CBM Letter Sound Fluency Test were significantly different between the groups (U = 0.00, p = 0.00). The groups, however, did not significantly differ on scores on the CBM Word Identification Fluency Test. This may be the result of the small sample size and insufficient power to detect a significant difference. The groups also did not significantly differ on scores on the WIAT-III Early Reading Skills, Word Reading, Pseudoword Decoding, or Spelling subtests (see Table 4 for *p* values). This may seem contrary to expectations, but in contrast to the CBM tests, these WIAT-III subtests are not timed and do not measure reading fluency. These results suggest that the groups differed in letter sound fluency ability, but did not differ in their abilities to read, decode, and spell accurately when provided with unlimited time.

Participants were also administered measures of phonological processing and symbol processing abilities as these skills have been found to be important for reading. Mean scores on these measures for the total sample and for the low and high fluency reading groups are also presented in Table 4. There were no significant differences between the low and high fluency groups on any of these measures (see Table 4 for *p* values).

fMRI Reading Tasks Performance

The fMRI reading tasks were performed at accuracy rates above chance levels on all runs (Figure 5). The Kolmogorov-Smirnov test of normality indicated that accuracy scores were not normally distributed on some runs so nonparametric statistical tests were used to compare performance between runs. The Friedman Test indicated that there was a significant difference in performance accuracy between runs [X^2 (5) = 24.65, p = 0.00]. Follow-up Wilcoxon Signed-Rank tests (adjusted for multiple comparisons) indicated that there was a significant difference in performance accuracy between runs 1 and 2 (Z = -3.30, p = 0.001), runs 1 and 4 (Z = -3.08, p = 0.002), and runs 1 and 5 (z = -2.71, p = 0.007). The higher performance on the first run may be a result of it being the easiest task, as well as attention being highest at the beginning of the experiment. Reaction times were also compared between runs. The Friedman Test indicated that there was no significant difference in reaction times between runs [X^2 (5) = 7.43, p = 0.19].

Performance accuracy and reactions times on both runs of each task were combined in order to provide mean accuracy scores and reaction times for each fMRI reading task (Figure 6). The Kolmogorov-Smirnov test of normality also indicated that accuracy scores were not normally distributed on all tasks. The Friedman Test indicated that there was a significant difference in accuracy between tasks [X^2 (2) = 24.65, p = 0.00]. Follow-up Wilcoxon Signed-Rank tests (adjusted for multiple comparisons) indicated that there was a significant difference in performance accuracy between the pictures and letters tasks ($Z = -2.85$, $p = 0.004$), and between the pictures and words tasks ($Z = -2.94$, $p = 0.003$). Reaction times were also compared between tasks. The Friedman Test indicated that there was a significant difference in reaction times between tasks [$X^2(2) = 9.13$, $p = 0.01$]. Follow-up Wilcoxon Signed-Rank tests (adjusted for multiple comparisons) indicated that there was a significant difference in reaction times between the pictures and words tasks ($Z = -2.28$, $p = 0.023$). This suggests that the letters and particularly the words tasks were more difficult as compared to the pictures task.

Performance accuracy and reaction times were also compared between the two reading fluency groups. The two-sample Kolmogorov-Smirnov Test indicated that there were no significant differences between the groups in performance accuracy or reaction times on any of the runs (Figure 7). Furthermore, there were no significant differences between the groups in performance accuracy or reaction times on any of the reading tasks (Figure 8). Therefore, this suggests that any differences between the reading fluency groups in functional activations on the fMRI experiment are not due to differences in performance accuracy or speed on the fMRI reading tasks.

fMRI Results

Comparison Between Low and High Fluency Groups

Second level mixed effects analyses were performed to identify differences in functional activations between the low and high fluency groups.

Letters > Rest Contrast

The minimum cluster size that yielded an overall significance level of $\alpha = 0.05$ for the specified individual voxel probability threshold of $p < 0.05$ as determined by Monte Carlo simulation for each ROI are listed in Table 5. The ROIs that contained statistically significant clusters are also indicated in Table 5. The locations of the significant differences in activations between the low and high fluency groups for the letters task greater than fixation rest contrast are indicated in Figure 9. The locations, sizes, and peak voxels of the statistically significant clusters are listed in Table 6.

As compared to the high fluency group, the low fluency group showed a significant cluster of hyperactivation in the right parietotemporal area, in the area of the middle temporal lobe and angular gyrus. There were also large clusters of hyperactivation in the left middle occipital gyrus and right superior parietal lobule. Outside of reading areas, a small cluster of hyperactivation was also found in the frontal lobe in the area of the right anterior cingulate cortex.

As compared to the high fluency group, the low fluency group had significant clusters of hypoactivation in the two left hemisphere posterior reading systems. There was a large cluster in the left parietotemporal area, in the inferior parietal lobule supramarginal gyrus. There was also a significant cluster in the left occipitotemporal area in the left fusiform gyrus, as well as a larger cluster in the corresponding right occipitotemporal area in the right fusiform gyrus. In another potential reading area, there were two smaller clusters of hypoactivation in the left insular cortex and a large cluster of hypoactivation in the right insular cortex. Smaller hypoactivations were also found in the temporal lobes in the right and left middle temporal gyri. Outside of reading and language systems, there were significant hypoactivations bilaterally but with a left lateralization in the prefrontal cortex.

Words > Rest Contrast

The minimum cluster size that yielded an overall significance level of $\alpha = 0.05$ for the specified individual voxel probability threshold of $p < 0.05$ as determined by Monte Carlo simulation for each ROI are listed in Table 7. The ROIs that contained statistically significant clusters are also indicated in Table 7. The locations of the significant differences in activations between the low and high fluency groups for the words task greater than fixation rest contrast, are indicated in Figure 10. The locations, sizes, and peak voxels of the statistically significant clusters are listed in Table 8.

As compared to the high fluency group, the low fluency group showed a significant cluster of hyperactivation in the inferior parietal lobule angular gyrus within the right parietotemporal area. The largest clusters of hyperactivation were located bilaterally in the superior parietal lobules. There was also a small cluster in the right insular cortex. In the temporal lobe, there was a significant cluster of hyperactivation in the left middle temporal gyrus. Outside of reading and language areas, there was a significant cluster of hyperactivation in the prefrontal cortex in the right middle frontal gyrus.

As compared to the high fluency group, the low fluency group showed significant clusters of hypoactivation in all three of the left hemisphere reading areas. There were two significant clusters of hypoactivation in the left parietotemporal area, one in the inferior parietal lobule supramarginal gyrus and one in the posterior middle temporal gyrus. There were bilateral hypoactivations in the occipitotemporal area in the left and right fusiform gyri. Lastly, there was a significant cluster of hypoactivation in the left inferior frontal gyrus, in the pars opercularis. In other possible reading areas, there were significant clusters of hypoactivation bilaterally in the insular cortex. Also, there were significant clusters in the right middle temporal gyrus and the right anterior superior temporal gyrus.

Pictures > Rest Contrast

The minimum cluster size that yielded an overall significance level of $\alpha = 0.05$ for the specified individual voxel probability threshold of $p < 0.05$ as determined by Monte Carlo simulation for each ROI are listed in Table 9. The ROIs that contained statistically significant clusters are also indicated in Table 9. The locations of the significant differences in activations between the low and high fluency groups for the pictures task greater than fixation rest contrast, are indicated in Figure 11. The locations, sizes, and peak voxels of the statistically significant clusters are listed in Table 10.

As compared to the high fluency group, the low fluency group showed a significant cluster of hyperactivation in the left inferior parietal lobule in the supramarginal gyrus. There was also a large cluster of hyperactivation in the corresponding right inferior parietal lobule in the supramarginal gyrus. In other possible reading areas, there was a large cluster of hyperactivation in the area of the left superior parietal lobule and occipital gyrus. Within the temporal lobe language areas, there were significant clusters of hyperactivation in the left and right superior temporal gyrus, and the posterior right middle temporal gyrus. There was also a significant cluster in the right insular cortex. In non-reading areas, there were significant hyperactivations in the right prefrontal cortex in the right middle frontal gyrus, the right cingulate gyrus, and bilateral basal ganglia.

As compared to the high fluency group, the low fluency group showed significant clusters of hypoactivation in two of the left hemisphere reading areas. In the left parietotemporal area, there was a significant cluster in the inferior parietal lobule in the supramarginal gyrus. There was also a significant cluster in the left inferior frontal gyrus. In the corresponding right hemisphere occipitotemporal area, there was a significant cluster of hypoactivation in the posterior inferior temporal gyrus. In other possible language areas, there were significant hypoactivations in the left insular cortex and the right anterior middle temporal gyrus.

CHAPTER 4: DISCUSSION

The purpose of the current study was to compare the neural systems for reading in fluent and nonfluent beginning readers using fMRI. This study examined differences in functional activations in the neural systems for reading between a low fluency and high fluency group of beginning readers during fMRI reading tasks. Beginning readers were divided into low fluency and high fluency groups based on their level of fluency of grapheme-phoneme correspondences. Participants completed three different reading tasks, modeled on CBM tests of reading fluency, during the fMRI experiment. The Goldberg and Costa (1981) theory of hemisphere differences provided a theoretical framework for conceptualizing the development of reading fluency and the results of the study. Fluency has been identified as an important component of skilled reading, yet few studies have tried to examine its underlying neural processes.

Differences between Fluency Groups on the Letters Task

For the letters task, participants saw individual letters and heard individual phonemes, decided whether they matched or did not match, and indicated their response by pushing a button. This task involved phonemic awareness, visual recognition of letters, and knowledge of grapheme-phoneme correspondences. Both fluency groups performed the letters task at above chance levels, and there was no significant difference between the groups in accuracy or reaction time. This suggests that differences in fMRI functional activations were not a result of differences in task performance.

Within the parietotemporal area, the low fluency group showed weaker activation in the left inferior parietal lobule in the supramarginal gyrus, and stronger activation in the right middle temporal gyrus / right angular gyrus, as compared to the high fluency group. These differences between the groups may suggest differences in phonological processing and processing involved in mapping graphemes to phonemes. Conceptualizing these results within the Goldberg and Costa theory, this may reflect greater involvement of the right hemisphere in the low fluency group for processing novel material and assembling a new descriptive system for phonological processing. The greater left hemisphere involvement in the high fluency group may reflect utilization of more routinized descriptive codes for phonological processing and grapheme-phoneme mapping stored in the left hemisphere. These results also suggest that as readers develop fluency in grapheme-phoneme mapping, there is a change in relative hemisphere superiority in the parietotemporal system from the right hemisphere to the left hemisphere.

In the occipitotemporal area, the low fluency group showed weaker activation in bilateral areas of the fusiform gyrus, with a larger cluster of hypoactivation in the right hemisphere, as compared to the high fluency group. This suggests differences between the fluency groups in the visual processing and visual recognition of letters. The low fluency group also showed small clusters of hypoactivation in the right and left middle temporal gyri, possibly part of this visual recognition system. Within the framework of the Goldberg and Costa theory, the greater activation in the high fluency group may reflect that a descriptive system for visual recognition of letters has begun to develop. The larger activation in the right hemisphere than the left, may reflect greater involvement of the right hemisphere for assembling this new descriptive system, and the left hemisphere activations may reflect a shifting in relative hemisphere superiority from the right hemisphere to the left hemisphere in the course of fluency development. The hypoactivations in the low fluency group, and the greater right hemisphere hyperactivations for the high fluency group, suggests that visual recognition of letters has not become a fully formed and well-routinized code for either group.

In other possible reading areas, as compared to the high fluency group, the low fluency group showed weaker activation in the right and left insular cortex, suggesting differences between the groups in phonological processing. The hypoactivation in the low fluency group, corresponding to hyperactivation in the high fluency group, may suggest that a descriptive system for phonological processing has begun to develop in the high fluency group. The larger right hemisphere activation may reflect greater involvement of the right hemisphere in assembling this new descriptive system, and the left hemisphere activations may reflect a shifting in relative hemisphere superiority from the right hemisphere to the left hemisphere in the course of fluency development. The low fluency group also showed greater activation as compared to the high fluency group in the right superior parietal lobule and in an area of the left middle occipital gyrus. The greater activation in these areas may reflect greater involvement of visual attention for the low fluency group.

In other brain areas, as compared to the high fluency group, the low fluency group showed greater activation in the area of the right dorsal anterior cingulate cortex. Given the role of the anterior cingulate cortex in response selection, error detection, and conflict monitoring, this may suggest that the task was more difficult for the low fluency group. Lastly, in the low fluency group, there were multiple clusters of hypoactivation in the middle frontal gyrus. These activations were difficult to interpret, due to their unusual pattern around the edge of the brain. These activations may reflect noise rather than true differences in brain activity.

These results have similarities to other studies that have compared different groups of readers on letter reading tasks. A previous study of young children at-risk and not-at-risk of developing reading problems (mean age 6.4 years) found increased left lateralization in the parietotemporal area in the children not-at-risk of developing reading problems while they pronounced the sounds associated with single letters (Simos, Fletcher, Foorman, et al., 2002). Another study with 8- to 12-year-old children found that normal reading children had significantly greater activity than children with dyslexia in the right occipitotemporal cortex and left occipitalparietal area during orthographic processing of single letter pairs (Temple et al., 2001). The same study also found reduced left-hemisphere temporoparietal activity in children with dyslexia as compared to the normal reading children during a letter rhyming task (Temple et al., 2001). A study of 5-year-old beginning readers found that at the beginning of kindergarten, children with on-track pre-literacy skills recruited bilateral temporoparietal regions during a letter processing task, while children at-risk for reading difficulty showed no activations (Yamada et al., 2010). After three months of kindergarten, the on-track readers had left-lateralized activation in the temporoparietal region, while the at-risk children showed bilateral activation and recruitment of frontal regions including the anterior cingulate cortex. This study did not find greater recruitment in the posterior ventral temporal region in any of the groups for letters as compared to false fonts (Yamada et al., 2010). Lastly, a recent study of phonemic perception and reading development, compared children 7- to 12-years of age with high phoneme perception and low phoneme perception on a phonemic perception task (Conant, Liebenthal, Desai, & Binder, 2014). This study found greater left lateralized processing in the high group and more right-lateralized processing in the low group in the posterior temporoparietal regions. Furthermore, right hemisphere activation was inversely related to reading ability in the children with low phonemic perception, suggesting that the extent of lateralization may be associated with development of phonemic perception (Conant et al., 2014).

In summary, the results from the present study are in line with other studies that have found differences in lateralization between groups of different reading ability on letter reading tasks. These previous studies have similarly found greater activation in the left temporoparietal area in more skilled readers and bilateral activation in the occipitotemporal area in child readers.

Differences between Fluency Groups on the Words Task

For the words task, participants saw individual words and heard individual words, decided whether they matched or did not match, and indicated their response by pushing a button. This task required reading of the words and phonological processing of the auditory word. The words could be read by either the direct or indirect route, therefore, either visual recognition ability or the ability to sound out the word through knowledge of grapheme-phoneme correspondences were required. Both groups performed the words task at above chance levels, and there was no significant difference between the groups in accuracy or reaction time. This suggests that differences in the fMRI activations were not a result of differences in task performance.

Within the parietotemporal area, the low fluency group as compared to the high fluency group, showed greater activation in the right angular gyrus, and weaker activation in the left parietal lobule in the supramarginal gyrus. This suggests differences between the groups in phonological processing and word decoding by linking graphemes to phonemes. Conceptualizing these results within the Goldberg and Costa theory, this may reflect greater involvement of the right hemisphere in the low fluency group for processing novel material and assembling a new descriptive system for phonological processing. The greater left hemisphere involvement in the high fluency group may reflect utilization of more routinized descriptive codes for phonological processing and word decoding by grapheme-phoneme mapping stored in the left hemisphere. These results also suggest that as readers develop fluency in grapheme-phoneme mapping, there is a change in relative hemisphere superiority in the parietotemporal system from the right hemisphere to the left hemisphere.

Within the occipitotemporal area, the low fluency group showed weaker activation in the left and right fusiform gyri and left posterior middle temporal gyrus, as compared to the high fluency group. This difference between the groups in the engagement of the occipitotemporal area may reflect differences between the groups in the visual processing and visual recognition of words. Within the framework of the Goldberg and Costa theory, the greater activation in the high fluency group may reflect that a descriptive system for visual recognition of words has begun to develop. The bilateral activations may reflect the involvement of the right hemisphere in assembling this new descriptive system, and a shifting in relative hemisphere superiority from the right hemisphere to the left hemisphere in the course of fluency development. The hypoactivations in the low fluency group, and the bilateral hyperactivations for the high fluency group, suggests that visual recognition of words has not become a fully formed and well-routinized code for either group.

The low fluency group also showed weaker activation in the left inferior frontal gyrus as compared to the high fluency group in the area of the pars opercularis (Brodmann Area 44), near the middle frontal gyrus, as compared to the high fluency group. The inferior frontal system has been found to be involved in many different language processes but the posterior region of the inferior frontal gyrus corresponding to Brodmann Area 44 may be more specialized for phonological processing (Poldrack et al., 1999). The difference between the groups in engagement of this area may suggest differences in phonological processing. Within the framework of the Goldberg and Costa model, the greater left hemisphere involvement in the high fluency group may reflect utilization of a more routinized descriptive code for phonological processing stored in the left hemisphere.

In other possible reading areas, the low fluency group showed a cluster of hypoactivation in the left insular cortex and clusters of hypoactivation and hyperactivation in the right insular cortex. These differences between the groups may suggest differences in the engagement of the insular cortex for phonological processing. Within the context of the Goldberg and Costa model, the right hyperactivation in the low fluency group may reflect greater involvement of the right hemisphere for processing novel material and assembling a new descriptive system for phonological processing. The bilateral hyperactivations in the high fluency group may reflect the involvement of the right hemisphere for assembling this new descriptive system, and a shifting in relative hemisphere superiority from the right hemisphere to the left hemisphere in the course of fluency development. As compared to the high fluency group, the low fluency group showed greater activation in the left and right superior parietal lobule, with larger clusters in the right hemisphere. This difference in engagement of the superior parietal lobules may suggest greater involvement of visual attention in the low fluency group.

Lastly, as compared to the high fluency group, the low fluency group showed weaker activation in the right anterior superior gyrus. This difference was located in an area possibly involved in semantic processing suggesting differences in the groups in the processing of word meaning. As compared to the high fluency group, the low fluency group also showed greater activation in the right middle frontal gyrus possibly reflecting greater involvement of auditory working memory while completing the task. This suggests that the words task may have been more difficult for the low fluency group.

These results have similarities to other studies that have compared different groups of readers on word reading tasks. One of the first studies to report increasing left lateralization with age, compared children and adults on an implicit word-processing task and found that learning to read was associated with increased activity in left hemisphere middle temporal and inferior frontal gyri, and decreased activity in right inferotemporal area (Turkeltaub et al., 2003).

One of the first studies of dyslexia in children compared children with dyslexia to children without reading impairment (7-18 years of age) while reading pseudoword (nonword rhyme task) and real words (semantic category judgment task) (Shaywitz et al., 2002). They found that children without reading impairment showed greater activation than children with dyslexia in the left hemisphere inferior frontal, superior temporal, parietotemporal, and middle temporal-middle occipital gyri. They also found that the level of activation in the left occipitotemporal region was positively correlated with reading skill. Another study compared children (mean age 8.3 years) with age-appropriate and poor reading ability on a reading and mental letter substitution task and found stronger left hemisphere involvement in normal readers, more bilateral activation in poor readers, and found that activation in the left inferior frontal gyrus and insula increased with better reading skills (Bach et al., 2010).

A recent study of phonological and auditory processing in beginning readers (5.47-8.89 years of age), whose reading abilities ranged from reading disability to superior ability, found that reading circuitry in beginning readers was more broadly distributed when presented with pseudowords or words visually or auditorily (Pugh et al., 2013). This study also found positive correlations between reading ability and left hemisphere temporoparietal, occipitotemporal, and inferior frontal areas, and right hemisphere parietal and temporal areas.

Lastly, a longitudinal study followed children 7- to 12-years of age with a wide range of reading skills for 4 years to examine changes in cortical sensitivity to visual word forms (Ben-Shachar et al., 2011). This study found age-related increases in activation in the left hemisphere occipitotemporal area near the location of the visual word form area during an implicit word processing task, which matched the change in the individual's ability to read sight words. The right homologue of this region did not demonstrate a developmental change.

In summary, the results from the present study are in line with other studies that have found differences in lateralization between groups of different reading ability. These previous studies similarly found more broadly distributed and greater bilateral activations in beginning readers, and greater activation in left parietotemporal and inferior frontal areas in more skilled readers. While the current study found bilateral hyperactivation in the occipitotemporal area in the more fluent readers, these previous studies suggest that it becomes left-lateralized with age and skill development.

Differences between Fluency Groups on the Pictures Task

For the pictures task, participants saw pictures and heard spoken words, decided whether they matched or not, and indicated their response by pushing a button. This task involved similar processes as the letters and words tasks including visual processing, speech processing, response selection, and motor response, but did not involve reading. Both groups performed the pictures task at above chance levels, and there was no significant difference between the groups in accuracy or reaction time. This suggests that differences in the fMRI activations were not a result of differences in task performance.

Although the pictures task did not involve reading, there were differences between the groups in similar brain areas possibly due to other similarities in the fMRI tasks. Within the parietotemporal area, the low fluency group showed a large cluster of hyperactivation in the right inferior parietal lobule in the supramarginal gyrus and smaller clusters of hyperactivation and hypoactivation in the left inferior parietal lobule in the supramarginal gyrus, as compared to the high fluency group. These differences between the groups may suggest differences in phonological processing of the spoken words. Conceptualizing these results within the framework of the Goldberg and Costa model, the larger cluster of hyperactivation in the right hemisphere in the low fluency group may reflect greater involvement of the right hemisphere for processing novel material and assembling a new descriptive system for phonological processing. The smaller left hemisphere hyperactivations may reflect a shifting in relative hemisphere superiority from the right hemisphere to the left hemisphere in the course of fluency development. The left hemisphere hyperactivation in the high fluency group may reflect utilization of a more routinized descriptive code for phonological processing stored in the left hemisphere. These results also suggest that as readers develop fluency in grapheme-phoneme mapping, there is a change in relative hemisphere superiority in the parietotemporal system from the right hemisphere to the left hemisphere.

In the occipitotemporal area, the low fluency group showed weaker activation in the right inferior temporal gyrus as compared to the high fluency group. This suggests differences between the groups in visual processing of the pictures. The location of this hypoactivation in the right hemisphere may reflect that the pictures were nonlinguistic stimuli and the right hemisphere may be more involved with visual processing of nonlinguistic stimuli such as objects (Nakamura et al., 2005).

As compared to the high fluency group, the low fluency group showed weaker activation in the left inferior frontal gyrus, in the pars triangularis (Brodmann Area 45). The inferior frontal system has been found to be involved in many different language processes but the anterior region of the inferior frontal gyrus corresponding to Brodmann Area 45 may be more specialized for semantic processing (Poldrack et al., 1999). This finding may reflect differences between the groups in the semantic processing of the spoken words and the pictures of objects. Framing this within the Goldberg and Costa model, the greater left hemisphere involvement in the high fluency group may reflect utilization of a more routinized descriptive code for semantic processing stored in the left hemisphere.

The low fluency group showed weaker activation in the left insular cortex and greater activation in the right insular cortex, as compared to the high fluency group. These differences between the groups may suggest differences in the engagement of the insular cortex for phonological processing of the spoken words. Within the Goldberg and Costa framework, this may reflect greater involvement of the right hemisphere in the low fluency group for processing novel material and assembling a new descriptive system for phonological processing. The greater left hemisphere involvement in the high fluency group may reflect utilization of a more routinized descriptive code for phonological processing stored in the left hemisphere. These results also suggest that as readers develop fluency in grapheme-phoneme mapping, there is a change in relative hemisphere superiority in the insular cortex from the right hemisphere to the left hemisphere. As compared to the high fluency group, the low fluency group showed greater activation in the left superior parietal lobule, which may suggest greater involvement of visual attention in the low fluency group.

Lastly, the low fluency group showed multiple small clusters of hyperactivation in the temporal lobe, middle frontal gyrus, cingulate gyrus, and striatum. This suggests the low fluency group may have engaged areas of the brain involved in auditory and speech processing, working memory, response selection and error monitoring, and motor responding, more than the high fluency group. This suggests that the pictures task may have been more difficult for the low fluency group despite the task not involving reading.

Differences in Reading Systems between Fluency Groups

Across the three different tasks, there were similarities in the results. Within the three reading systems, there were differences between the groups in activations in the parietotemporal area across all three tasks, suggesting differences in phonological processing during all three tasks. The differences were largest during the letters and words tasks possibly reflecting additional differences in processing grapheme-phoneme correspondences. There were also differences between the groups in activations in the occipitotemporal area across all three tasks, suggesting differences in visual processing during all three tasks. The differences were bilateral and larger during the letters and words tasks possibly reflecting greater differences in visual recognition of letters and words. There were differences in activations between the groups in the inferior frontal gyrus during the words and pictures tasks suggesting differences in phonological and semantic processing of the spoken words. There was no significant difference between the groups during the letters task possibly because this task involved letters only and not words.

In other possible reading areas, there were differences between the groups in activations in the insular cortex during all three tasks suggesting differences in phonological processing. Across all three tasks, the low fluency group had greater activation in the superior parietal lobules possibly reflecting greater involvement of visual attention. In other brain areas, the low fluency group had greater activation in the anterior cingulate cortex during the letters and pictures tasks suggesting that these tasks may have been more difficult for the low fluency group. There was no significant difference during the words task, suggesting that this task may have been difficult for both groups. Differences in the temporal lobes, prefrontal cortex, and striatum depended on the individual task and there were no similarities across tasks.

Reading Fluency and the Goldberg and Costa Theory

The purpose of the current study was to investigate differences in the neural systems for reading between fluent and nonfluent beginning readers. The Goldberg and Costa theory of hemisphere differences provided a framework for conceptualizing the development of reading fluency, previous neuroimaging findings, and the current study results. Overall, differences in hemisphere superiority between the low and high fluency groups depended on the particular brain area. This may suggest that the development of fluency and the underlying neural changes are independent for each component skill of reading.

Within the three brain systems for reading, there was greater activation in the left parietotemporal area in the high fluency group as compared to the low fluency group during all three tasks. This may reflect greater utilization of a more routinized descriptive system for phonological processing stored in the left hemisphere. This activation was larger in the letters and words tasks than the pictures task possibly reflecting utilization of a descriptive code for grapheme-phoneme mapping as well. In addition, there was also greater activation in the right parietotemporal area in the low fluency group as compared to the high fluency group during all three tasks. This may reflect greater involvement of the right hemisphere in the low fluency group for processing novel material and assembling a new descriptive system for phonological processing. These results suggest a change in relative hemisphere superiority from the right hemisphere to the left hemisphere in the parietotemporal system as readers develop fluency in grapheme-phoneme mapping.

There was greater activation in the right and left occipitotemporal area in the high fluency group as compared to the low fluency group during the letters and words tasks. This may reflect that a descriptive system for visual recognition of letters and words has begun to develop in the high fluency group. The bilateral activations may reflect the involvement of the right hemisphere in assembling this new descriptive system and the shifting in relative hemisphere superiority from the right hemisphere to the left hemisphere in the course of fluency development. The bilateral activations may also reflect that visual recognition of letters or words has not become fully formed and well-routinized codes. These results correspond with previous studies that have found that the parietotemporal region is recruited earlier in reading development and that the occipitotemporal system develops later and is related to development of reading skill (Blomert, 2011; Turkeltaub et al., 2003).

Lastly, there was greater activation in the left inferior frontal area in the high fluency group as compared to the low fluency group during the words and pictures tasks. This may reflect greater utilization by the high fluency group of more routinized descriptive systems for phonological and semantic processing of words stored in the left hemisphere.

Although there have been no similar neuroimaging studies of reading fluency, previous studies have compared groups of readers of different ages and reading ability. In general, these studies have found increased left lateralization in reading systems in adults as compared to children (Turkeltaub et al., 2003) and children with normal reading development as compared to children with dyslexia or at-risk of developing reading difficulties (Simos, Fletcher, Foorman, et al., 2002; Yamada et al., 2010). Longitudinal studies have also found increased left lateralization with age and reading development (Ben-Shachar et al., 2011; Yamada et al., 2010). The results from the current study are in line with these previous studies in that increased left lateralization was found in the more skilled reading group as compared to the less skilled reading group. The Goldberg and Costa theory and the findings from the current study suggest that the increased left lateralization found in the more skilled reading group in other studies may be a result of greater fluency in reading skills.

Numerous studies have identified that the neural systems for reading in skilled adult readers are located in the left hemisphere (Schlaggar & McCandliss, 2007). Research has also found involvement of right hemisphere homologous regions but the role of the right hemisphere in reading has not been systematically investigated (Yamada, 2010). Studies of adults with dyslexia and children with dyslexia or at risk of developing reading problems have suggested that the right hemisphere involvement may be a compensatory mechanism for faulty left hemisphere reading systems (Yamada et al., 2010). The current study supports previous research (Pugh et al., 2013; Yamada et al., 2010) that suggests that engagement of the right hemisphere is a normal part of early reading development, consistent with what would be predicted based on the Goldberg and Costa theory. Yamada et al. (2010) propose that the right hemisphere homologue of the posterior dorsal region may be recruited as a "scaffolding mechanism" to help with task demands in unskilled readers including beginning readers and individuals with dyslexia. Pugh et al. (2013) speculate that right hemisphere involvement as well as the involvement of the anterior cingulate, prefrontal networks, and possibly subcortical areas, reflects greater semantic, attentional, and cognitively controlled processing as children learn how to read. The current study suggests a different framework of hemisphere differences for understanding the involvement of the right hemisphere in reading that can also incorporate these other explanations. Within the Goldberg and Costa framework, Yamada and colleagues' (2010) "scaffolding mechanism" could be conceptualized as the development of a new descriptive system related to reading. Pugh and colleagues' (2013) speculation would be consistent with the role of the right hemisphere in processing novel material and assembling new descriptive systems for reading.

Limitations of the Present Study and Directions for Future Research

Although the current study attempted to improve upon previous research in many ways, it is not without limitations. The most significant limitation of the current study is the small sample size. The small sample size limited statistical power and consequently limited the statistical analyses that could be performed on the data. A number of factors affected participant recruitment including the need to travel across an international border, scheduling availability limiting participation to work and school hours, and general misunderstanding regarding the safety of fMRI research. The narrow age range and strict inclusion criteria while an advantage of the current study, also made recruiting participants difficult. It appears many other studies with children may have experienced the same difficulty and have used small sample sizes (Aylward et al., 2003; Schlaggar et al., 2002; Simos, Fletcher, Bergman, et al., 2002; Yamada et al., 2010), large age ranges (Ben-Shachar et al., 2011; Bitan, Cheon, et al., 2007; Conant et al., 2014; Frost et al., 2009; Schlaggar et al., 2002; Shaywitz et al., 2002; Temple et al., 2001; Turkeltaub et al., 2003), more lenient inclusion criteria (Landi et al., 2010), or have conducted their research over long periods of time (Church et al., 2008; Pugh et al., 2013; Simos, Fletcher, Foorman, et al., 2002; Specht et al., 2009). Future research needs to recruit more participants to increase statistical power. This may involve exploring different ways to recruit participants, eliminating barriers to participation, and conducting the research over a longer time period.

Another factor that contributed to the small sample size was the inherent difficulties in conducting fMRI research with young children. Young children experience more anxiety than adolescents and adults, lose focus more quickly than adults, and have greater head motion than adults (Davidson et al., 2003; Poldrack et al., 2002). One study also found greater head motion in children with dyslexia as compared to children with normal reading (Poldrack et al., 2002). In the current study, two participants declined to attempt the fMRI experiment due to anxiety, and two participants' fMRI data could not be used due to anxiety or excessive motion. For the participants included in the analyses, some individual runs also needed to be excluded due to excessive motion during those runs. One large-scale fMRI study of language development in normal children found that failure rates were significantly higher for younger children than older children or adolescents, with a 47% failure rate for 6-year-old children and 32% failure rate for 7-year-old children (Byars et al., 2002). In comparison, the present study had a failure rate of 20%. Future research should consider additional methods for reducing anxiety and motion to help increase the amount of useable data.

The small sample size also affected the assignment of participants to reading fluency groups. Due to the small sample size, all participants who had successfully completed the fMRI experiment were included in the analyses and participants were assigned to fluency groups based on a median split of their CBM letter sound fluency scores. Consequently, assignment to reading fluency groups was based on an arbitrary criterion and participants scoring near the cutoff may not have been assigned to the correct group, or at least not differed meaningfully from the adjacent participant assigned to the other group. Future research should attempt to assign participants to groups based on a research or clinically supported criteria such as those participants who have achieved Grade 1 benchmark and those who have not. Participants who score close to the cutoff may need to be excluded from data analyses to account for measurement error and to reduce the chance that participants are assigned to the incorrect group.

The present study compared two groups of beginning readers of low fluency ability and high fluency ability as determined by one fluency measure. The reason or cause for a participant's level of fluency was not taken into consideration. A participant's level of fluency may have been related to amount of reading exposure, instruction, or practice; school board membership; variations in schools and teachers; or inherent difficulties with learning to read, possibly indicating a reading disability. Grouping all low fluency participants into one group may have introduced a confound in the fMRI data. Given the preliminary nature of the current research, this study was interested in examining differences between fluent and nonfluent readers regardless of the cause of low fluency. Future research could separate nonfluent participants into groups based on whether they are nonfluent due to experience (e.g., insufficient exposure, instruction, and practice) versus those who are nonfluent because they have a reading disability, in order to examine differences between different types of low fluency readers. Also, the present study used a cross-sectional design to compare two groups of readers and examine neural differences related to fluency. Longitudinal studies are needed to further investigate developmental changes in reading fluency and the associated neural changes. An added advantage is that each participant becomes his or her own control.

The present study attempted to design a reading task for use during the fMRI experiment that modeled Curriculum Based Measurement tests of reading fluency, was developmentally appropriate, and that also met the conditions for fMRI paradigms. The task was designed to include a response so that engagement in the task and performance could be monitored. These tasks used a “match” or “non-match” response paradigm. Due to the small sample size and in order to increase statistical power, all blocks were included in the analyses. Consequently, matching or “congruent” blocks and non-matching or “incongruent” blocks were treated the same. Previous studies have found differences in functional activations between “congruent” and “incongruent” combinations of visual and auditory stimuli (van Atteveldt, Formisano, Goebel, & Blomert, 2004) and “consistent” or “inconsistent” pairs of orthographic and phonologic information (Bitan, Burman, et al., 2007). Grouping all blocks together for analyses within the current study may have created a confound in the fMRI data. With a larger sample size, future research could separate the congruent and incongruent blocks for analyses in order to reduce any effects of visual-auditory congruency and incongruency on the results. Another limitation of the fMRI paradigm was the use of a block design. In this design, all trials within each block are grouped together for analyses. Consequently, correct and incorrect trials are treated the same. It is possible that incorrect trials are not exactly the same as the participants may not have paid attention or engaged in the task, or may have used a different approach on that trial. Future research may wish to explore other experimental designs or analysis approaches.

Lastly, due to the small sample size, the current study interpreted the neuroimaging results qualitatively. Future studies could use quantitative approaches to analyze the fMRI data and to compare results between the two fluency groups, the three reading tasks, and the two hemispheres. For example, some studies have calculated a "lateralization index" (Bach et al., 2010) or "lateralization quotient" (Yamada et al., 2011) to examine the laterality of activations. Given the importance of lateralization in the current study, calculating a lateralization quotient may have provided a more accurate way to determine laterality and compare the fluency groups.

Conclusion

In conclusion, the present study provides preliminary evidence that beginning readers with different levels of reading fluency may engage neural systems for reading differently. This study also suggests a theory, the Goldberg and Costa theory of hemisphere differences, that provides a framework for conceptualizing the development of skilled reading and that accounts for neuroimaging findings. The present study compared beginning readers with high and low fluency in knowledge of grapheme-phoneme correspondences. Overall, differences in hemisphere superiority between the low and high fluency groups depended on the particular brain area. This may suggest that the development of fluency and the underlying neural changes are independent for each component skill of reading.

Within the three brain systems for reading, the present study found greater activation in high fluency as compared to low fluency beginning readers in the left parietotemporal area during letter and word reading tasks, as well as a picture viewing task, a brain area involved in phonological processing, grapheme-phoneme mapping, and word decoding. There was also greater activation in low fluency as compared to high fluency beginning readers in the corresponding right parietotemporal area. Conceptualizing these results within the Goldberg and Costa theory, the greater left hemisphere involvement in the high fluency group may reflect utilization of more routinized descriptive codes for phonological processing, grapheme-phoneme mapping, and word decoding stored in the left hemisphere. The greater right hemisphere involvement in the low fluency group may reflect processing of novel material and assembling of new descriptive systems for these skills. These results also suggest that as readers develop fluency in grapheme-phoneme mapping, there is a change in relative hemisphere superiority in the parietotemporal system from the right hemisphere to the left hemisphere. There was also greater activation in the high fluency group as compared to the low fluency group in the left inferior frontal area during the words and pictures tasks, an area involved in phonological and semantic processing. This may reflect utilization by the high fluency group of more routinized descriptive systems for phonological and semantic processing of words, stored in the left hemisphere. The present study also found greater activation in high fluency as compared to low fluency beginning readers in bilateral occipitotemporal areas during letter and word reading tasks, an area involved in visual recognition of letters and words. Within the framework of the Goldberg and Costa theory, this suggests that a descriptive system for visual recognition of letters and words has begun to develop in the high fluency group. The bilateral activations may reflect the involvement of the right hemisphere in assembling this new descriptive system and a shifting in relative hemisphere superiority from the right hemisphere to the left hemisphere in the course of fluency development.

Developmentally, readers first develop fluency in phonemic awareness and knowledge of grapheme-phoneme correspondences before developing fluency in visual word recognition. Furthermore, research has suggested that the parietotemporal system develops first, whereas the occipitotemporal system develops later in reading development, following skill development. Previous neuroimaging studies that have compared adults and children, and children with normal reading development to children with dyslexia or at-risk of developing reading difficulties, as well as longitudinal studies of children, have found greater left hemisphere lateralization in the more skilled reading group. The Goldberg and Costa theory and the findings from the current study suggest that increased left hemisphere lateralization in the more skilled reading group may be related to greater fluency in reading skills. Furthermore, the current study supports previous research that suggests that engagement of the right hemisphere is a normal part of early reading development. More research is needed to further our understanding of the neural mechanisms underlying reading fluency, its development, and its role in skilled reading and reading disability.

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Table 1

Participant demographic and background information

	Total n = 16	**High fluency group n = 8**	**Low fluency group n = 8**
Gender	9 males, 7 females	5 males, 3 females	4 males, 4 females
School Board			
Public	8	2	6
Catholic	8	6	2
Age started to read (mean/SD)	4.73 (0.62)	4.71 (0.57)	4.75 (0.71)
Frequency of Reading			
Daily	14	7	7
4-6 times per week	2	1	1
Enjoys reading	13	6	7
Parent reported concerns with:			
Language development	4	2	2
Reading development	4	3	1
School performance	3	2	1
Learning problems	3	3	0
Psychological or behavioural problems	2	2	0
Learning disability diagnosis	0	0	0
Exceptionality identification	0	0	0
School interventions for reading	4	2	2
Outside reading help	4	3	1
Family history reading problems	3	2	1

Table 2

Mean age and mean scores on the WISC-IV

	Total **n = 16**		**High fluency** **n = 8**		**Low fluency** **n = 8**		**p-values high vs. low**
	Mean (SD)	**Range**	**Mean (SD)**	**Range**	**Mean (SD)**	**Range**	
Age in months	81.69 (5.40)	73 – 93	83.88 (5.08)	75 – 93	79.50 (5.07)	73 – 86	0.161
WISC-IV							
Estimated IQ	109.06 (15.49)	85 – 138	111.75 (11.54)	85 – 123	106.38 (19.09)	85 – 138	0.574
Blocks	12.19 (3.19)	6 – 18	12.38 (3.07)	6 – 16	12.00 (3.51)	8 – 18	0.645
Vocabulary	10.94 (3.21)	6 – 16	11.63 (2.92)	8 – 16	10.25 (3.54)	6 – 15	0.328
Digit Span	10.44 (2.13)	6 – 14	10.75 (2.25)	6 – 14	10.13 (2.10)	8 – 14	0.382
Coding	10.00 (3.06)	7 – 17	10.50 (3.51)	7 – 17	9.50 (2.67)	7 – 15	0.645

Note. SD = standard deviation; WISC-IV = Wechsler Intelligence Scale for Children – 4th Edition.

Table 3

Mean T-scores on the BASC-2 Parent Rating Scales

	Total n = 16		**High fluency** n = 8		**Low fluency** n = 8		**p-values high vs. low**
	Mean (SD)	**Range**	**Mean (SD)**	**Range**	**Mean (SD)**	**Range**	
Externalizing Problems	44.88 (6.52)	38 – 57	46.50 (7.71)	38 – 57	43.25 (5.06)	38 – 53	0.574
Hyperactivity	47.50 (7.14)	38 – 66	48.75 (8.65)	38 – 66	46.25 (5.55)	40 – 53	0.645
Aggression	45.63 (5.83)	36 – 57	47.63 (6.74)	41 – 57	43.63 (4.27)	36 – 50	0.328
Conduct Problems	43.38 (7.55)	34 – 59	44.38 (8.40)	34 – 59	42.38 (7.03)	34 – 56	0.645
Internalizing Problems	48.31 (8.66)	33 – 68	50.38 (6.02)	39 – 59	46.25 (10.70)	33 – 68	0.195
Anxiety	52.63 (10.74)	33 – 78	54.00 (8.38)	38 – 62	51.25 (13.13)	33 – 78	0.382
Depression	47.50 (6.04)	37 – 61	49.25 (5.18)	45 – 61	45.75 (6.67)	37 – 59	0.195
Somatization	45.94 (8.18)	36 – 59	47.63 (8.45)	36 – 59	44.25 (8.08)	36 – 56	0.442
BSI	46.31 (5.88)	37 – 58	47.13 (6.98)	37 – 58	45.50 (4.90)	37 – 55	0.959
Atypicality	48.81 (7.19)	41 – 63	48.13 (7.53)	41 – 60	49.50 (7.29)	41 – 63	0.574
Withdrawal	47.31 (7.60)	34 – 58	45.50 (7.65)	34 – 58	49.13 (7.59)	39 – 58	0.382
Attention Problems	46.63 (8.98)	33 – 59	48.13 (9.61)	36 – 59	45.13 (8.68)	33 – 56	0.328
Adaptive Skills	53.88 (7.34)	38 – 68	53.00 (9.52)	38 – 68	54.75 (4.80)	48 – 62	0.721
Adaptability	53.75 (7.14)	39 – 64	50.13 (7.77)	39 – 60	57.38 (4.34)	51 – 64	0.083
Social Skills	52.25 (9.65)	30 – 70	51.13 (11.86)	30 – 70	53.38 (7.48)	41 – 66	0.798
Leadership	56.31 (8.51)	38 – 70	54.50 (10.54)	38 – 70	58.13 (6.03)	52 – 70	0.574
Activities of Daily Living	52.69 (7.18)	39 – 65	54.25 (6.23)	47 – 62	51.13 (8.13)	39 – 65	0.442
Functional Communication	51.38 (8.42)	35 – 64	52.13 (10.51)	35 – 64	50.63 (6.35)	39 – 57	0.721

Note. BASC-2 = Behaviour Assessment System for Children, 2nd Edition; SD = standard deviation; BSI = Behavioural Symptoms Index.

Table 4

Mean scores on the reading, phonological processing, and symbol processing measures

	Total n = 16		**High fluency n = 8**		**Low fluency n = 8**		**p-values high vs. low**
	Mean (SD)	**Range**	**Mean (SD)**	**Range**	**Mean (SD)**	**Range**	
Months of Grade 1 completed at first appt.	6.94 (4.37)	0 – 10	8.63 (2.88)	2 – 10	5.25 (5.12)	0 – 10	0.234
CBM (number correct/minute)							
LSF	52.44 (15.37)	27 – 79	65.00 (7.07)	57 – 79	39.88 (9.76)	27 – 55	0.000
WIF	55.69 (29.03)	8 – 92	65.63 (28.05)	16 – 92	45.75 (28.17)	8 – 80	0.105
WIAT-III (standard score)							
Early Reading Skills	105.19 (12.53)	80 – 121	108.88 (10.92)	93-121	101.50 (13.65)	80 – 120	0.279
Word Reading	101.31 (14.49)	75 – 129	102.63 (13.97)	82-129	100.00 (15.83)	75 – 125	0.721
Pseudoword Decoding	101.25 (14.75)	76 – 133	103.50 (13.50)	90-131	99.00 (16.50)	76 – 133	0.721
Spelling	100.38 (11.03)	69 – 115	102.75 (8.84)	92-115	98.00 (13.03)	69 – 113	0.442
Phonological Processing (z-score)							
Auditory Closure	1.87 (1.11)	-0.95 – 3.15	2.15 (0.73)	1.30 – 3.15	1.58 (1.39)	-0.95 – 3.11	0.721
Auditory Analysis	0.34 (1.72)	-1.74 – 3.30	-0.02 (1.097)	-1.38 – 1.60	0.69 (2.21)	-1.74 – 3.30	0.721
Sentence Memory	0.35 (1.13)	-1.74 – 2.61	0.88 (0.96)	-0.43 – 2.61	-0.18 (1.09)	-1.74 – 0.98	0.161
Symbol Processing (z-score)							
Underlining Test							
Individual Shape	-0.42 (1.12)	-2.59 – 1.24	-0.29 (0.969)	-1.72 – 0.96	-0.54 (1.31)	-2.59 – 1.24	0.902
Shape Sequence	-0.72 (1.49)	-3.84 – 1.12	-0.92 (1.64)	-3.84 – 0.48	-0.53 (1.43)	-2.88 – 1.12	0.710
Letter Sequence	-1.03 (1.01)	-2.68 – 0.77	-1.45 (0.70)	-2.30 – -0.42	-0.61 (1.13)	-2.68 – 0.77	0.128
Pronounceable Non-word	-0.79 (0.88)	-2.74 – 0.24	-0.47 (.49)	-1.22 – 0.05	-1.11 (1.10)	-2.74 – 0.24	0.383
Word	-0.73 (1.08)	-2.51 – 1.40	-1.01 (.97)	-2.51 – 0.19	-0.44 (1.17)	-1.77 – 1.40	0.456

Note. SD = standard deviation; CBM = curriculum based measurement; LSF = Letter Sound Fluency Test; WIF = Word Identification Fluency Test; WIAT-III = Wechsler Individual Achievement Test – 3rd Edition.

Table 5

Minimum cluster size as determined by Monte Carlo simulation for each ROI for the letters task > fixation rest contrast

Region of Interest	**BA**	**Minimum Cluster Size**	**Significant Cluster**
Group LF > HF			
IPL (including ANG and SMG)	39, 40	104.00	**yes**
STG and MTG (including Wernicke's Area)	21, 22, 42	59.40	**yes**
Occipitotemporal Area (including FG)	19, 37	121.20	**yes**
IFG (including Broca's Area)	44, 45	31.70	no
Superior Parietal Lobule	5, 7	302.90	**yes**
Insular Cortex		56.50	no
Dorsolateral Prefrontal Cortex	9, 46	57.90	no
Dorsal Anterior Cingulate Cortex	24, 32	105.40	**yes**
Striatum (caudate and putamen)		93.60	no
Group LF < HF			
IPL (including ANG and SMG)	39, 40	147.4	**yes**
STG and MTG (including Wernicke's Area)	21, 22, 42	115.90	**yes**
Occipitotemporal Area (including FG)	19, 37	106.60	**yes**
IFG (including Broca's Area)	44, 45	88.40	no
Superior Parietal Lobule	5, 7	80.00	no
Insular Cortex		143.90	**yes**
Dorsolateral Prefrontal Cortex	9, 46	82.10	**yes**
Dorsal Anterior Cingulate Cortex	24, 32	142.60	no
Striatum (caudate and putamen)		99.00	no

Note. BA = Brodmann's Area; LF = low fluency group; HF = high fluency group; IPL = Inferior Parietal Lobule; ANG = Angular Gyrus; SMG = Supramarginal Gyrus; STG = Superior Temporal Gyrus; MTG = Middle Temporal Gyrus; FG = Fusiform Gyrus; IFG = Inferior Frontal Gyrus.

Table 6

Significant differences in fMRI activations between the low fluency and high fluency groups for the letters task > fixation rest contrast

Region	**BA**	**Side**	**k**	**Peak Voxel MNI**			**T**
				x	**y**	**z**	
Group LF > HF							
Middle Occipital Gyrus	19	L	1550	-36	-76	25	3.80
Frontal Lobe Sub-Gyral	6	R	110	22	8	51	3.27
Middle Temporal Gyrus	39	R	207	50	-69	34	3.16
Precuneus	31	R	1326	8	-70	30	3.14
Group LF < HF							
Inferior Parietal Lobule	40	L	1076	-60	-31	48	5.23
Declive		R	1806	46	-70	-18	5.16
Middle Frontal Gyrus	8	L	584	-45	30	40	4.69
Insula	13	R	1127	45	-4	-11	4.37
Precentral Gyrus	6	L	195	-60	3	37	4.26
Temporal Lobe Sub-Gyral	21	R	174	52	-10	-18	3.5
Culmen		L	505	-40	-57	-21	3.37
Middle Temporal Gyrus	21	R	211	42	-4	-36	3.26
Middle Frontal Gyrus	8	R	280	4	59	37	3.13
Middle Frontal Gyrus	46	R	106	48	42	7	2.89
Insula	13	L	335	-42	14	-3	2.84
Insula	13	L	184	-44	-15	-9	2.75
Middle Temporal Gyrus	21	L	121	-50	2	-24	2.51

Note. LF = low fluency group; HF = high fluency group; BA = Brodmann’s Area; R = right hemisphere; L = left hemisphere; k = cluster size; MNI = Montreal Neurological Institute Coordinates.

Table 7

Minimum cluster size as determined by Monte Carlo simulation for each ROI for the words task > fixation rest contrast

Region of Interest	**BA**	**Minimum Cluster Size**	**Significant Cluster**
Group LF > HF			
IPL (including ANG and SMG)	39, 40	140.40	**yes**
STG and MTG (including Wernicke's Area)	21, 22, 42	95.50	**yes**
Occipitotemporal Area (including FG)	19, 37	130.60	**yes**
IFG (including Broca's Area)	44, 45	61.60	no
Superior Parietal Lobule	5, 7	257.60	**yes**
Insular Cortex		67.70	**yes**
Dorsolateral Prefrontal Cortex	9, 46	90.10	**yes**
Dorsal Anterior Cingulate Cortex	24, 32	124.40	no
Striatum (caudate and putamen)		147.90	no
Group LF < HF			
IPL (including ANG and SMG)	39, 40	91.40	**yes**
STG and MTG (including Wernicke's Area)	21, 22, 42	129.70	**yes**
Occipitotemporal Area (including FG)	19, 37	92.80	**yes**
IFG (including Broca's Area)	44, 45	94.90	**yes**
Superior Parietal Lobule	5, 7	29.70	no
Insular Cortex		135.20	**yes**
Dorsolateral Prefrontal Cortex	9, 46	105.80	**yes**
Dorsal Anterior Cingulate Cortex	24, 32	219.30	no
Striatum (caudate and putamen)		60.50	no

Note. BA = Brodmann's Area; LF = low fluency group; HF = high fluency group; IPL = Inferior Parietal Lobule; ANG = Angular Gyrus; SMG = Supramarginal Gyrus; STG = Superior Temporal Gyrus; MTG = Middle Temporal Gyrus; FG = Fusiform Gyrus; IFG = Inferior Frontal Gyrus.

Table 8

Significant differences in fMRI activations between the low fluency and high fluency groups for the words task > fixation rest contrast

Region	**BA**	**Side**	**k**	**Peak Voxel MNI**			**T**
				x	**y**	**z**	
Group LF > HF							
Precuneus	7	R	1140	27	-52	56	3.52
Precuneus	7	L	331	-21	-61	57	3.47
Precuneus	7	R	2692	18	-70	45	3.36
Middle Temporal Gyrus	21	L	165	-66	-16	-9	2.99
Middle Frontal Gyrus	9	R	99	46	33	22	2.68
Angular Gyrus	39	R	203	46	-55	40	2.42
Claustrum		R	83	32	16	10	2.19
Group LF < HF							
Inferior Parietal Lobule	40	L	335	-58	-39	46	6.26
Middle Temporal Gyrus	39	L	258	-60	-61	12	4.56
Fusiform Gyrus	19	R	499	50	-70	-14	4.03
Middle Temporal Gyrus	21	R	299	64	-36	-8	3.89
Fusiform Gyrus	37	L	549	-45	-48	-18	3.75
Superior Temporal Gyrus	38	R	897	54	9	-20	3.62
Insula	13	R	417	45	-13	4	3.38
Fusiform Gyrus	37	R	128	44	-48	-21	3.23
Inferior Frontal Gyrus	9	L	363	-51	8	22	3.02
Parahippocampal Gyrus	36	R	114	28	-43	-12	3.02
Declive		L	115	-39	-82	-12	2.95
Insula	13	L	313	-45	-1	9	2.71

Note. LF = low fluency group; HF = high fluency group; BA = Brodmann's Area; R = right hemisphere; L = left hemisphere; k = cluster size; MNI = Montreal Neurological Institute Coordinates.

Table 9

Minimum cluster size as determined by Monte Carlo simulation for each ROI for the pictures task > fixation rest contrast

Region of Interest	**BA**	**Minimum Cluster Size**	**Significant Cluster**
Group LF > HF			
IPL (including ANG and SMG)	39, 40	199.40	**yes**
STG and MTG (including Wernicke's Area)	21, 22, 42	120.40	**yes**
Occipitotemporal Area (including FG)	19, 37	149.00	**yes**
IFG (including Broca's Area)	44, 45	89.60	no
Superior Parietal Lobule	5, 7	400.00	**yes**
Insular Cortex		156.70	**yes**
Dorsolateral Prefrontal Cortex	9, 46	141.10	**yes**
Dorsal Anterior Cingulate Cortex	24, 32	270.10	**yes**
Striatum (caudate and putamen)		145.70	**yes**
Group LF < HF			
IPL (including ANG and SMG)	39, 40	99.20	**yes**
STG and MTG (including Wernicke's Area)	21, 22, 42	116.60	**yes**
Occipitotemporal Area (including FG)	19, 37	79.90	**yes**
IFG (including Broca's Area)	44, 45	89.80	**yes**
Superior Parietal Lobule	5, 7	41.30	no
Insular Cortex		57.00	**yes**
Dorsolateral Prefrontal Cortex	9, 46	50.00	no
Dorsal Anterior Cingulate Cortex	24, 32	78.50	no
Striatum (caudate and putamen)		42.80	no

Note. BA = Brodmann's Area; LF = low fluency group; HF = high fluency group; IPL = Inferior Parietal Lobule; ANG = Angular Gyrus; SMG = Supramarginal Gyrus; STG = Superior Temporal Gyrus; MTG = Middle Temporal Gyrus; FG = Fusiform Gyrus; IFG = Inferior Frontal Gyrus.

Table 10

Significant differences in fMRI activations between the low fluency and high fluency groups for the pictures task > fixation rest contrast

Region	**BA**	**Side**	**k**	**Peak Voxel MNI**			**T**
				x	**y**	**z**	
Group LF > HF							
Inferior Parietal Lobule	40	R	6428	36	-33	43	5.00
Superior Temporal Gyrus	22	L	754	-56	-12	-5	3.95
Superior Temporal Gyrus	22	R	237	56	-21	-0	3.30
Precentral Gyrus	6	R	412	54	9	33	3.20
Cuneus	19	L	529	-26	-85	34	3.11
Supramarginal Gyrus	40	L	458	-40	-48	40	2.93
Cingulate Gyrus	24	R	807	3	11	34	2.93
Insula		R	326	44	15	-5	2.74
Middle Frontal Gyrus	8	R	310	28	39	37	2.72
Caudate		R	239	14	15	-5	2.63
Middle Temporal Gyrus	22	R	156	58	-45	3	2.43
Putamen		L	314	-32	-12	-8	2.41
Group LF < HF							
Inferior Parietal Lobule	40	L	162	-57	-45	46	3.11
Temporal Lobe Sub-Gyral	21	R	316	51	-4	-20	2.82
Inferior Frontal Gyrus	45	L	217	-54	26	13	2.72
Inferior Temporal Gyrus	37	R	230	57	-67	-0	2.48
Insula	13	L	58	-34	2	18	2.38

Note. LF = low fluency group; HF = high fluency group; BA = Brodmann's Area; R = right hemisphere; L = left hemisphere; k = cluster size; MNI = Montreal Neurological Institute Coordinates.

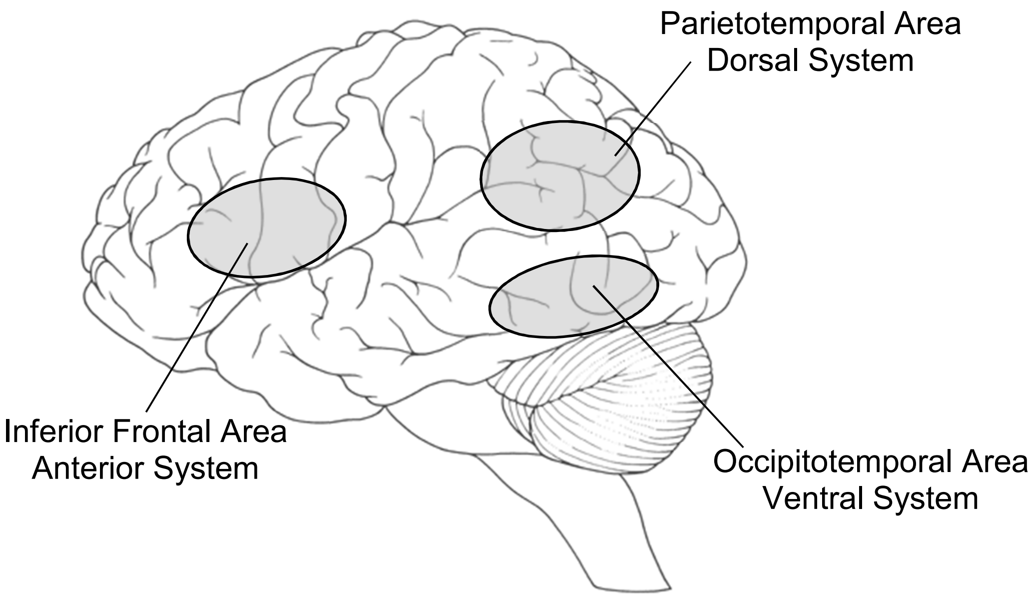

Figure 1. Approximate locations in the left cerebral hemisphere of the three neural systems for reading. Modified from http://msjensen.cehd.umn.edu/imagebank/Nerve/default.asp

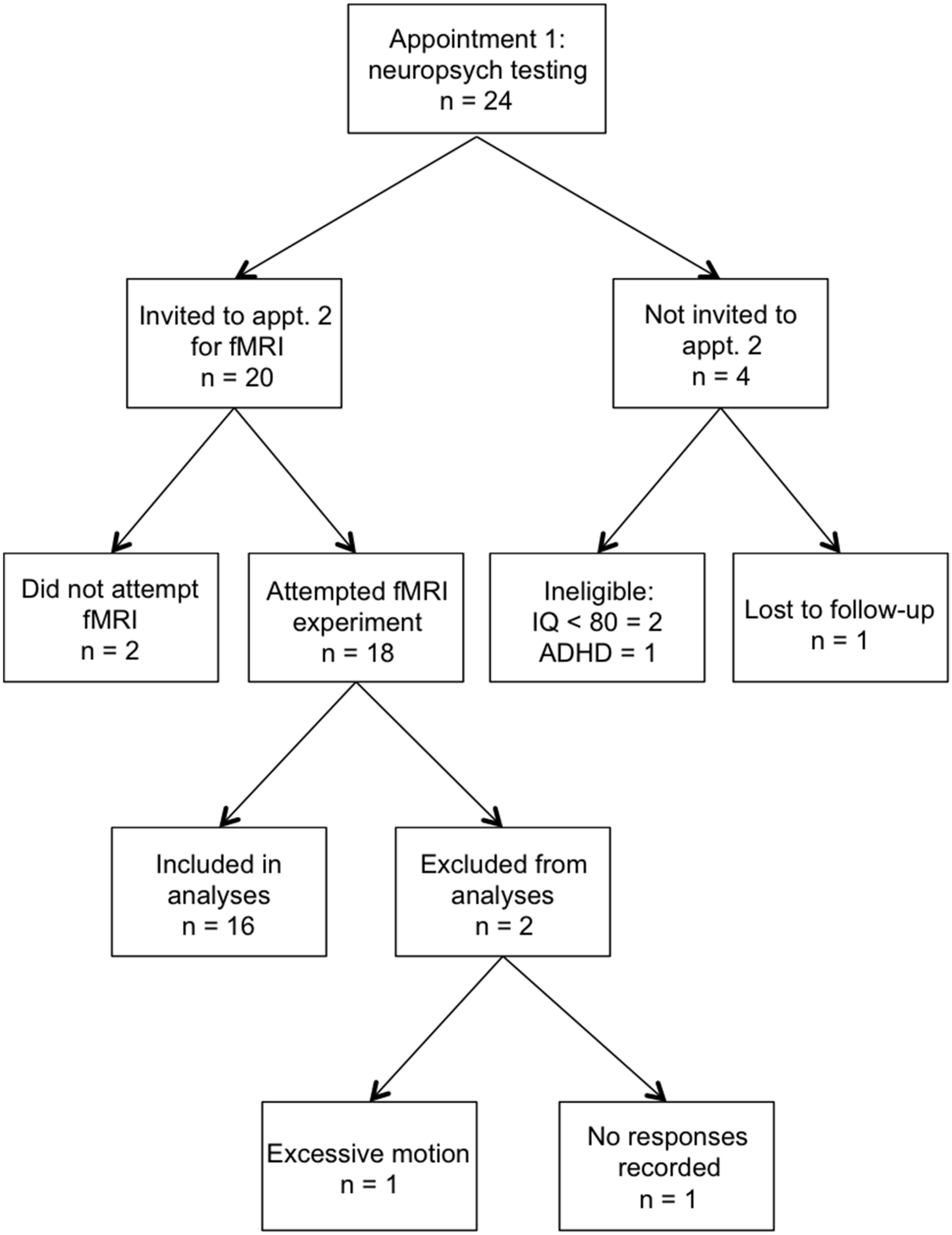

Figure 2. Diagram indicating participant flow through the experiment process.

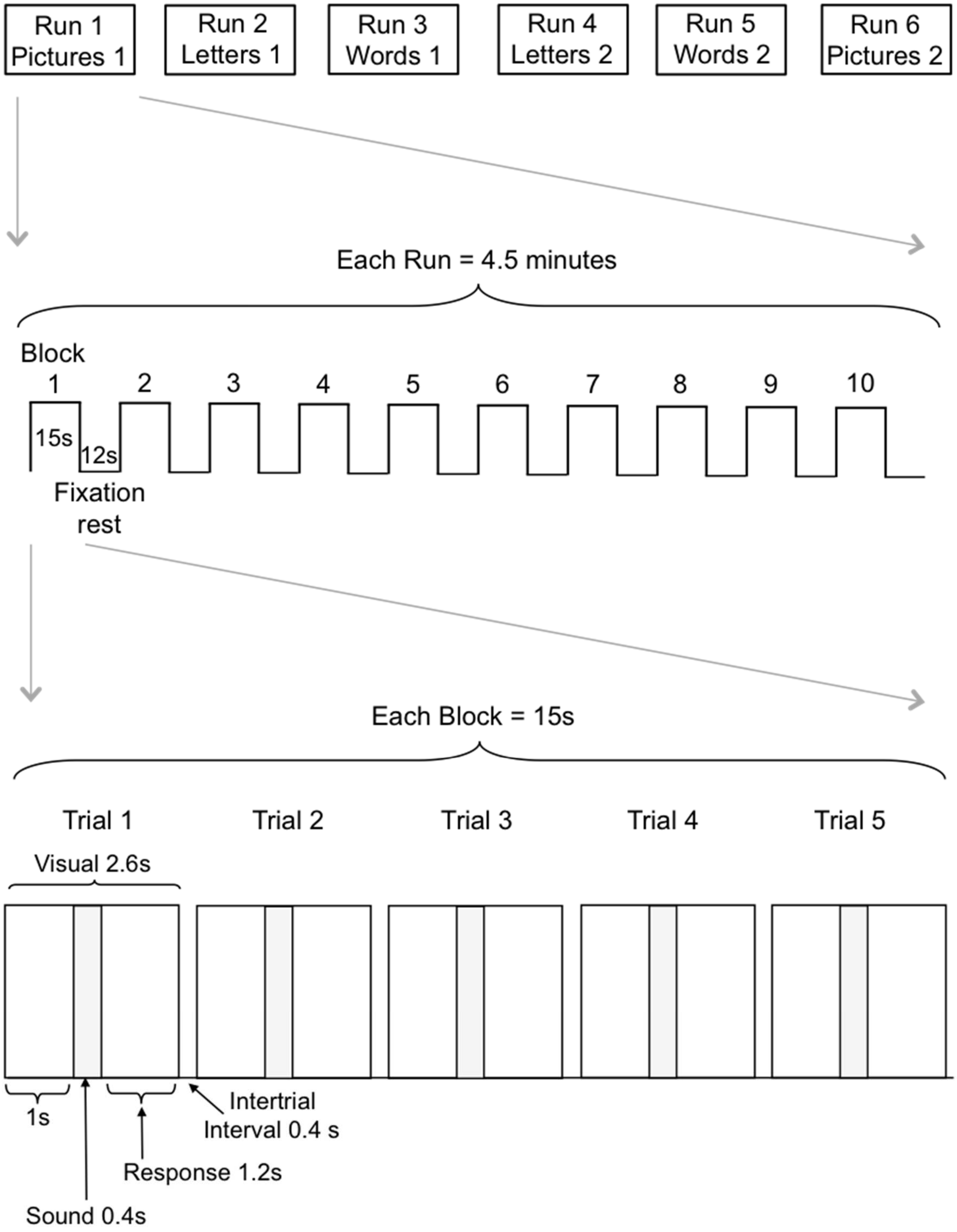
Run 1
Pictures 1
Run 2
Letters 1
Run 3
Words 1
Run 4
Letters 2
Run 5
Words 2
Run 6
Pictures 2
Each Run = 4.5 minutes
Block
1
2
3
4
5
6
7
8
9
10
15s
12s
Fixation
rest
Each Block = 15s
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5
Visual 2.6s
1s
Intertrial
Interval 0.4 s
Response 1.2s
Sound 0.4s

Figure 3. Diagram representation of the fMRI reading paradigm. The reading paradigm consisted of three different tasks: letter and phoneme matching, word and spoken word matching, and picture and spoken word matching. Each task was presented twice in two separate runs. Each run contained ten 15-second task blocks each separated by a 12-second fixation rest. Each block contained 5 trials. For each trial, the visual was presented first and remained on the screen for 2.6 seconds. One second following its presentation, the sound was presented during a 0.4 second silent period in the scanning. The participant then had 1.2 seconds to respond whether the visual and sound matched, or did not match. Trials were separated by a 0.4s inter-trial interval consisting of a blank screen.

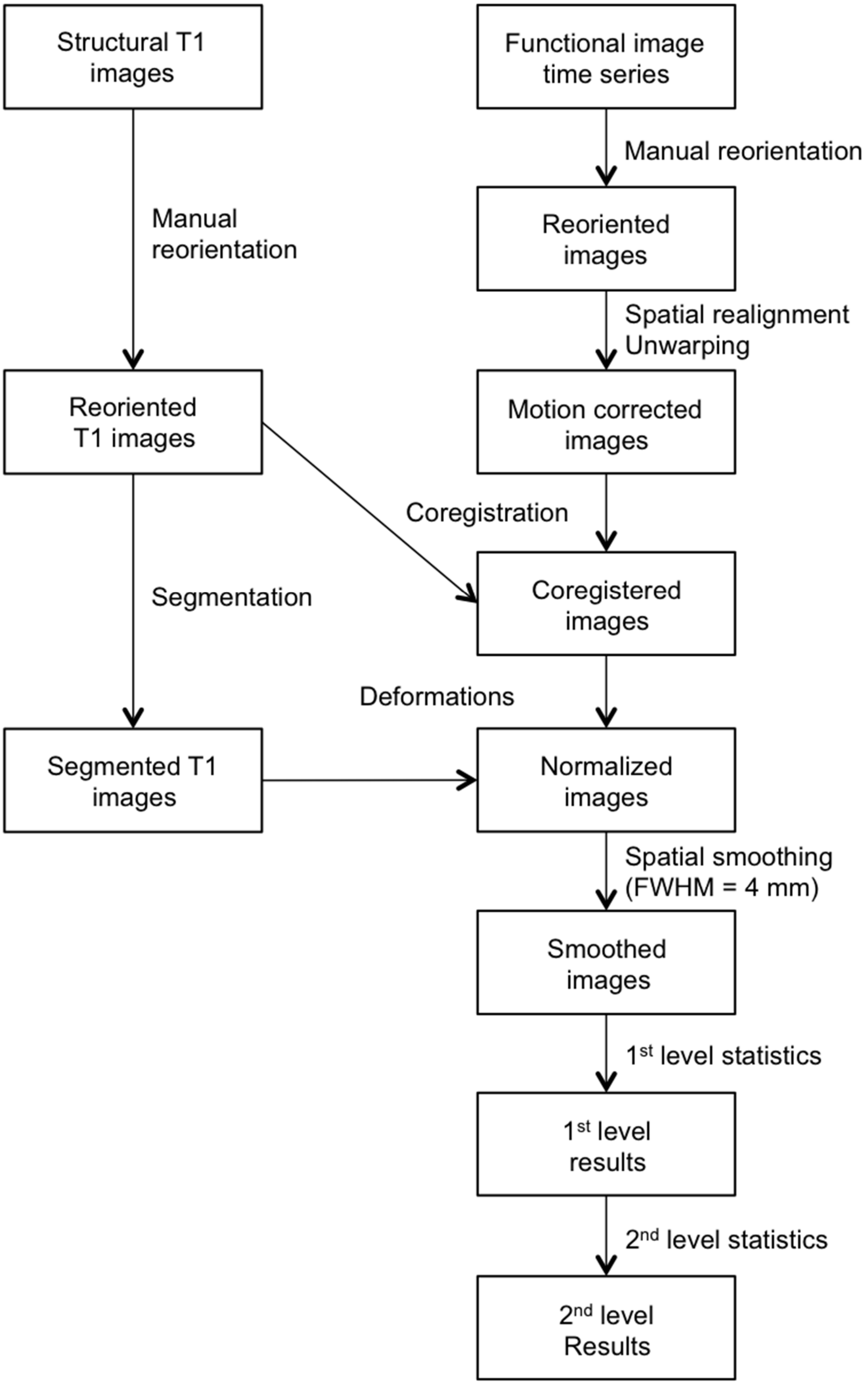

Figure 4. Diagram representation of the fMRI data preprocessing and statistical analyses.

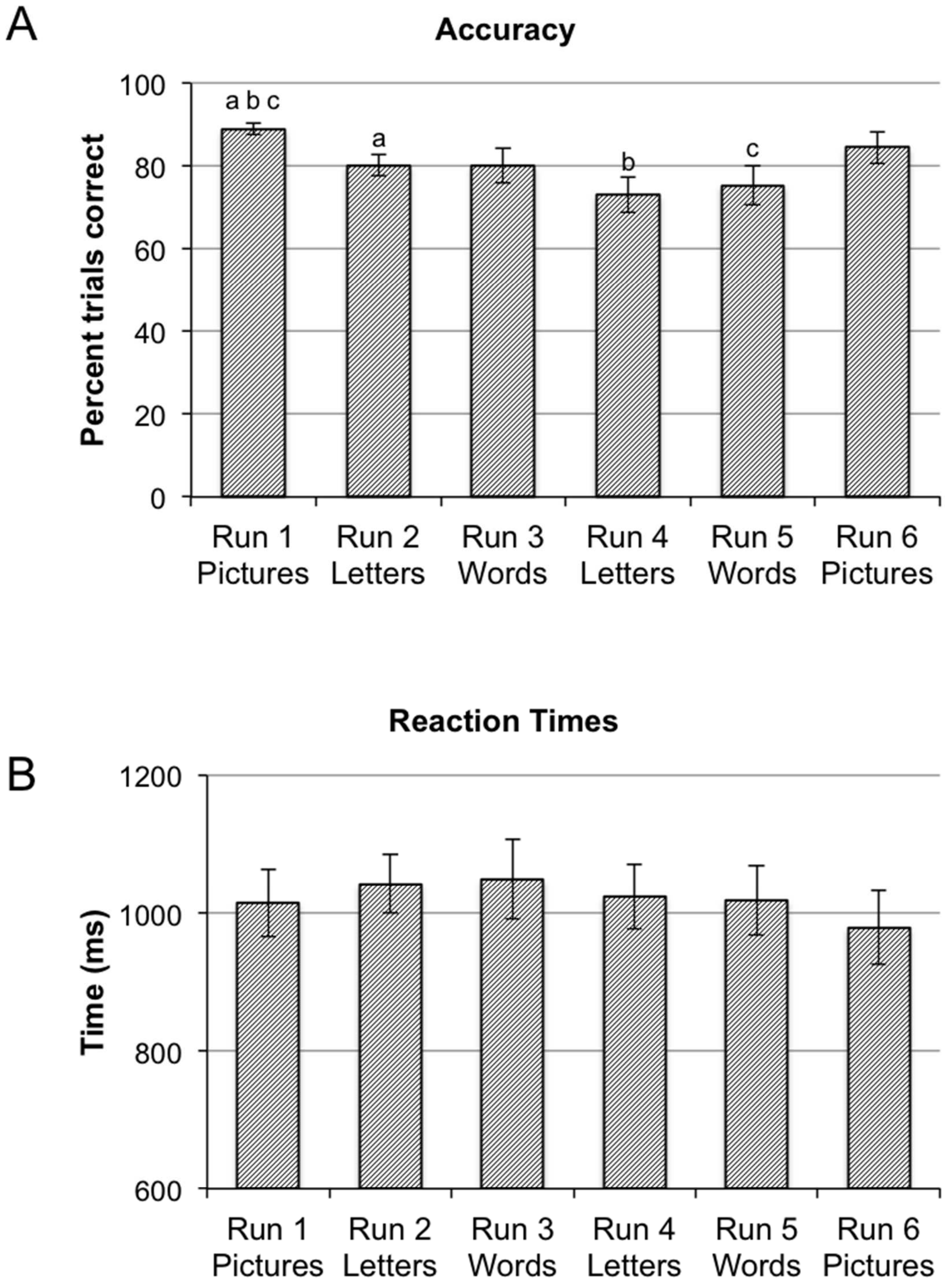

Figure 5. Mean and SEM of the percentage of total trials correct (A) and mean and SEM reaction time for all trials (B) on each run of the fMRI reading task for all participants (n=16). a, b, c = $p < 0.01$.

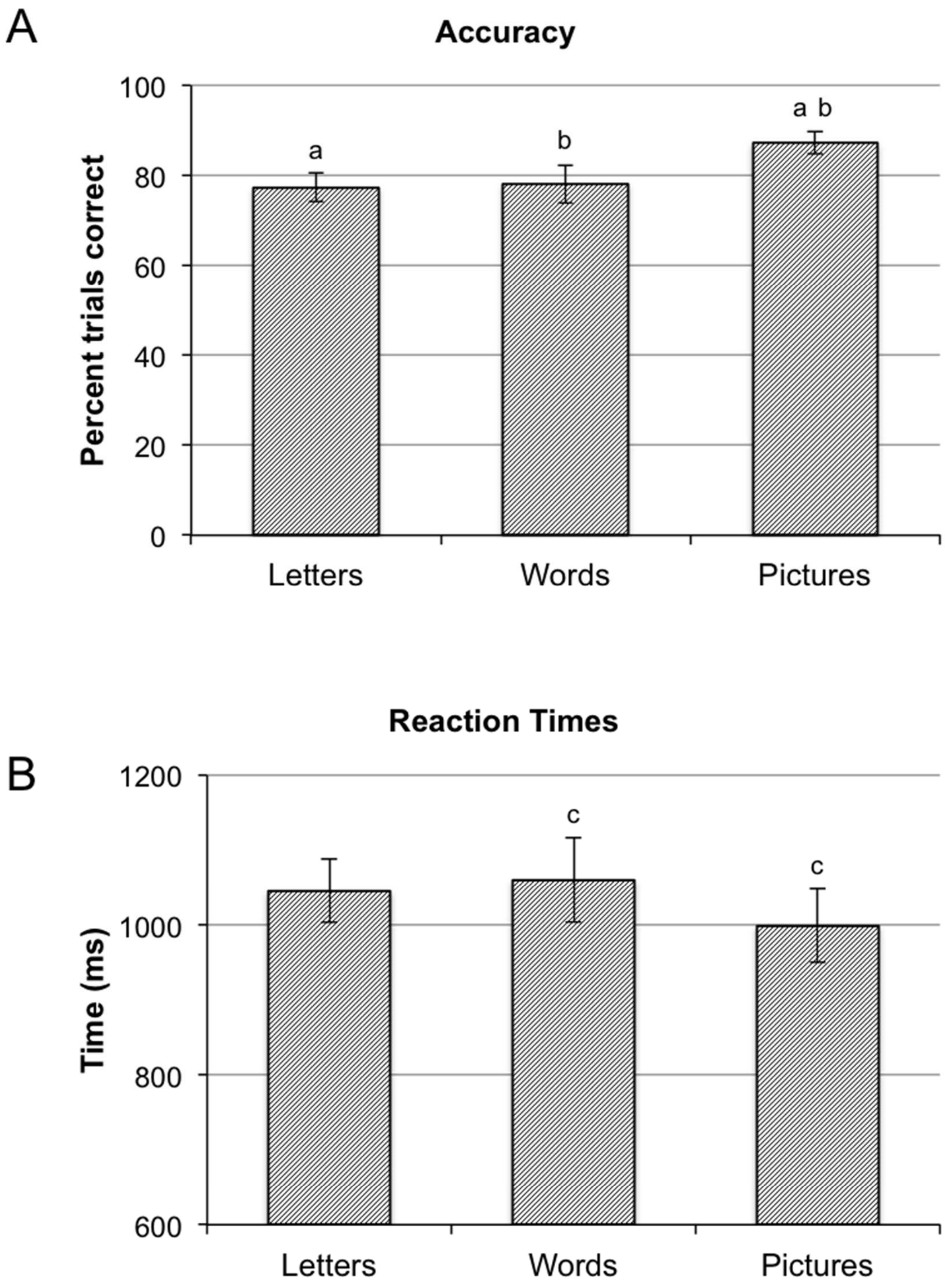

Figure 6. Mean and SEM of the percentage of total trials correct (A) and mean and SEM reaction time for all trials (B) on each task of the fMRI reading task for all participants (n=16). a, b, c = $p < 0.25$.

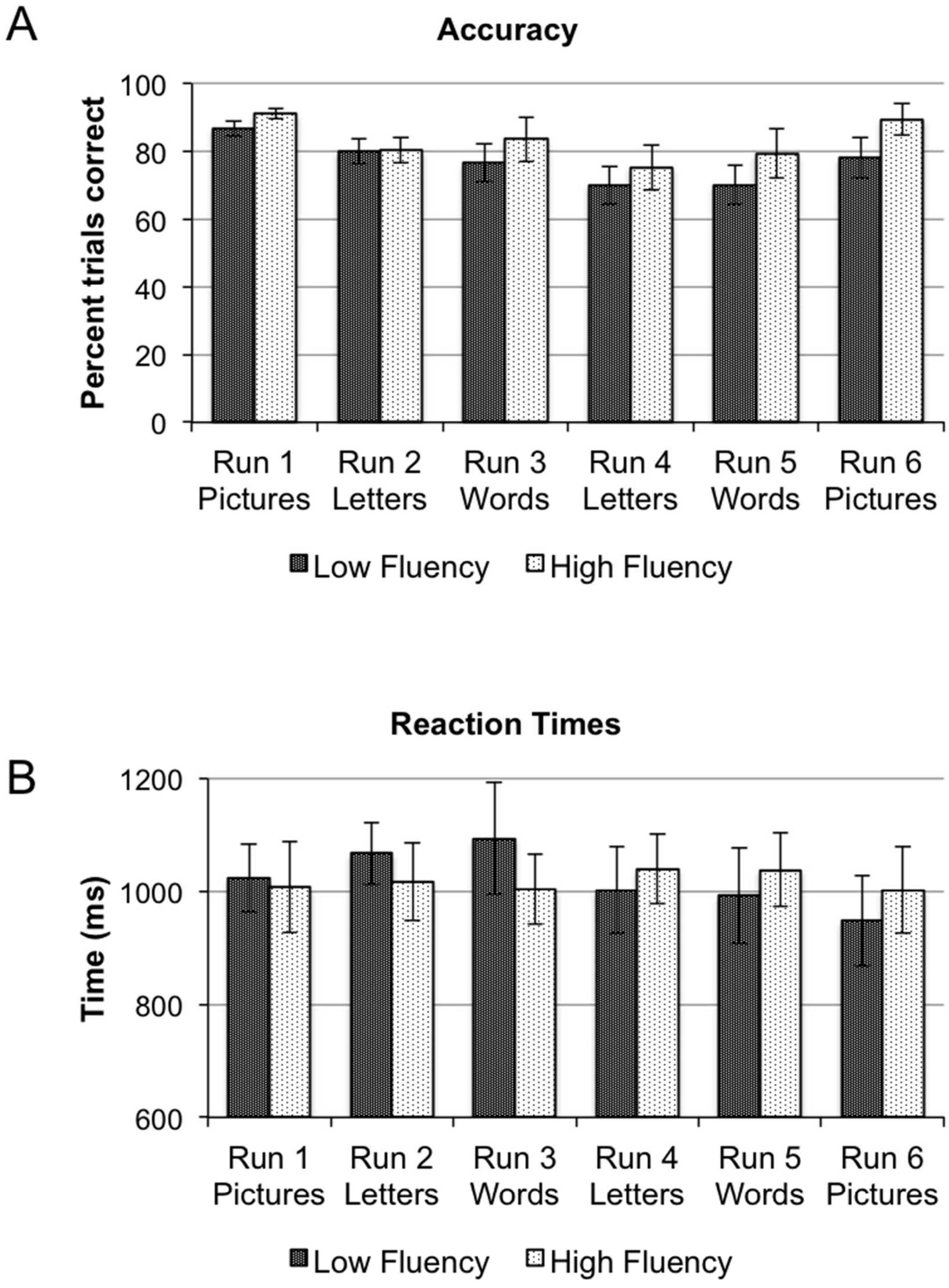

Figure 7. Mean and SEM of the percentage of total trials correct (A) and mean and SEM reaction time for all trials (B) on each run of the fMRI reading task for low (n=8) and high (n=8) fluency groups.

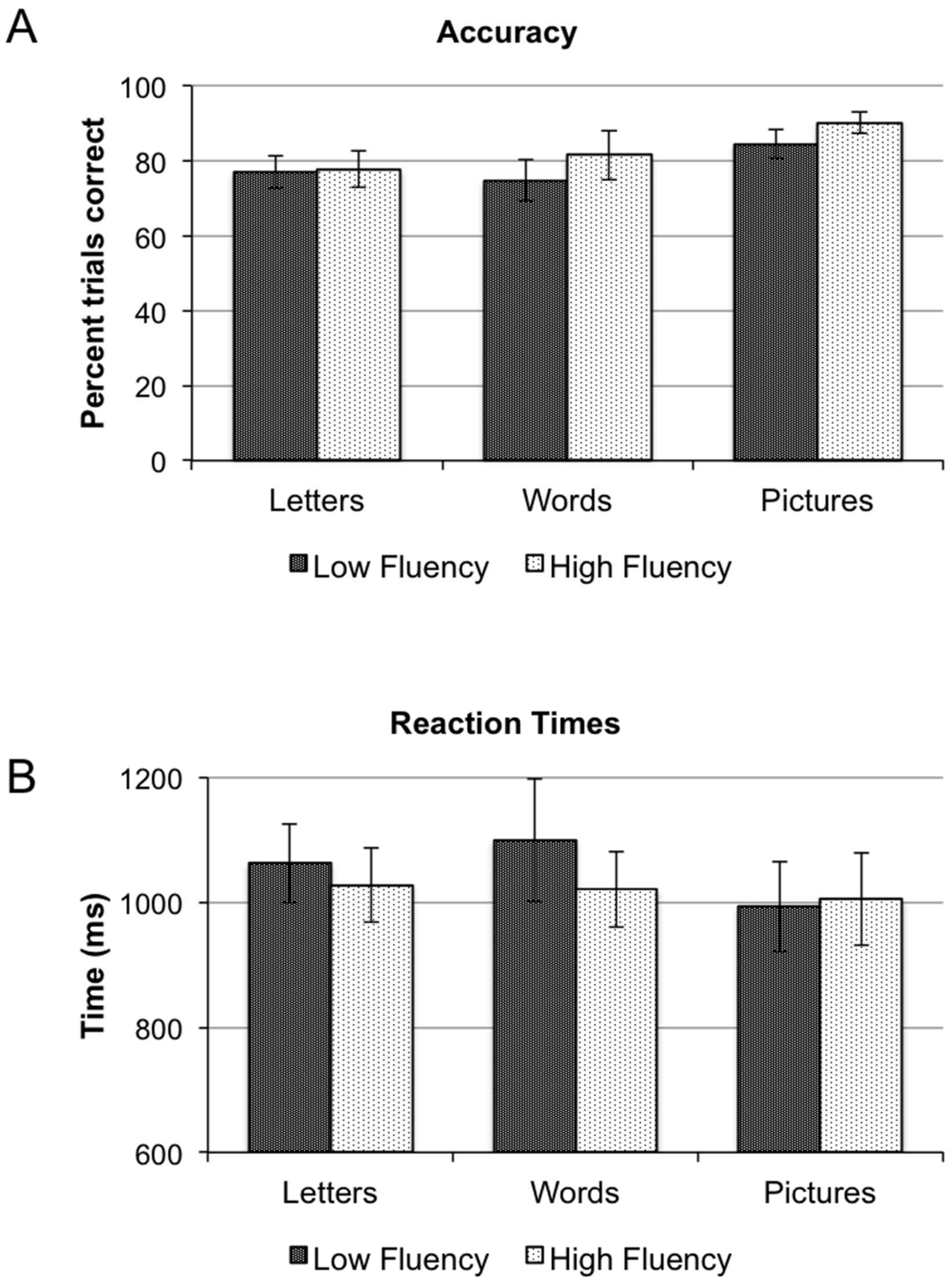

Figure 8. Mean and SEM of the percentage of total trials correct (A) and mean and SEM reaction time for all trials (B) for each task of the fMRI reading task for low (n=8) and high (n=8) fluency groups.

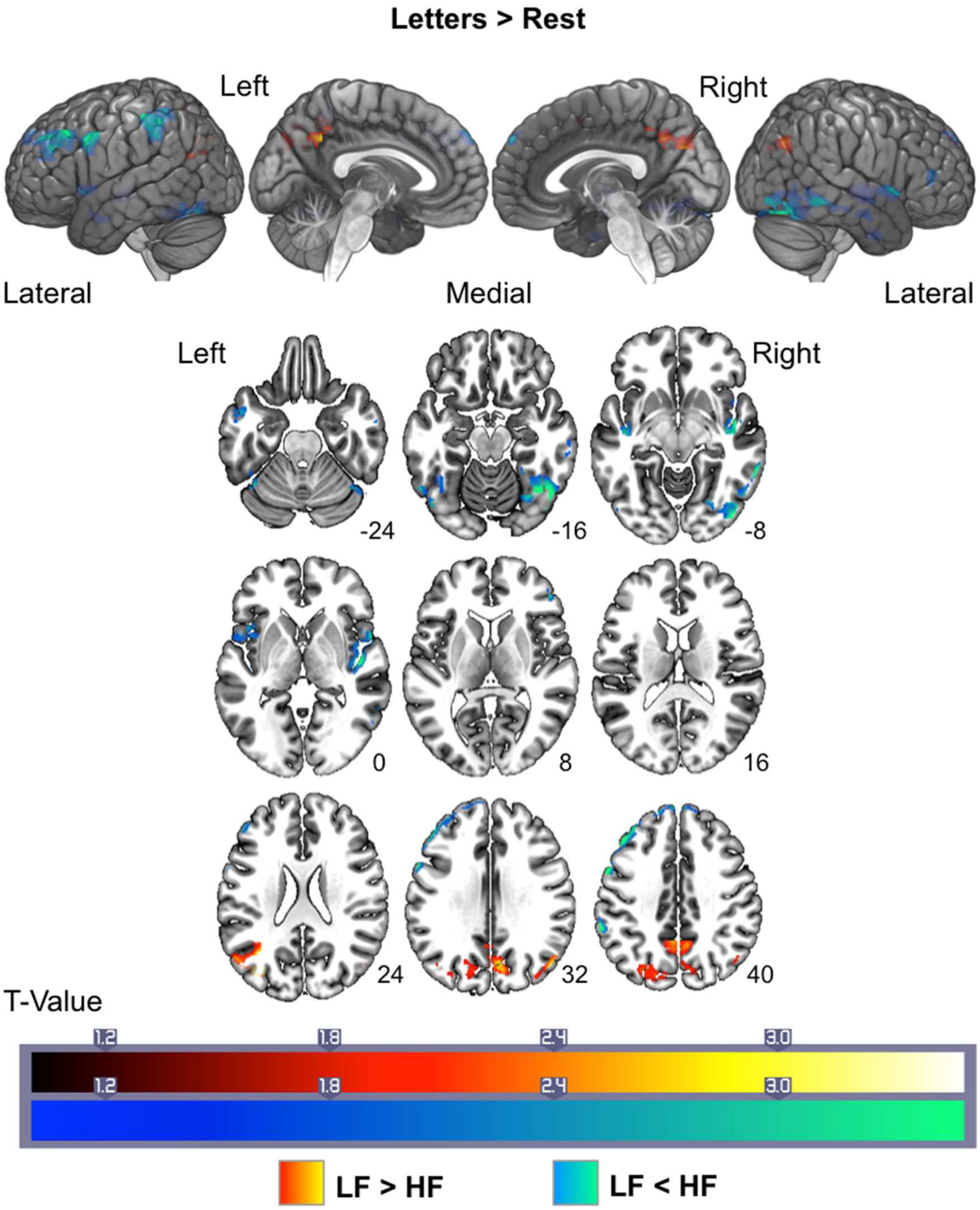

Figure 9. Statistical maps from a random-effects GLM analysis comparing the low fluency and high fluency reading groups on the letters task > fixation rest contrast. Red-yellow indicates greater activation in the low fluency group as compared to the high fluency group and blue-green indicates greater activation in the high fluency group as compared to the low fluency group. Significant activations are overlaid on the MNI brain template, $p<0.05$ (cluster-level corrected for multiple comparisons).

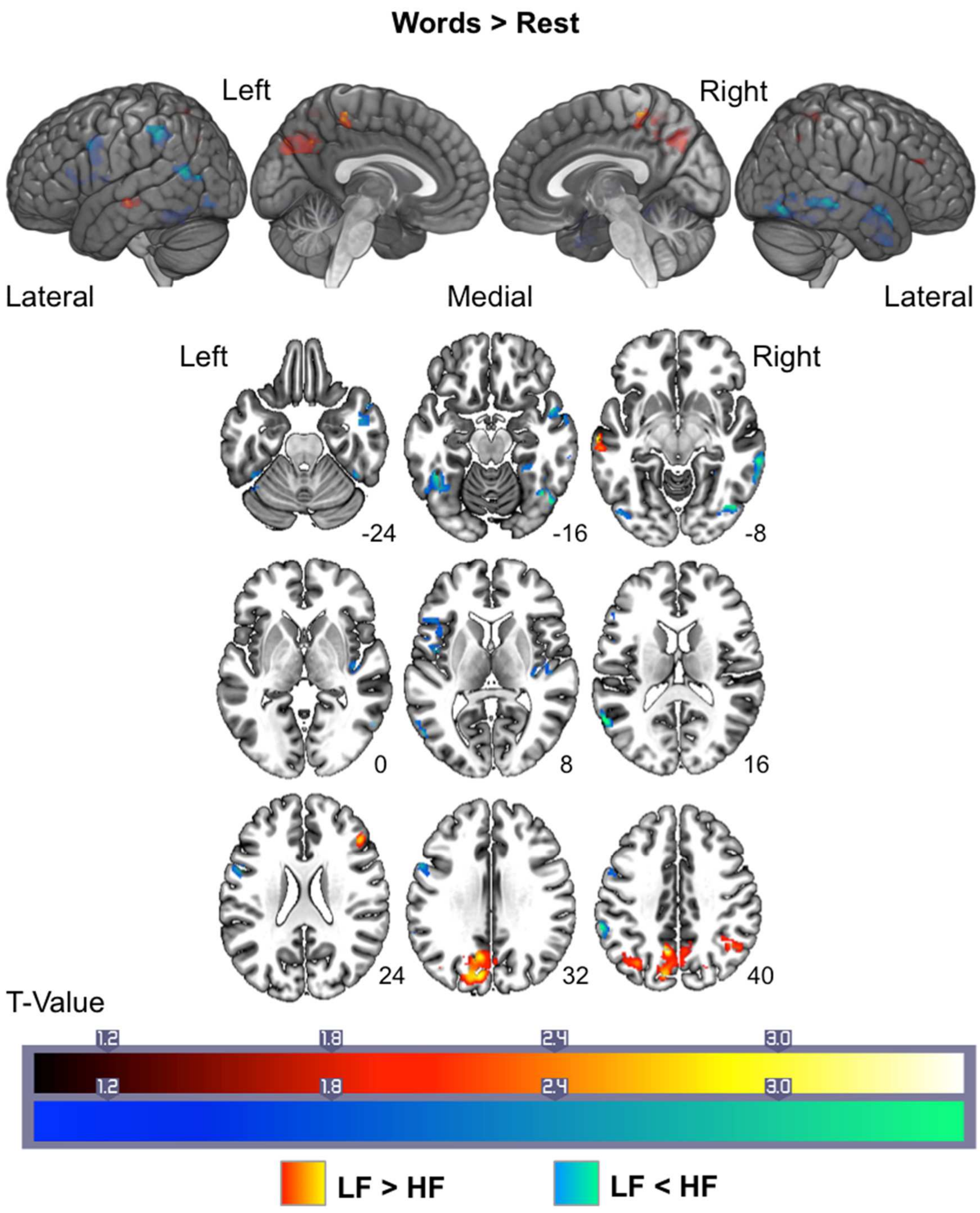

Figure 10. Statistical maps from a random-effects GLM analysis comparing the low fluency and high fluency reading groups on the words task > fixation rest contrast. Red-yellow indicates greater activation in the low fluency group as compared to the high fluency group and blue-green indicates greater activation in the high fluency group as compared to the low fluency group. Significant activations are overlaid on the MNI brain template, $p<0.05$ (cluster-level corrected for multiple comparisons).

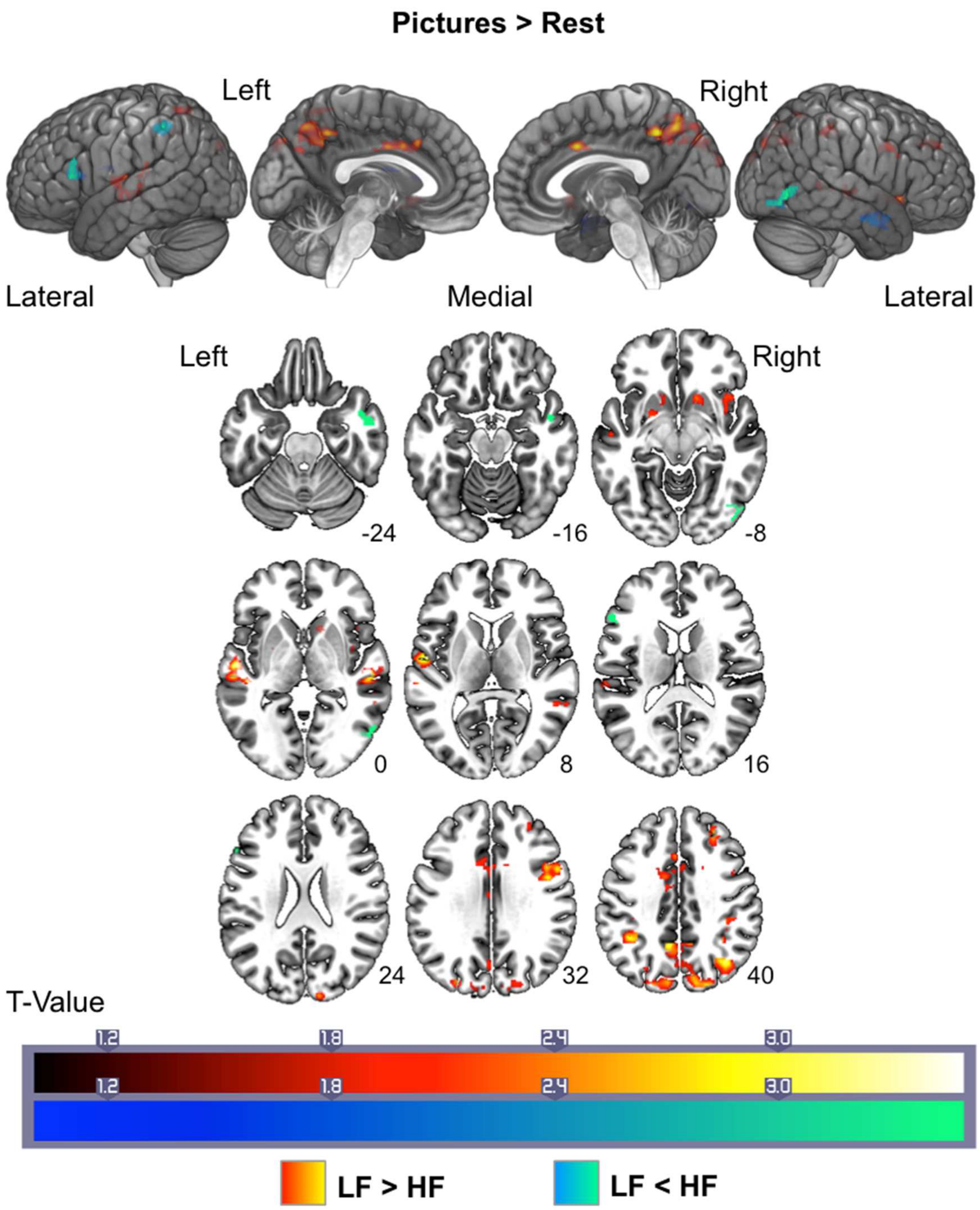

Figure 11. Statistical maps from a random-effects GLM analysis comparing the low fluency and high fluency reading groups on the pictures task > fixation rest contrast. Red-yellow indicates greater activation in the low fluency group as compared to the high fluency group and blue-green indicates greater activation in the high fluency group as compared to the low fluency group. Significant activations are overlaid on the MNI brain template, p<0.05 (cluster-level corrected for multiple comparisons).

APPENDICES

Appendix A

Glossary of Neuroimaging Terms

Block Design: an experimental design in which stimuli are presented sequentially within a condition, and each condition is presented continuously for a period of time. The goal is to maintain cognitive engagement in the task to allow for the hemodynamic response to reach its maximum level. Each block is followed by a moment of rest to allow for the hemodynamic response to return to baseline. Blocks of one condition are usually alternated with block(s) of different conditions.

Cluster: a group of voxels "clustered" together through initial thresholding.

Coil: a device designed to either create a magnetic field ("transmit"), detect a changing magnetic field ("receive"), or both.

Co-Registration: alignment of low-resolution fMRI images onto a high-resolution structural MRI image. This allows for viewing the activations in the context of a good quality brain image which can assist with interpretation.

Echo-planar Imaging (EPI): an imaging technique in which a complete image is obtained from a single excitation pulse. It enables very rapid imaging making it the predominant method in fMRI.

First-Level Analysis: statistical analysis of one individual's imaging data. The purpose is to determine which voxels are activated in response to the stimulation.

Fixed-effects Analyses: these statistical methods assume that all participants activate equally and are only interested in within-session errors. The results from these analyses are not valid for the population from which the group of participants were taken.

General Linear Model (GLM): a statistical analysis approach that compares activation signals between different task conditions on a voxel-wise or region-of-interest basis. General linear modeling sets up a model, or a general pattern that you would expect to see in the data, and fits this model to the data. A good fit between the model and the data suggests that the data were caused by the stimulation that was applied to the participant in the fMRI experiment.

Hemodynamic Response (HR): the time course of the BOLD response to an event. It rises and peaks approximately 5-6 seconds after stimulus onset and then returns to baseline. The slow nature of the response limits the temporal resolution of fMRI.

Paradigm: the construction, organization, timing, and behavioural predictions of cognitive tasks performed by the participant during an fMRI experiment.

Pre-Processing: a series of mathematical operations performed on the imaging data that prepare it for statistical analysis. The purpose is to remove artifacts from the data and condition the data in order to maximize the sensitivity of statistical analysis.

Random Effects (of Mixed-Effects) Analyses: statistical methods that take into account between session errors and make fewer assumptions about the data. These results are valid for the population from which the group of participants were drawn. These analyses tend to give more "conservative" results.

Region of Interest (ROI): an area on the brain image defined automatically or manually for data analysis. Predictions can be tested based solely on the regions of interest, rather than brain wide. Corrections for multiple tests done for each voxel are then reduced.

Registration: the process of transforming data from different individuals into one coordinate system so that data can be compared across individuals. Human brains differ in size and shape so they need to be transformed to fit a standard space.

Run: a single, continuous collection of fMRI images.

Second-Level Analysis: statistical analysis that combines results across sessions or subjects to create a single result or that compares different groups of subjects.

Signal-to-noise Ratio (SNR): the ratio between the signal intensity of the object and the standard deviation of the background noise.

Spatial Resolution: the ability of an instrument to image two separate sources of signal as separate entities. The smaller the distance between the two sources of signal, the better the spatial resolution.

Statistical Map: the output from the first-level analyses. A 3D data set showing the statistical test results for each voxel. It indicates the areas in the image where the brain activated in response to the stimulus.

Stereotaxic Space: a three-dimensional arrangement. In neuroimaging research, brain images are usually warped to fit into a common stereotaxic space so that images from different individuals can be compared.

Stimulation: the carrying out of some cognitive or physical activity.

Subtraction Logic: two events are compared that supposedly differ by only one factor. Since absolute signal strength in fMRI is meaningless on its own, brain activation levels need to be considered relative to another condition. Therefore, all neuroimaging experiments rely on subtraction logic to understand the data.

T1-weighted MRI: a type of magnetic resonance image that is best for delineating anatomical structures and differentiating between white and gray matter. In these images, fat-based tissues are bright, water-based tissues are mid-gray, and cerebrospinal fluid is dark.

Temporal Resolution: the shortest amount of time that can be measured between two different events in an imaging experiment.

Tesla: the unit of magnetic flux density or field strength. One Tesla is 20 000 times the Earth's magnetic field.

Thresholding: the process of selecting and applying a significance level to the statistical map in order to determine which parts of the brain were significantly activated in response to stimulation.

TR (time to repetition): the time between two excitation pulses. It is the time it takes to collect a set of images covering the whole brain. The TR determines the sampling rate of the experiment.

Volume: a set of images covering the entire brain; also referred to as an image or a scan.

Voxel: a three-dimensional volume element in an image.

Voxelwise: on a voxel-by-voxel basis.

Note: Adapted from "Neuroimaging in Developmental Clinical Neuroscience" by J. M. Rumsey and M. Ernst (Eds.), 2009, New York, NY: Cambridge University Press.

Appendix B

Parental Permission/Research Informed Consent

Title of Study: An fMRI study of fluent and non-fluent beginning readers

Principal Investigators (PIs):

Jennifer Long, M.Sc.
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University of Windsor
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401 Sunset Avenue
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Jeffrey A. Stanley, Ph.D.
Wayne State University
Tolan Park Medical Bldg. 5B
3901 Chrysler Service Dr.
313-577-9090

In this document "you" is defined as you, your child or ward.

Purpose

You are being asked to allow your child to be in a research study investigating beginning readers because he/she is a Grade 1 or Grade 2 student and is between the ages of 6 and 7. This study is being conducted at the University of Windsor and Wayne State University. The estimated number of study participants to be enrolled is about 40. **Please read this form and ask any questions you may have before agreeing to be in the study.**

In this research study, the purpose is to examine whether certain findings in the results of this study can help us understand how the brain works while young children read. These findings may also help us understand brain differences that contribute to difficulties with learning how to read. The following will be collected: relevant demographic and background information; tests to measure reading ability and mental functions such as the ability to think and remember, these are called psychological tests; 2 brain images using a Magnetic Resonance (MR) machine.

As stated above, 2 types of images will be collected during the scan.

- Magnetic Resonance Imaging (MRI) which is a scan that takes pictures of the structure of the brain.
- functional Magnetic Resonance Imaging (fMRI) which measures activity in the brain. For the fMRI scan we will ask your child to do some simple reading tasks while he/she is in the scanner. He/she will be asked to silently read letters and words appearing one at a time on a screen. Following presentation of the visual letter or word, he/she will hear a spoken letter sound or word through headphones. One task will ask him/her to indicate if a letter matches a spoken letter sound or not. In the second task, he/she will be asked to indicate if a word matches a spoken word or not. In the third task, pictures of objects will be shown on the screen. He/she will be asked to indicate if the picture matches a spoken word or not. Brain images will be collected while these tasks are being done.

Prior to every MR examination, a verbal description of the scanner and procedures are provided and an opportunity to ask questions is provided.

Study Procedures

If you and your child agree to take part in this research study, he/she will be asked to participate in the following procedures.

1. An interview and testing session involving you and your child and Jennifer Long and a Research Assistant will be conducted at the University of Windsor and includes: 1) obtaining informed consent and child assent; 2) reviewing the inclusion/exclusion criteria of the study; 3) reviewing the MR exclusion criteria; and 4) conducting an evaluation which involves obtaining information about your child, answering questions about his/her behaviours and feelings, and several tests to measure his/her reading ability and mental functions such as the ability to think and remember.

   The evaluation will involve:
   - A parent/guardian interview to obtain necessary demographic and background information about your child related to reading and a parent questionnaire that asks about your child's behaviours and feelings.
   - Your child will complete several psychological tests that will measure verbal and nonverbal intelligence, reading level, beginning reading skills, reading fluency, language sound and symbol processing abilities, attention, memory, and handedness.

   This evaluation will take your child approximately 2 hours to complete his/her portion of the testing and 1 hour for you to complete the parent interview and questionnaire. You will be able to complete the interview and questionnaire while your child is completing the testing so that the visit will take approximately 2 hours.

2. If your child is eligible to continue with the study, the next step will be collecting the MRI and fMRI data. This will be done at a second appointment scheduled on a different date. This appointment will take place at Wayne State University in Detroit, Michigan because the equipment needed for this technique is not available in Windsor. Travel time to Wayne State University is approximately 15 minutes from the Detroit-Windsor tunnel (this does not include the time it may take to go through American customs which can vary depending on the day and time).

3. At the time of the MR examination, your child will receive an additional interview by our MR technologist to make sure your child is metal free. Your child will be excluded for safety reasons if any metal is found. After the interview, your child will be given headphones to wear to minimize the noise

the machine makes. You or MR staff can be in the scanner room next to the bed during the exam to comfort your child if needed. Your child will be placed on a long, narrow bed to which the head-coil has been attached, and he/she will be asked to slide his/her head into the head-coil. The bed is then slid into the center of the MR scanner. Your child will be asked to lie very still while the information is gathered.

This data will be collected in one scanning session.

- A structural MRI and fMRI will be performed. For the fMRI, your child will be asked to perform simple reading tasks while in the scanner. He/she will be asked to silently read letters and words appearing one at a time on a screen. Following presentation of the visual letter or word, he/she will hear a spoken letter sound or word through headphones. One task will ask him/her to indicate if a letter matches a spoken letter sound or not. In a second task, he/she will be asked to indicate if a word matches a spoken word or not. In the third task, pictures of objects will be shown on the screen. He/she will be asked to indicate if the picture matches a spoken word or not. Brain images will be collected while these tasks are being done.
  There will be a 15-minute training session before this scan. The training session involves practicing the fMRI reading tasks on a desktop computer outside of the scanner to become familiar with the tasks. This scan takes approximately 50-60 minutes to complete.

4. We will provide your child with a unique study number, protecting your child's identity.

5. This study will involve two separate visits: visit number one at the University of Windsor for parent interview and questionnaire and child psychological testing, and visit number two at Wayne State University in Detroit for scanning.

Benefits:

There will be no direct benefit for your child; however, information from this study may benefit other children learning how to read in the future.

Risks:

By taking part in this study, you or your child may experience the following risks:

- People sometimes become upset or frustrated during psychological testing, interviewing, or when filling out questionnaires. However, each of the measures for this study has been used extensively with hundreds of children and parents without significant problems. Breaks will be provided as needed.

Your child will receive praise and encouragement throughout the testing and it will be emphasized that he/she simply try his/her best.

- People may become concerned regarding their privacy during the study. Your child will be assigned a unique study number and any data collected will be identified with that number to protect your child's identity.

- It is possible that confidentiality may be breached during this study. Because of this possibility, there is a social risk of the public being made aware of information collected during the study.

- The specific risks associated with the fMRI examination have to do with the ability of the strong magnet that is part of the imager to attract iron-containing metal objects. Your child will be instructed to place everything he/she has brought with him/her in a locker, including watches, jewelry, or anything else that could be damaged by the machine. Your child will not be enrolled in the study if your child: 1) is afraid of confined spaces, 2) has a pacemaker in his/her heart, 3) has had major surgery within the past 3 weeks, 4) has had brain surgery for an aneurysm, 5) has a neurostimulator, or 6) has metal fragments in or near the eye or brain.

- Your child will wear ear protection (headphones) to reduce noise disturbances since the fMRI scanner produces loud knocking sounds.

- There could be adverse effects that are delayed or very mild, such that they have not yet been recognized. Most people experience no ill effects from the large magnetic field, but some people do report claustrophobia (fear of being in enclosed small spaces), dizziness, mild nausea, headaches, and a metallic taste in their mouth, double vision or sensation of flashing lights. These symptoms, if present, subside shortly after leaving the fMRI scanner. No serious ill effects have been reported to date at any site operating at this field strength.

- It is important that you understand that these MRI scans are performed strictly for research purposes only. When we scan, we are looking for changes in the activity and structure of the brain between children of different reading ability. We don't scan looking for specific illnesses such as tumors, stroke, or trauma like your child's doctor would. Our MRI information is limited. However, if we believe that we have found a brain abnormality in your child's MRI scan, the principle investigator of the study will contact you to inform you of your need to further investigate this issue with your child's doctor. If your child's doctor wishes, he or she may contact the principle investigator for further information.

The following information must be released/reported to the appropriate authorities if at any time during the study there is concern that:

- Child abuse or neglect has possibly occurred.
- You or your child discloses illegal criminal activities, illegal substance abuse, or violence.

There may also be risks involved from taking part in this study that are not known to researchers at this time.

Study Costs

Participation in this study will be of no cost to you.

Compensation:

For taking part in this research study, you and your child will be paid for your time and inconvenience. For completing part 1, you and your child will each receive a $10.00 gift card for Chapters or McDonald's Restaurants at visit #1, and for completing part 2, your child will be paid $50.00 cash at visit #2. For visit #2, tolls for crossing the border and parking costs at Wayne State University will be reimbursed. You will also receive a summary of your child's performance on all the psychological measures. Please note that this summary is not a psychological assessment report.

If for whatever reason, you complete part but not all of the study, the terms of the payment will be as follows: 1) Parent interview, questionnaire, and child testing (visit #1): two $10.00 gift cards for Chapters or McDonald's Restaurants and brief summary; 2) MRI and fMRI Scans (visit #2): $50.00 cash.

Research Related Injuries

In the event that this research related activity results in an injury, treatment will be made available including first aid, emergency treatment, and follow-up care as needed. Care for such will be billed in the ordinary manner to you or your insurance company. No reimbursement, compensation, or free medical care is offered by Wayne State University, Children's Hospital of Michigan, Harper Hospital, or the Detroit Medical Center. If you think that your child has suffered a research related injury, contact the PI right away at 313-577-9090.

Confidentiality

All information collected about your child during the course of this study will be kept confidential to the extent permitted by law. Your child will be identified in the research records by a unique code number. Information that identifies your child personally will not be released without your written permission. However, the Institutional Review Board (IRB) at Wayne State University, or federal agencies with appropriate regulatory oversight [e.g., Food and Drug Administration (FDA), Office for Human Research Protections (OHRP), Office of Civil Rights (OCR), etc.] may review your records.

When the results of this research are published or discussed in conferences, no information will be included that would reveal your child's identity.

Voluntary Participation/Withdrawal

Taking part in this study is voluntary. You have the right to choose not to allow your child to take part in this study. You and/or your child are free to only answer questions that you want to answer. You are free to withdraw your child from participation in this study at any time. Your decisions will not change any present or future relationship with the University of Windsor, Wayne State University or its affiliates, or other services you or your child are entitled to receive.

The Principal Investigators (PIs) may stop your child's participation in this study without your consent. If your child has any side effects that are very serious or if your child becomes ill during the course of the research study your child may have to drop out, even if you would like to continue. The PIs will make the decision and let you know if it is not possible for your child to continue. The decision that is made is to protect your child's health and safety, or because your child did not follow the instructions to take part in this study.

While taking part in this study you will be told of any important new findings that may change your willingness to continue to take part in the research.

Questions

If you have any questions about this study now or in the future, you may contact Jennifer Long or Joseph Casey, Ph.D. at the following phone number (519) 253-3000, ext. 2220. If you have any question about the fMRI scan, you may contact Jeffrey A. Stanley, Ph.D. at (313) 577-9090. If you have questions or concerns about you or your child's rights as a research participant, the Research Ethics Coordinator at the University of Windsor can be contacted at (519) 253-3000, ext. 3948, or the Chair of the Institutional Review Board at Wayne State University can be contacted at (313) 577-1628. If you are unable to contact the research staff, or if you want to talk to someone other than the research staff, you may also call (313) 577-1628 to ask questions or voice concerns or complaints.

Consent to Participate in a Research Study:
To voluntarily agree to have your child take part in this study, you must sign on the line below. If you choose to have your child take part in this study, you may withdraw him/her at any time. You are not giving up any of your or your child's legal rights by signing this form. Your signature below indicates that you have read, or had read to you, this entire consent form, including the risks and benefits, and have had all of your questions answered. You will be given a copy of this consent form.

Name of Participant	Date of Birth
Signature of Parent/ Legally Authorized Guardian	Date
Printed Name of Parent Authorized Guardian	Time
*Signature of Parent/ Legally Authorized Guardian	Date
*Printed Name of Parent Authorized Guardian	Time
**Signature of Witness (When applicable)	Date
Printed Name of Witness	Time
Oral Assent (children age 7-12) obtained by	Date
Signature of Person Obtaining Consent	Date
Printed Name of Person Obtaining Consent	Time

* Both parent's signatures should be obtained however both are required for level 3 studies

** Use when parent/guardian has had consent form read to them (i.e., illiterate, legally blind, translated into foreign language).

Appendix C

Child Assent Form

Title: An fMRI study of fluent and non-fluent beginning readers

Study Investigators: Jennifer Long, M.Sc., Joseph Casey, Ph.D., Jeffrey Stanley, Ph.D.

Why am I here?

This is a research study. Only people who choose to take part are included in research studies. You are being asked to take part in this study because you are in Grade 1. Please take time to make your decision. Talk to your family about it and be sure to ask questions about anything you don't understand.

Why are they doing this study?

This study is being done to find out how the brain works while children read.

What will happen to me?

If you decide to take part in this research study, this is what you will do:

You will visit us two times. Today is the first visit.

Today, you will do some activities that are kind of like schoolwork. For example, I will ask you some questions, you'll work with paper and a pencil, and you will do some reading. All you need to do is try your best. We will give you little breaks to rest if you need them.

For the second visit, you will visit a university in Detroit. There you will have pictures of your brain taken by a special machine. Don't worry, this machine won't hurt you. While the machine is taking the pictures of your brain, you will read some letters and words that you see on a computer screen. You will have to lie very still while this is happening.

How long will I be in the study?

You will be in the study for two visits. The first visit will take about 2 hours and the second visit will take about 1 hour.

Will the study help me?

You will not benefit from being in this study; however information from this study may help other kids with learning to read in the future.

Will anything bad happen to me?

Kids sometimes become frustrated when answering the questions or doing the reading activities. The most important thing to remember is that you try your best. You can take little breaks to rest if you need to.

The machine that we will use to take pictures of your brain has a big magnet in it which will attract metal objects. Before you go in the machine, we will ask you and your parents/guardian questions to make sure you don't have any metal in your body.

The machine makes loud noises so you will wear headphones to block the sounds.

People sometimes feel scared inside the machine. Your parent/guardian or a staff member can stand beside you. If you feel too scared, you can stop and leave the machine.

Will I get paid to be in the study?

For taking part in this research study, you will receive a $10 gift card for Chapters or McDonald's at the end of today's visit. If you come visit us again in Detroit, you will receive $50 at the end of that visit.

Do my parents or guardians know about this?

This study information has been given to your parents/guardian and they said that you could be in it. You can talk this over with them before you decide.

What about confidentiality?

Every reasonable effort will be made to keep your information confidential. This means no one will know who the kids are that did this study and no one will know what answers you gave. However, we do have to let some people look at your study records.

We will keep your records private unless we are required by law to share any information. The law says we have to tell someone if you might hurt yourself or someone else. The study doctor can use the study results as long as you cannot be identified.

The following information must be released/reported to the appropriate authorities if at any time during the study there is concern that:
child abuse or elder abuse has possibly occurred,
you disclose illegal criminal activities, illegal substance abuse, or violence

What if I have any questions?

If you have questions about the study, your parents/guardian can contact Jennifer Long or Joseph Casey, Ph.D. at (519) 253-3000, ext. 2220. If you have questions about the machine that takes pictures of your brain, your parents/guardian can contact Jeffrey Stanley, Ph.D. at (313) 577-9090. If you have questions or concerns about your rights as a research participant, your parents/guardian can contact the Research Ethics Coordinator at the University of Windsor at (519) 253-3000, ext. 3948, or the Chair of the Institutional Review Board at Wayne State University at (313) 577-1628.

Do I have to be in the study?

You don’t have to be in this study if you don’t want to or you can stop being in this study at any time. Please discuss your decision with your parents and the researchers. No one will be angry if you decide to stop being in the study.

Appendix D

Initial Phone Call Script

Thank you for calling to find out more about our research study. My name is Jennifer and I am a Ph.D. student at the University of Windsor in the Clinical Neuropsychology program. The purpose of this research study is to look at how the brain works while young children read. As part of the study, we will ask you and your child to attend two separate appointments, the first at the University of Windsor and the second at Wayne State University in Detroit, Michigan. At the first appointment, you will complete an interview and a questionnaire about your child and your child will complete a variety of tasks that measure reading, thinking, and memory abilities. At the second appointment, your child will participate in a functional magnetic resonance imaging (fMRI) experiment. fMRI is a safe and non-invasive research technique that takes pictures of your child's brain as he/she performs a reading task. Do you think you and your child might be interested in participating in this study?

[If No]: Thank you very much for calling.

[If Yes]: Before enrolling your child in this study, we need to determine if he/she is eligible. So what I would like to do is ask you a few questions about your child. There is a possibility that some of these questions may make you feel uncomfortable or distressed; if so, please let me know. You also need to understand that all information that I receive from you by phone, including your name and any other identifying information will be strictly confidential and will be kept protected. The purpose of these questions is only to determine whether your child is eligible to participate in this study. Remember your participation is voluntary, you do not have to answer these questions and you may withdraw your participation at any time.

Do I have your permission to ask you these questions?

Date: ______________________________

What is your relationship to the child? ☐ Mother ☐ Father ☐ Legal Guardian

How old is your child? _________________

What grade is your child in? ________Has your child repeated any grades? ☐ Yes ☐ No

Is your child right-handed or left-handed? ☐ Right-handed ☐ Left-handed

What hand does your child write with? ____

Does he/she do everything with this hand? ____

What is your child’s first language? ☐ English ☐ French ☐ Other ______________

What is your child’s primary language? ☐ English ☐ French ☐ Other ___________

Does your child have any metal in his/her body (e.g. pacemaker, aneurysm clip, non-removable jewelry, etc.)? ☐ Yes ☐ No
If Yes, specify: ____

Does your child become nervous or anxious in enclosed and confined spaces (e.g. elevator, closet)? ☐ Yes ☐ No

The fMRI part of this study requires your child to lie still for about 45 minutes. Do you think your child will be able to do this? ☐ Yes ☐ No

Has your child been diagnosed with a learning disability? ☐ Yes ☐ No
[If yes] What type of learning disability? ______________________________

Has your child been diagnosed with ADHD? ☐ Yes ☐ No
[If yes] Who made this diagnosis (e.g., family doctor, pediatrician, psychiatrist, psychologist) ____

Has your child been diagnosed with a psychiatric problem (e.g. anxiety, depression)? ☐ Yes ☐ No
[If yes] What is the diagnosis? _______________________________________

Has your child ever had a head injury? ☐ Yes ☐ No Did they lose consciousness? ☐ Yes ☐ No
[If yes] Can you describe the injury or event? __________________________
____
For how long did they lose consciousness? _____________________________
Were there any long-term side effects? ________________________________

Does your child have any major medical conditions or neurological conditions, past or current? ☐ Yes ☐ No
[If yes] What condition? ____

Has your child had any major surgeries? ☐ Yes ☐ No
[If yes] What type of surgery? ______________________________________
When did this surgery take place? ___________________________________

Is your child currently taking any medications? ☐ Yes ☐ No
If “Yes”, specify medication(s): _____________________________________
____

☐ ELIGIBLE:

Based on your answers to these questions, your child may be eligible to participate in this study. I would like to invite you to participate in the first appointment at the University of Windsor. At this appointment, all information about the study procedures will be explained and you may ask questions. Then if you and your child decide that you would like to participate, you will complete the interview and questionnaire, and your child will complete the reading, thinking, and memory tasks. Would you like to schedule the first appointment at the University of Windsor now?

Appointment date and time: ____

☐ NOT ELIGIBLE:

Based on your answer to these questions, it does not appear that your child meets the requirements of this study. Thank you for your time and consideration.

Initial Email Script

Thank you for emailing to find out more about our research study. My name is Jennifer and I am a Ph.D. student at the University of Windsor in the Clinical Neuropsychology program. The purpose of this research study is to look at how the brain works while young children read. As part of the study, we will ask you and your child to attend two separate appointments, the first at the University of Windsor and the second at Wayne State University in Detroit, Michigan. At the first appointment, you will complete an interview and a questionnaire about your child and your child will complete a variety of tasks that measure reading, thinking, and memory abilities. At the second appointment, your child will participate in a functional magnetic resonance imaging (fMRI) experiment. fMRI is a safe and non-invasive research technique that takes pictures of your child’s brain as he/she performs a reading task. Do you think you and your child might be interested in participating in this study?

If yes, please call me at 226-346-8869. Or, email me your phone number and a good time to call and I will contact you. I would like to speak to you on the phone, so that I may ask you a few questions, answer any questions you have, and schedule the first appointment.

Thank you for your time and interest in this study.

Appendix E

Parent Interview Script

Today's Date: ___________________________

I would like to ask you some questions about you and your child. The purpose of these questions is to gather information that is related to his/her reading development. I may ask you some questions that you have already been asked on the phone. This is just to make sure that your child does meet all of the eligibility requirements for this study. If any of these questions make you feel uncomfortable, please let me know. You may also decline to answer any questions that you do not want to answer. Please feel free to stop me at any point if you have any questions.

CHILD BASIC INFORMATION

Child's ID #: __________________________________ Gender: ________________

Child's Birth Date (mm/yyyy): __________________________ Age: ____________

School Board: _______________________________________ Grade: ___________

Who does your child currently live with? ____________________________________

PARENT/GUARDIAN INFORMATION

What is your relationship to the child? ☐ Mother ☐ Father ☐ Other _____________

Are you presently employed? ☐ No ☐ Yes, Part-time ☐ Yes, Full-time ☐ Retired

What is your current job title? ____

What is the highest level of education you completed? ___________________________

What is your marital status? ☐ Married ☐ Single, never married ☐ Divorced
☐ Separated ☐ Widowed

Do you have a spouse or is there another significant caregiver for the child (e.g. mother, father, step-parent, other legal guardian if applicable)? ☐ Yes ☐ No

What is his/her relationship to the child? _____________________________________

Is he/she presently employed? ☐ No ☐ Yes, Part-time ☐ Yes, Full-time ☐ Retired

What is his/her current job title? ____

What is the highest level of education he/she completed? ___________________________

What is his/her marital status? ☐ Married ☐ Single, never married ☐ Divorced
☐ Separated ☐ Widowed

CHILD BACKGROUND INFORMATION

Has your child ever repeated a grade? ☐ Yes ☐ No *[If yes]* What grade did he/she repeat? ____

What is your child's first language? ☐ English ☐ French ☐ Other ________________

What is your child's primary language? ☐ English ☐ French ☐ Other _____________

Are there any other languages that your child speaks fluently? ______________________

____

Does your child wear glasses? ☐ Yes ☐ No

When was your child's last vision test? ____

Does your child have any other vision problems? ☐ Yes ☐ No

[If yes] Can you describe these problems? ____

____

Are these problems treated or corrected?____

____

When was your child's last hearing test? ____

Does your child have any hearing problems? ☐ Yes ☐ No

[If yes] Can you describe these problems? ____

____

Are these problems treated or corrected? ____

____

At what age did you child start to (estimate in months):
Crawl? ____
Walk alone? ____
Feed self with spoon? ____
Scribble? ____
Speak single words? ____
Speak sentences (more than 2 words)? ______________________________________
Describe an activity? ____

Have you had any concerns about your child's oral language development? ☐ Yes ☐ No

[If yes] What were your concerns? ____

____

Do you still have concerns? ____

At what age did your child start to read? ______________________________________

Have you had any concerns about your child's reading development? ☐ Yes ☐ No

[If yes] What are your concerns? ____

____

____

How often does your child read? ____

Does your child enjoy reading? ____

What does your child read? ____

Have you ever had any concerns about your child's learning? ☐ Yes ☐ No

Have you ever had any concerns about your child's school performance? ☐ Yes ☐ No

[If yes] What are your concerns? ____

____

____

When did these concerns start? ____

Do you still have these concerns? ______________________________________

In your opinion, does your child have any learning problems? ☐ Yes ☐ No
[If yes] What type of learning problems? _________________________________

____

When did these problems start? ____

Does he/she still have these problems? ___________________________________

Has your child ever been diagnosed with a learning disability? ☐ Yes ☐ No

[If yes] What type of learning disability?__________________________________

When did he/she receive this diagnosis? __________________________________

Who made this diagnosis (e.g., psychologist, school board)? ____________________

Does your child receive any help or interventions for this learning disability? ________

____

Has your child been identified by the school as having an exceptionality? ☐ Yes ☐ No

[If yes] Which one? ____

Has your child ever received any special help <u>at school</u>, for example, special class placement, tutoring, speech/language therapy? ☐ Yes ☐ No

[If yes] What type of help did he/she receive? ______________________________

____

____

When did this help start? ____

Does he/she still receive this help? _____________________________________

How often does he/she receive this help? _________________________________

Has your child received any additional, outside of school, reading instruction, tutoring, or extra help (For example, Kumon, Sylvan, Oxford, private tutoring, library programs)? ☐ Yes ☐ No

[If yes] What kind of services did he/she receive? ______________________________

____

____

When did these services start? ____

Does he/she still receive these services? ______________________________________

[If no] For how long did your child receive these services? _______________________

Does anyone in your family, immediate or extended, have a reading disability or problems with reading? ☐ Yes ☐ No

[If yes] Who and what type of problem? ______________________________________

____

____

Do you have any concerns about your child's behaviours, feelings, or psychological health? ☐ Yes ☐ No

[If yes] What are your concerns? ____

____

____

When did these concerns start? ____

Do you still have these concerns? ____

Do you have any concerns about your child's health? ☐ Yes ☐ No

[If yes] What are these concerns? ____

____

[Ask the following questions if information provided at the initial phone call was unclear]

Has your child been diagnosed with ADHD? ☐ Yes ☐ No
[If yes] When did he/she receive this diagnosis? ________________________________
Who made this diagnosis (For example, family physician, pediatrician, psychiatrist, psychologist)? ____

Has your child ever been diagnosed with a psychiatric problem (For example, anxiety, depression)? ☐ Yes ☐ No
[If yes] What has he/she been diagnosed with? _______________________________
When did he/she receive this diagnosis? _____________________________________
Does he/she still have this diagnosis? ______________________________________
Does he/she receive any treatment or interventions? (For example, medication, therapy)?
____

Has your child ever had a head injury? ☐ Yes ☐ No
Did he/she lose consciousness? ☐ Yes ☐ No
[If yes] Can you describe the injury or event? ________________________________
____
[If loss of consciousness] How long did he/she lose consciousness? _______________
At what age did this injury happen? ____
Did he/she experience any side effects afterward? ______________________________
____
Did he/she receive any treatments? ____

Does your child have any major medical conditions or neurological conditions, past or current? ☐ Yes ☐ No
[If yes] What condition(s) does he/she have? _________________________________
When did it start? ____
Does he/she still have it? ____
How was/is it treated? ____

Has your child ever had any major surgeries? ☐ Yes ☐ No
[If yes] What kind of surgery? ____
At what age did this surgery take place? ______________________________________

Is your child currently taking any medications? ☐ Yes ☐ No
[If yes] What medication(s) is your child currently taking? _______________________

____

[Verify]

Does your child have any metal in his or her body (e.g. pacemaker, aneurysm clip, non-removable jewelry, etc.)? ☐ Yes ☐ No
[If yes specify] ____

Does your child become afraid or anxious in enclosed or confined spaces (e.g., elevator, closet)?
☐ Yes ☐ No

The fMRI part of this study requires your child to lie still for about 45 minutes. Do you think your child will be able to do this? ☐ Yes ☐ No

[When finished]
Thank you for answering these questions.

How did you hear about this study?
☐ Letter from Child's School
☐ Windsor Activity Guide
☐ Windsor Parent Magazine
☐ Learning Disabilities Association (event, newsletter, flyer)
☐ Mom2Mom (website, newsletter, sale)
☐ Internet Which site? _________________________
☐ Poster Where? ____________________________
☐ Word of Mouth

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